National Environmental Science Programme

Final Report

Best Practice Coral Restoration for the Great Barrier Reef

Synthesis of Results

Ian M. McLeod, David Bourne, Daniela M. Ceccarelli, Lisa Boström-Einarsson, Nathan Cook, Stella E. Fulton, Boze Hancock, Peter Harrison, Margaux Hein, Agnès Le Port, Roima Paewai-Huggins, Hillary A. Smith and Adam Smith

JAMES COOK UNIVERSITY AUSTRALIA

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Cover photographs: (front) Snorkeler investigating a coral nursery. Image: Grumpy Turtle Productions; (back) Macroalgae removal and coral larval seeding experimental plots on Magnetic Island. Image: Ian McLeod.

This report is available for download from the NESP Tropical Water Quality Hub website:
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ACRONYMS

AIMS .... Australian Institute of Marine Science
COTS .... Crown-of-thorns Starfish
GBR .... Great Barrier Reef
GBRF .... Great Barrier Reef Foundation
GBRMP .... Great Barrier Reef Marine Park
GBRMPA ..... Great Barrier Reef Marine Park Authority
ICRI .... International Coral Reef Initiative
JCU .... James Cook University
NESP .... National Environmental Science Program
QPWS .... Queensland Parks and Wildlife Service
RRRC .... Reef and Rainforest Research Centre Limited
RTP .... Reef Trust Partnership
TWQ.............. Tropical Water Quality
UNEP .... United Nations Environment Programme

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EXECUTIVE SUMMARY

As coral cover in the Great Barrier Reef (GBR) continues to degrade, pressure is growing for direct interventions to assist the recovery of corals. A range of coral restoration and assisted recovery techniques have been trialled overseas and in Australia, however there has not to date been an evaluation of what will work best in GBR conditions.

This project was established in 2017 to:

- Review coral restoration methods around the world and assess the evidence of their success (Section 2)
- Trial the most promising coral restoration techniques in GBR conditions (Section 3)
- Bring together knowledge of coral restoration techniques for best practice guidelines for the GBR (Section 4)

In this report we summarise the outputs and outcomes of the National Environmental Science Program Tropical Water Quality Hub Project 4.3 'Best practice coral restoration for the Great Barrier Reef' (December 2017 - December 2020). These outputs included three book chapters, nine peer-reviewed journal articles, and six reports (listed in Appendix 1) including:

- A global review of coral restoration techniques with 407 unique case studies from around the world
- A published review of the efficacy of macroalgae removal for reef recovery
- A published review of methods for substrate stabilisation for reef recovery and their efficacy
- A book chapter summarising coral restoration in Australia to date
- An interactive visualisation of an open access database we created to allow for customised interrogation

This project also supported a series of in-water experiments and pilot studies (summarised in Section 3), including:

- Helping to establish Australia's first coral nursery and assistance with early monitoring and reporting for the Reef Restoration Foundation
- Establishing a long-term experiment at Magnetic Island investigating the efficacy of macroalgae removal and larval propagation to enhance coral recovery in partnership with the Earthwatch Institute Australia and other organisations
- Supporting the project planning and monitoring for coral restoration trials at Agincourt Reef (offshore from Cairns) and the Whitsunday Islands.

One of the primary goals of this project was to produce best-practice guidelines for GBR coral restoration projects. We worked with a broad team of national and international collaborators to produce best practice guidance, including:

- Producing content to update the Reef Resilience Network's restoration section on their website (https://reefresilience.org/restoration/)

- Producing content for the Reef Resilience Network's online restoration course and helping to facilitate the mentored version of the course
- Co-authoring the major global report 'A Manager's Guide to Coral Reef Restoration Planning and Design' and mentoring teams from Guam and the Northern Mariana Islands local government to plan restoration in their waters using the guide
- Co-authoring the major global report with UNEP and ICRI 'Coral reef restoration as a strategy to improve ecosystem services. A guide to coral restoration methods'
- Producing webinars and consolidating the best available best practice guidance to create the 'GBR toolkit for local-scale coral restoration' in partnership with GBRF and RRAP.

The novelty of the many intervention strategies presented here represent an important shift in the use of coral restoration - away from assessing the feasibility and efficacy of individual techniques, towards developing practical solutions with specific objectives linked to long-term outcomes in a changing climate. Many of the current projects present coral restoration as one of many strategies to strengthen the resilience of Australian coral reefs in the face of rising anthropogenic and climate change associated pressures. Restoring reefs to some arbitrary historical baseline is not the goal, rather, much of the research is focused on how restoration can be used in the context of adaptation to forecast disturbances such as increases in sea-surface temperatures. This approach requires research partnerships that extend beyond traditional coral reef science to include engineers, social scientists, citizen scientists, modellers, economists, infrastructure development experts, and project managers.

Coral restoration using existing methods in Australia is therefore best applied at the local reef scale where there is sufficient evidence of successful outcomes in terms of coral growth and survival. The RRAP is focused on producing an innovative suite of safe, acceptable, and cost-effective interventions to help protect the GBR from climate change, and increase the scalability of options. However, current techniques and methods used at a smaller-scale, such as a popular dive site, can bring about socio-cultural and economic benefits valuable to local livelihoods and communities. Further, while existing methods may not match the scale of the crisis facing coral reefs in a climate impacted future, restoration and adaptation techniques could be key to maintain remnant live reefs, effectively buying time as the world takes urgent global action on climate.

1.0 INTRODUCTION

Coral reefs surround much of Australia's tropical coastline and make an important contribution to the nation's identity and economy through associated cultural values, fisheries, tourism, and recreation. The Great Barrier Reef (GBR) is the world's largest coral reef system, extending along 2,300km of the east coast of Australia. The economic contribution of the GBR to Australia through reef-dependent industries such as tourism and fishing was estimated at AUD 6.4 billion for 2015-2016 (Deloitte Access Economics, 2017).

Despite world-leading research and management, including in large Marine Protected Areas, the GBR is following global trends of declining coral health (De'ath et al., 2012; Dietzel et al., 2020). Until recently, management of reefs in the Great Barrier Reef Marine Park (GBRMP) has focused on reducing stressors such as overfishing (through management and zoning), coastal development (through permitting and mitigation), and on improving water quality (through improved land and wastewater management) to facilitate natural resilience and recovery. Until recently, in-water restoration was not commonly undertaken; however, terrestrial-based restoration activities such as replanting land cleared for agriculture, riparian planting to stabilise riverbanks and engineering projects to restore water movement in wetlands are established approaches used to improve water quality from GBR catchments. Similarly, islands within the GBRMP have been actively managed through actions such as weed control, removal of pest animal species, and replanting of native species. Recently, more active management tools such as crown-of-thorn starfish (COTS) control have become an important part of reef management, with large-scale control on the GBR beginning in 2012 (GBRMPA, 2020).

In the last five years, there have been a series of damaging events such as large-scale coral bleaching, COTS outbreaks and cyclones that have caused further rapid declines in live coral cover in shallow waters (Cheal et al. 2017, Hughes et al. 2017). In 2017, seventy scientists, managers, Traditional Owners and stakeholders came together for a 'Reef Summit' to discuss what could be done to help address coral health decline. Following the summit, a 'Reef Blueprint for Resilience' was produced, in which reef restoration was highlighted for the first time as a potential tool to improve the resilience of the GBR (GBRMPA, 2017). The 'Reef Blueprint for Resilience' included a vision for 2020 with one component being "*Coordinated restoration trials are in place at demonstration sites, providing opportunities to test, evaluate and - where appropriate - scale up restoration methods to ecologically relevant scales".*

Coral restoration is relatively new to Australia, but has been used around the world for decades. This project was established in 2017 to:

1. Review coral restoration methods around the world and assess the evidence of their success (Section 2)
2. Trial the most promising coral restoration techniques in GBR conditions (Section 3)
3. Bring together knowledge of coral restoration techniques for best practice guidelines for the GBR (Section 4)

In addition to this project, many other research projects, programs and pilot restoration projects began around the same time with coral restoration and adaptation becoming a primary research focus in Australia between 2018 and 2020. Our team collaborated widely with relevant scientists, managers, restoration practitioners, stakeholders, and end-users in Australia and around the world to make sure resources were used most efficiently and knowledge gained shared as widely as possible.

The largest investment in this space has been the Reef Restoration and Adaptation Program (RRAP). The initial RRAP program objectives (2018) were to assess existing restoration techniques, and to develop new interventions and delivery methods to assist the GBR to recover from major disturbances and to assist its adaptation to a changing climate. The present project partnered with RRAP as there were shared goals of reviewing coral restoration tools used around the world, evidence of their success and their potential suitability for the GBR. This collaboration facilitated earlier delivery of the global review for coral restoration methods and allowed for the inclusion of an online interactive visualisation of the coral restoration database. https://www.gbrcoralrestoration.org/restoration-database

At the commencement of this project, there had been some early experiments and pilot studies investigating the efficacy of restoration to facilitate coral recovery in the GBR. These included transplanting corals, removing overgrown macroalgae and larval propagation (McLeod et al. *In Press*). The GBR Restoration Symposium was held in Cairns in July 2018 and was attended by over 300 people (Burrows et al. 2019), with several members of this project on the organisational committee. There have been a growing number of coral restoration projects in Australia over the last three years, with many having direct input from our project. These are described in Section 3.

Interest in coral restoration increased globally at the same time. The US National Oceanic and Atmospheric Administration commissioned the National Academy of Science to review interventions to increase the resilience of coral reefs (A/Prof David Bourne from this project was a member of the assembled NAS expert panel that produced two main reports from this review). The Coral Restoration Consortium, a community of practice composed of scientists, managers, coral restoration practitioners and educators hosted the Reef Futures conference in Florida in December 2018 with over 500 attendees. In late 2018, Australia joined Monaco and Indonesia to provide Secretariat services for the International Coral Reef Initiative (ICRI). ICRI is a partnership between Nations and organisations which strives to preserve coral reefs and related ecosystems around the world. In 2019, an ICRI *ad-hoc* committee on reef restoration was formed Co-Chaired by Ian McLeod from this project (McLeod et al. 2019a). This has served as one of the primary coordinating bodies for coral restoration around the world.

In 2019, the United Nations Environment Assembly passed resolution 4/13 on “Sustainable coral reefs management”. Following this resolution, the United Nations Environment Programme (UNEP) supported the development of a compilation of best practices for coral reef restoration. Our project has worked closely with UNEP on these, and Margaux Hein from this project worked as a full-time consultant for UNEP to lead the creation of best practice guidance material (e.g. Hein et al. In Press). A summary of best practice information drawing from our reviews and pilot studies is included in Section 4.

This report summarises the learnings from our research and in-water experiments, and reviews early coral restoration projects in the GBR, including ours. Section 5 shares best practice guidance from these reviews and projects and Section 6 discusses future directions.

2.0 GLOBAL REVIEWS OF CORAL RESTORATION TECHNIQUES

At the start of this project there was a lack of detailed reviews of restoration methods and their success in different environments. We collaborated with a wide range of scientists and managers from around the world to help to fill this critical knowledge gap. Our main review included 407 unique coral restoration case studies from peer-reviewed journal articles, an online survey, government and consultancy reports, and online sources. This information was shared in a range of ways including:

- A NESP TWQ Hub report 'Coral restoration in a changing world: A global synthesis of methods and techniques' (Boström-Einarsson et al. 2018)
- A database shared on the project website and hosted on Dryad (Dryad Digital Repository. doi:10.5061/dryad.p6r3816)
- A review contributed as part of the RRAP Investment Case (Hardisty et al. 2019) that was awarded AU $100 million in funding
- An interactive visualisation of the review data built using Tableau and hosted on the project website
- A peer-reviewed open-access journal article (Boström-Einarsson et al. 2020) that was recommended to F1000 as a top-quality article. This article had been cited 29 times within ten months of publishing. It has an Altmetric score of 195 (a measure of attention received by research articles), placing it in the top 5% of research outputs.

Additional collaborative reviews led by this team:

- Supporting coral reef recovery with small structures and substrate stabilisation: State of knowledge, considerations for management and implementation (Ceccarelli et al. 2020)
- Rehabilitation of coral reefs through removal of macroalgae: state of knowledge and considerations for management and implementation (Ceccarelli et al. 2018).

In addition to these outputs, we also collaborated with a wide range of authors in Australia and around the world to co-author two other reviews:

- Motivations, success, and cost of coral reef restoration (Bayraktarov et al. 2019)
- Optimizing return-on-effort for coral nursery and outplanting practices to aid restoration of the Great Barrier Reef (Suggett et al. 2019).

A short description of the main findings from these reviews follows.

2.1 Coral restoration – A systematic review of current methods, successes, failures and future directions

We conducted a systematic literature review of peer-reviewed journal articles, a review of grey literature, and an online survey of coral restoration practitioners. More than 40 separate categories of data were recorded from each case study including data on (1) the information source, (2) the case study particulars (e.g. location, duration, spatial scale, objectives), (3) specific details about the methods, (4) coral details (e.g. genus, species, morphology), (5) monitoring details, and (6) the outcomes and conclusions. The first phase of this review was completed in 2018 and was published as a NESP report with a supporting online database, and an open-access journal article (Figure 2.1). A second phase was completed in October 2020, and included another round of practitioner's surveys and a review of all literature published until 30th June 2020, bringing the total to 407 coral restoration projects reviewed.

Ten main coral restoration methods or techniques were identified. The effectiveness of each method, and techniques associated with each intervention were evaluated. We found that coral restoration projects were generally short-term, with the median of 12 months of monitoring being reported. Most projects were relatively small, with a median size of restored area of 100 m^2. A surprising result was how many coral taxa were used in projects, with 251 different species from 79 coral genera with 10 different growth morphologies found to be used. Overall, coral restoration projects focused on fast-growing branching corals (61% of studies), and reported survival between 60 and 70%. There were challenges associated with getting useful information because projects typically had 1) a lack of clear and achievable objectives, 2) a lack of appropriate and standardised monitoring and reporting and, 3) poorly designed projects in relation to stated objectives.

Bayraktarov et al. (2019) reviewed scientific studies published in peer-reviewed and grey literature on the motivations for, costs and successes of coral reef restoration. They found that the main motivations to restore coral reefs were to further ecological knowledge and improve restoration techniques, with coral growth, productivity, and survival being the main variables measured. The median project cost was US $400,000/ha (2010 USD), ranging from US $6,000/ha for the nursery phase of coral gardening to US $4,000,000/ha for substrate addition to build an artificial reef.

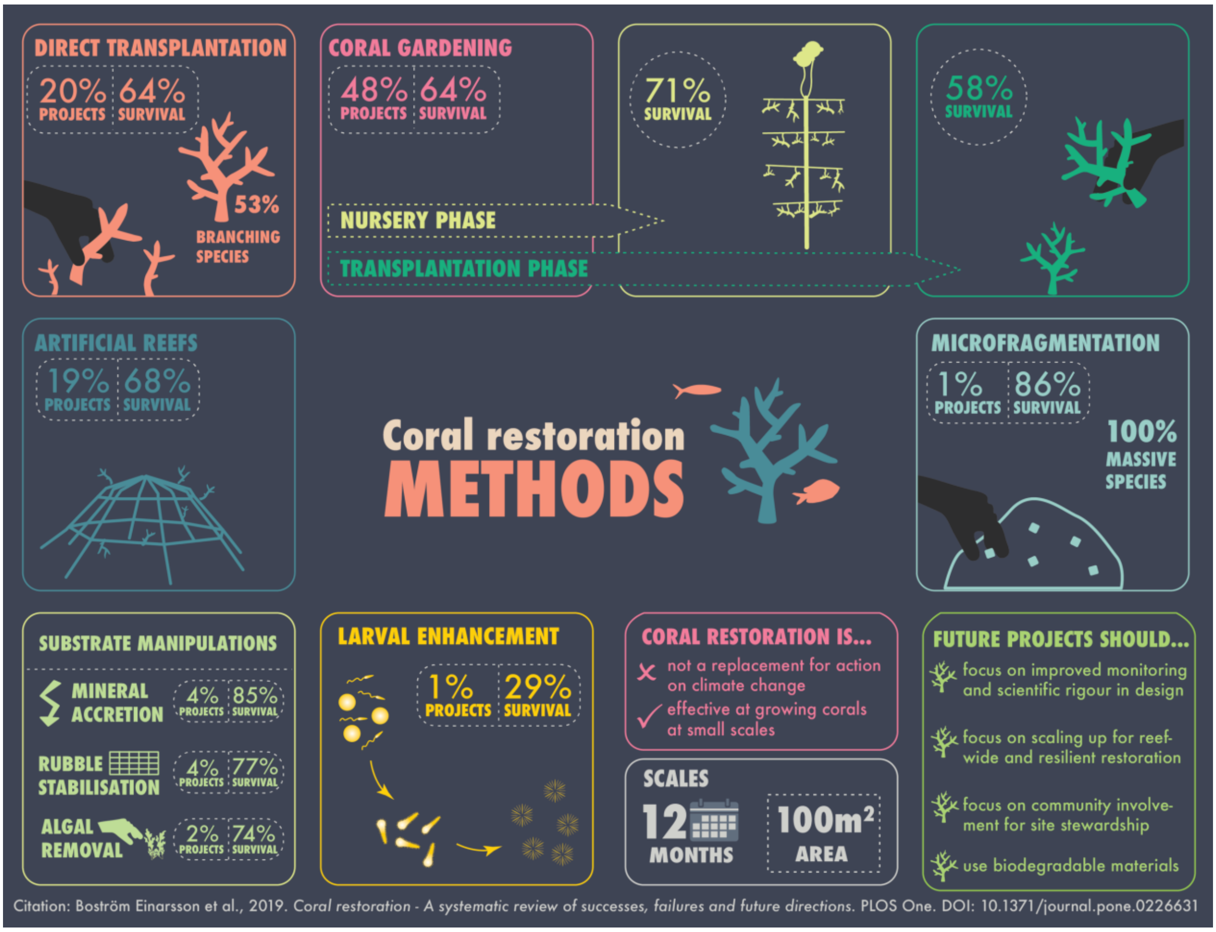


Figure 2.1: Summary of the main findings from Boström-Einarsson et al. (2020).

2.2 Macroalgae removal

Macroalgae are part of a healthy reef ecosystem and have both positive and negative effects on corals (Ceccarelli et al. 2018; Fulton et al. 2019). Removal of macroalgae has been proposed as an active intervention measure to aid reef recovery through increasing available substrate for coral settlement, and reducing competition. However, the effects (positive and negative) of removing macroalgae have not been rigorously tested. We reviewed and synthesised available knowledge of the ecological role of macroalgae on coral reefs and the potential benefits and risks associated with their active removal and published this as a journal article, ‘Rehabilitation of coral reefs through removal of macroalgae: state of knowledge and considerations for management and implementation’ (Ceccarelli et al. 2018). This also included appendices on (1) the distribution and abundance of macroalgae on the GBR, (2) the chemical role played by macroalgae on reefs, and (3) case studies of macroalgae removal on coral reefs. This review complemented the in-water macroalgae removal experiments at Magnetic Island as described in Section 3.

This review showed that the following considerations should guide the evaluation of algae removal as a management tool:

1. Establishing the need for the removal by demonstrating a phase shift or “threshold” abundance of macroalgae
2. Interaction with herbivory: Re-introducing or protecting herbivores prior to removing algal stands can allow the herbivores to establish control by consuming the juvenile macroalgae, and prevent macroalgal stands regenerating within a few months
3. Methods and logistics: Seasonality of macroalgae is likely to affect the success of removal; removal during the early growing season may be more effective than late in the growth period. The effects of climate change on algal seasonality will also need to be taken into account. The success of removal methodologies will depend on biological characteristics that can vary extensively among algal morphs and species
4. Potential negative effects of macroalgae removal: Removal of algal holdfasts may disturb or damage the substrate and may injure corals and other benthic organisms. The removal of plant biomass and physical structure may result in declines in the abundance of other taxa such as fishes. These potential risks should be considered and assessed prior to large-scale macroalgae removal on coral reefs
5. Response of corals to macroalgae removal and controlling chronic stressors: Algal reduction is not expected to translate into a uniform response in coral recruitment, growth, and survival. The success of removal projects may be enhanced by simultaneous interventions to enhance coral recruitment, and will also depend on the control of chronic stressors
6. Measures of success: The performance indicators for restoration success should be clearly defined and measured with standard scientific principles.

2.3 Substrate stabilisation

Substrate stabilisation involves the direct physical restoration and implementation of artificial substrates over areas of loose, unconsolidated reef rubble. The project team, with a wide range of collaborators, reviewed and synthesised available knowledge about the ecological role of coral rubble, natural coral recolonisation and recovery rates, and the potential benefits and risks associated with active interventions in this rapidly evolving field and published it as an open-access journal article (Figure 2.2, Ceccarelli et al. 2020). We found that there are fundamental knowledge gaps in this field, including baseline levels of rubble and the structural complexity of reef habitats in space and time. Methods ranged from using artificial structures or large rocks to laying down mesh or netting over the rubble to prevent further movement (Ceccarelli et al. 2020). Substrate stabilisation can also be complemented with coral transplantation to further assist reef recovery. However, there is a limited understanding of natural recovery processes and the potential for this type of active intervention to successfully restore local coral reef structures. The RRAP research will further investigate where and when it is appropriate to intervene (Hardisty et al. 2019).

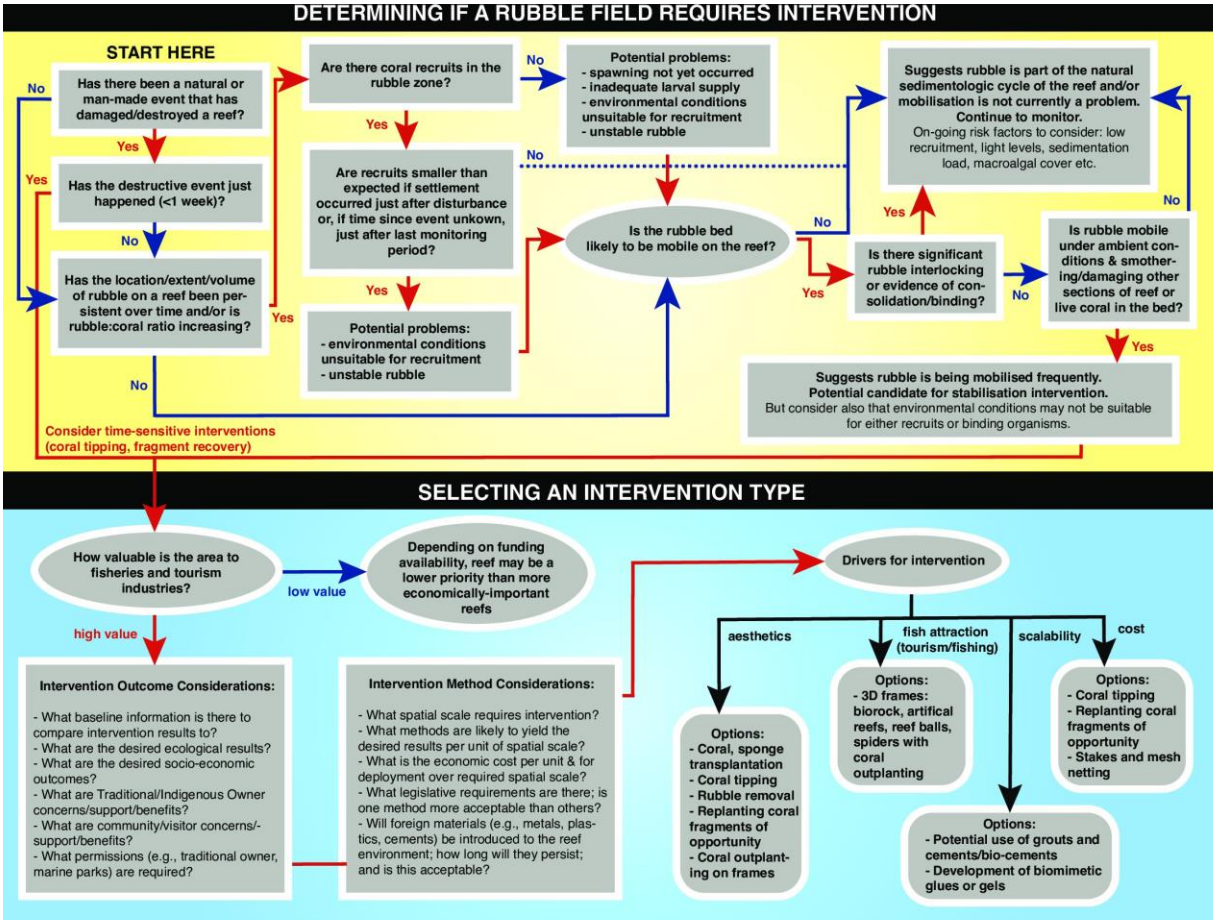


Figure 2.2: Decision tree showing considerations to take in rubble stabilisation interventions. From Ceccarelli et al. (2020).

3.0 CORAL RESTORATION IN AUSTRALIA

Alongside RRAP and other research programs, there is a growing number of coral restoration trials in the GBR (Figures 3.1, 3.2). This section presents an overview of newly-implemented in-water projects. See Appendix 2 for a table showing how NESP TWQ Hub Project 4.3 was involved in these restoration projects.

Figure 3.1: The locations of some recent in-water coral restoration projects in the GBR.

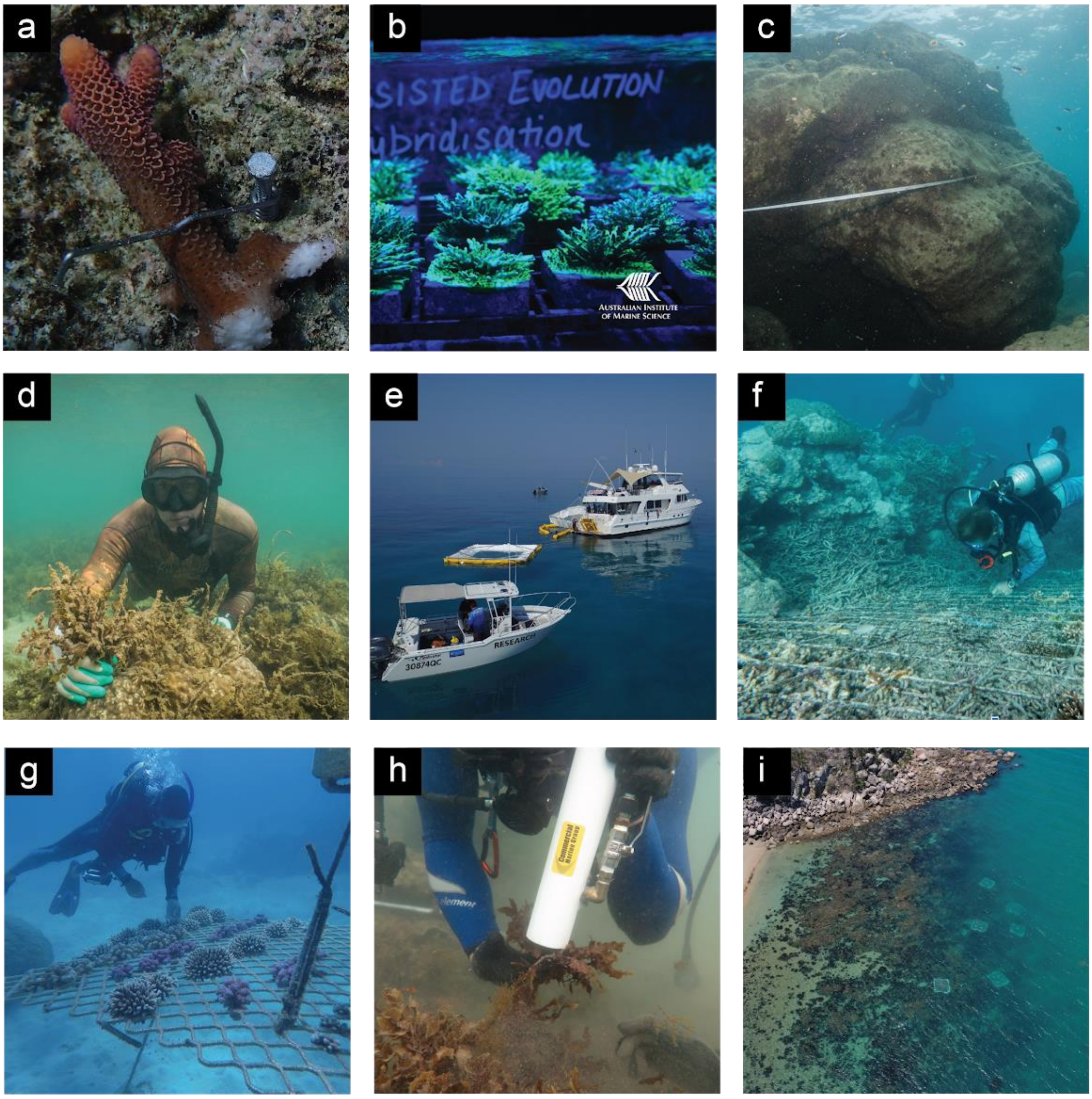


Figure 3.2: Coral restoration projects in the GBR, (a) CoralClip®, (b) assisted evolution research undertaken by AIMS, (c) coral bommie repositioning, (d) macroalgae removal, (e) larval propagation, (f) substrate stabilisation, (g) coral gardening, (h) an underwater vacuum used to assist with macroalgae removal, (i) larval propagation and macroalgae removal experiments. Images provided by Marie Roman/AIMS, Ian McLeod, Nathan Cook/Reef Ecologic, Ross Miller, Margaux Hein, David Suggett and Neil Mattocks.

3.1 Coral gardening

Coral gardening describes asexual coral propagation methods in which coral fragments are transplanted back onto a degraded reef after an intermediate nursery phase (Rinkevich 1995, Figure 3.3). It is the most widely used coral restoration method around the world (Boström-Einarsson et al. 2020). Coral fragments are either harvested from donor colonies or from fragments generated through natural or human disturbances, typically known as 'corals of opportunity' (sensu Rinkevich 1995). These are placed into land-based or in-water nurseries to recover and grow. The nursery phase allows for an exponential increase in coral branches available for outplanting generated by repeated fragmentation. This becomes coral restoration when they are successfully transplanted back onto reefs.

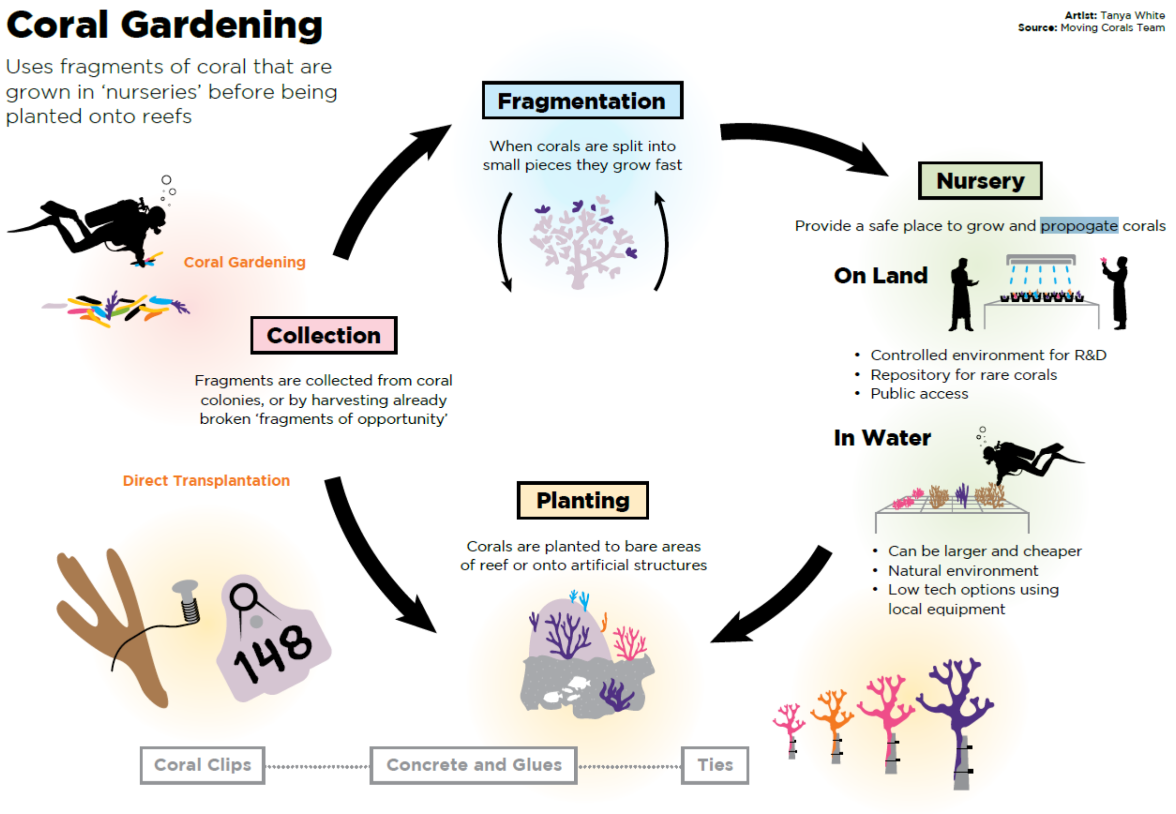


Figure 3.3: The coral gardening process.

Since 2017, four coral gardening projects have been established within the GBRMP including projects at Opal Reef, offshore from Port Douglas, Fitzroy Island, near Cairns, and at two reefs in the Whitsundays region (Figure 3.1). The first coral gardening project to be established on the GBR was led by the Reef Restoration Foundation (RRF) at Fitzroy Island. The project used the 'coral tree' nursery design developed by the Coral Restoration Foundation, in the Florida Keys, USA (Nedimyer et al. 2011). The original installation was supported with funding and assistance from this project. Six coral nursery trees were installed in December 2017 (Cook et al. 2018). Twenty four sections of coral colonies were harvested from two fringing reefs around Fitzroy Island; Hidden Beach and Shark Fin Bay. The species collected were visually identified as *Acropora nobilis*, *A. digitifera*, *A. muricata*, and *A. nasuta*. Coral sections were fragmented and attached to the coral tree nurseries. Ninety percent of the fragments survived resulting in 246 coral colonies. In July 2018, four more coral trees were installed. In September 2018, 192 corals from the nurseries were planted in the northern end of Welcome Bay, Fitzroy Island. These were planted into six 16m^2 plots at a density of two corals/meter. The fate of individually planted corals was not systematically monitored and there was no significant effect of coral planting on live coral cover after 12 months (Cook et al. 2020).

Coral gardening efforts at six major tourism reefs, close to Cairns-Port Douglas, were the largest-scale coral restoration project on the GBR to date. There, researchers from the

University of Technology Sydney (UTS) in partnership with local tourism company, Wavelength Reef Cruises, established two coral nurseries at Opal Reef (Figure 3.2g), and developed a new attachment device (Coralclip®, Figure 3.2a) to outplant both coral fragments and larval settlement devices in a targeted but versatile manner across reef terrains (Suggett et al. 2020). From 2018 to 2019 the team outplanted over 3500 coral fragments (Suggett et al. 2019). By October 2020 the team had outplanted over 5500 corals, comprising 23 species, among sites (D. Suggett *pers. comm.*). Despite the need for further testing, Coralclip® has proven to be fast (0.3-1.9 coral fragments per diver per minute), cheap (USD 0.6-3.0 per coral deployed) and successful (≤15% failure rate of clips deployment method after 3-7 months, Suggett et al. 2020).

Projects in the Whitsundays (Figure 3.1) were a result of government funding to support tourism values following Cyclone Debbie in March 2017. In November 2018, two coral gardening projects were established at Blue Pearl Bay and Manta Ray Bay by environmental consultants (Reef Ecologic) in partnership with a tourism promotion organisation (Tourism Whitsundays) and Daydream Island Resort. At each location, two types of coral nursery were trialled, (1) rope nurseries where coral fragments were fixed between strands of rope and attached to a frame suspended off the seafloor, and (2) table nurseries where coral fragments were attached to cement discs fixed to a tray suspended in mid-water. Each nursery held 700-1000 coral fragments, with approximately 50% of fragments surviving until being planted (N. Cook, unpublished data). In May 2019, 164 corals were planted in Blue Pearl Bay and 497 at Manta Ray Bay. Overall, 50% of outplanted corals survived until November 2019 (N. Cook, unpublished data). In June 2020 a further 955 corals were planted across both sites. Monitoring is ongoing.

A range of techniques were trialled as part of the Whitsundays project, with the following observations (N. Cook, *pers. obs*):

- Underwater putty and cement were effective adhesives for attaching corals to areas of bare rock, Coralclips® were not as effective in this project, and using silicone as an adhesive caused substantial mortality of outplanted corals;
- Biodegradable rope degraded too quickly for use in coral nurseries;
- Branching corals should be at least 10cm in length when outplanted so they can have some live coral tissue above the substrate;
- Coral bleaching caused mortality on coral nurseries, although the effects were partially mitigated by shading and water depth;
- Multi-storey nurseries provided more space for corals to grow and options to grow corals at the most advantageous depth;
- Coral gardening and associated research and monitoring can be done through community-based projects/ citizen scientists;
- Sedimentation needs to be taken into account when deciding outplant locations as areas with large amounts of sediment deposition were linked to lower survival rates of outplanted corals;
- Unexpected observed drivers of outplanted coral mortality included overgrowth by macroalgae (*Padina spp.*), and predation by bumphead parrotfish (*Bolbometapon muricatum*).

All of the above projects have involved extensive consultation with management and community stakeholders to ensure their support. For example the Whitsundays reef restoration project had over 678 individual interactions (meetings, presentations, phone calls and emails) engaging over 2850 people over an 18 month period (N. Cook *pers. comm.*) Volunteers have provided a substantial amount of in-kind time, labour and support for implementation, monitoring and maintenance. While more time and monitoring is necessary to evaluate the effectiveness of each of these techniques, site specificity will likely influence the choice of methods both in terms of ecological characteristics, and needs and capacities of the stakeholders and partners involved in the project.

3.2 Substrate stabilisation

The addition of structure for coral attachment has been trialled on cyclone damaged reefs around Agincourt 3, a diving platform at Agincourt Reef, offshore from Port Douglas (Figure 3.1). The primary goal for this trial was to improve the coral cover and aesthetics of a patch of rubble close to where divers enter the water. In 2018, Reef Ecologic, in partnership with the pontoon operator, Quicksilver Connections, installed six 4.5m^2 sheets of reinforcing steel mesh with a low-voltage electrical current applied to three panels (Figures 3.2f, 3.4). The electrical current was added in the hope that it would increase the growth rates and resilience of corals. Two panels were installed on top of a rubble patch and four on the sloping sides that were also dominated by unconsolidated rubble. Forty-eight coral fragments were then attached to each of the panels. Marine biologists working for Quicksilver Connections conducted regular maintenance of the system and corals, reattaching and realigning loose fragments and removing predatory snails (*Drupella* spp.). Overall, 37% of the coral fragments were alive after 12 months, with no difference in coral survival between the powered and unpowered panels. In August 2019, 294 additional coral fragments were attached to the frames and the power supply adjusted to lower the voltage delivered to the frames. This proved to be technically challenging and the power supply was switched off in December 2019. Ongoing husbandry and assessments were being conducted until early 2020 when COVID-19-related travel restricted opportunities to visit the site. In October 2020 monitoring began again. Live coral cover was estimated to have increased from 5% to 8.3% in control plots and from 0.9% to 46.8% on the panels (N. Cook, *unpublished data*). The panels on top of the rubble pile had the highest amount of live coral cover in October 2020 (over 70% each for both panels). Project proponents were generally happy with the result (G. Burns, *pers. comm*., Fig. 3.4).

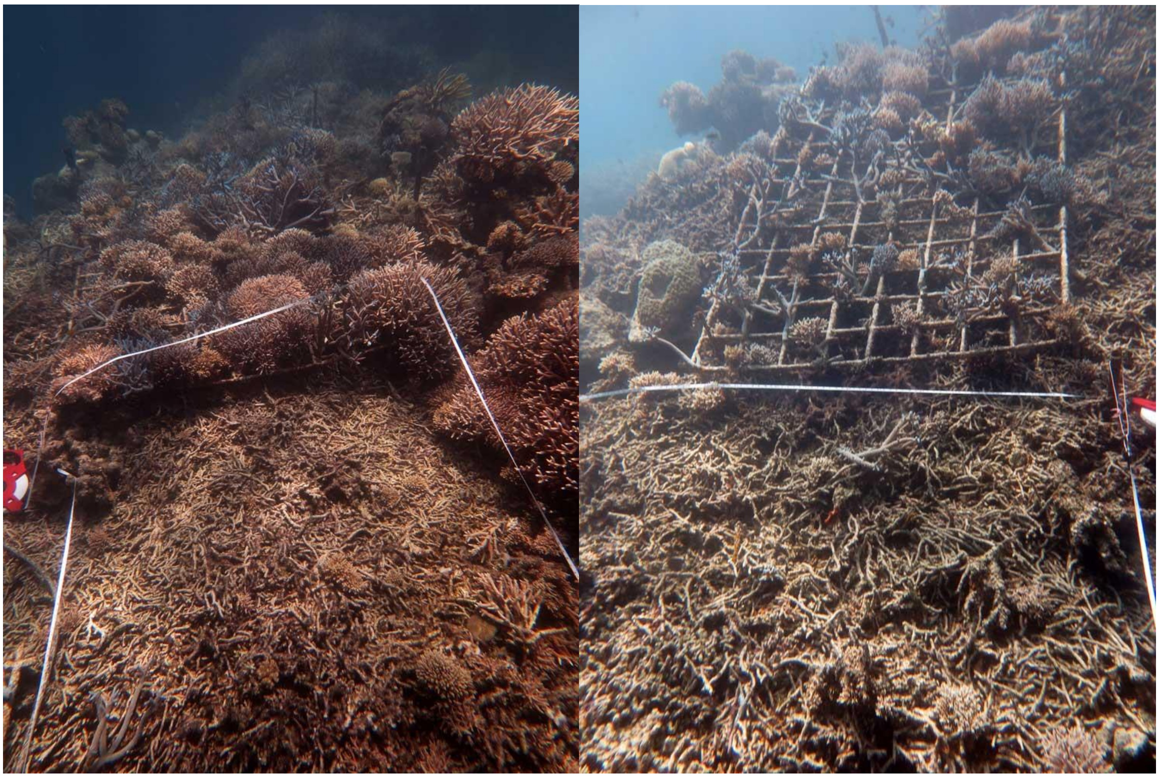


Figure 3.4: Transplanted corals growing on mesh at Agincourt Reef.

Reef Stars are hexagonal sand-coated steel structures that provide a stable base for coral fragments to grow. The following two projects using Reef Stars are recent and have not been formally written up, but the following information has been shared by the project proponents for this report.

Mars Sustainable Solutions (part of Mars Incorporated), and Reef Magic Cruises, a tourism company, installed Reef Stars at Moore Reef, 40 km offshore from Cairns (Figure 3.1) in two installations during June and October 2020. This project will investigate the effectiveness of Reef Stars to stabilise coral rubble and includes positive and negative controls. The restoration area was 20m x 30m and the proponents expected to fill this area in over the course of the next five years (A. McArdle, *pers. comm.*). As of October 2020, a total of 148 Reef Stars populated with fragments of broken coral from nearby reefs have been deployed over two installations (A. McArdle, *pers. comm.*). The first installation included 29 species of corals from five families, the second 26 species from four families, with most of the species coming from the Acroporidae family (E. Fisher, *pers. comm.*). Monitoring has begun and three maintenance trips have been undertaken. Transplanted coral fragments from the first installation had high survivorship (99.9%) within the first three months (A. McArdle, *pers. comm.*).

Another recent trial (November 2020) at Green Island, close to Cairns, is a collaboration between the GBRMPA, QPWS, Mars Incorporated, Great Adventures, Big Cat Green Island Cruises, the Coral Nurture Program and Gunggandji Traditional Owners. It included attaching more than 2600 coral fragments to a web of 165 Reef Stars on an area of unstable dead coral rubble and connecting an additional 200 coral fragments to adjacent suitable hard substrate using Coral Clips®. This project allowed for extensive engagement between Marine Park managers and other stakeholders, thereby enabling the continued development of new partnerships (a key focus of the GBRMPA produced ‘Great Barrier Reef Blueprint for Resilience’).

3.3 Coral repositioning

Severe Tropical Cyclone Debbie impacted the Whitsunday Islands in March 2017 and resulted in widespread damage to island infrastructure and fringing reef habitats (McLeod et al. 2019b). The cyclone dislodged a large number of 1-3 m diameter *Porites* spp. bommies from the reef slope at Manta Ray Bay and rolled them high into the intertidal zone of the reef flat. The QPWS and GBRMPA, repositioned the bommies to the subtidal reef flat in June 2017. The objectives of this activity were to restore coral reef habitat, improve aesthetics and access to the beach, provide substrate for future coral larvae settlement, increase habitat complexity, and demonstrate the value of proactive management (McLeod et al. 2019b). Experienced machinery operators repositioned the bommies subtidally by rolling them over the reef flat during a very low tide. A long-arm excavator then pushed them over the reef crest onto the reef slope, using the full 10m extension of the excavator arm. A compact track loader equipped with a grab bucket was also used to push coral rubble and smaller bommies into the subtidal area of the reef flat. An estimated 100 cubic metres (400 tonnes) of dead coral substrate was repositioned, at an estimated cost of AUD 30,000.

The repositioning of the *Porites* bommies has delivered positive environmental and social benefits. Boat access has been restored to the beach, corals have recruited to the repositioned bommies, and some remnant coral tissue survived on most bommies. Further, the bommies provide three-dimensional habitat structure on the outer reef flat, supporting reef fishes and other marine life. As the coral community re-colonises the surface of the bommies, it's expected that the shallow-water snorkeling experience for tourists will improve (McLeod et al. 2019b). The coral bommies were last surveyed in December 2019. Seventeen of the 23 coral bommies surveyed had live coral tissue (mean of 4.9%, range 0-20%) and there were 232 coral recruits on 21 repositioned coral bommies, up to 15 cm in diameter (D. Ceccarelli, unpublished data).

3.4 Macroalgae removal

Removal of macroalgae has been proposed as an active intervention measure to aid reef recovery through increasing available substrate for coral settlement and reducing competition for coral recruits. Macroalgae removal trials began at Magnetic Island, close to Townsville in 2016. Initial trials were led by Reef Ecologic. Two methods of macroalgae removal were tested, a plastic scraper to remove holdfasts, and hand removal (Figure 3.2g). Macroalgae cover was reduced from 38% to 7% from 2m x 2m plots immediately following removal, with no difference in speed or efficacy between methods (McLeod et al. *In Press*). There was no follow up monitoring from these early trials.

The project team, in collaboration with Earthwatch Institute Australia and a range of other partners, built on this work to quantify the ecological effects of macroalgae removal on reefs at Magnetic Island. In October 2018, 12 permanent 5m x 5m experimental plots were established across two sites (Florence Bay and Arthur Bay). In half of these plots, fleshy macroalgae, predominantly *Sargassum* spp., was removed just prior to coral spawning, whilst the remaining plots acted as controls. In July 2019, the number of experimental plots was doubled, expanding the area of experimental intervention (24 permanent 5m x 5m experimental plots). In addition, removal of macroalgae was conducted more frequently (approximately every 3 months) to maintain low biomass in the experimental plots. Monitoring of the plots included measurement of algal biomass (measured as number of holdfasts and height of algal thalli), counting coral recruits (juveniles) on both settlement tiles and natural substrata, measuring sediment deposition and turf algae dynamics, quantifying changes in benthic cover, examining changes in the number and function of fish communities (e.g. juveniles, herbivores), and tracking bleaching susceptibility between control and algae-removal plots. After initial surveying of benthic composition, macroalgae were removed by hand (freediving and on SCUBA, see Mastroianni 2019 for detailed methodology on removal and monitoring). Consistent with other published work, we found that macroalgae growth follows a seasonal pattern, reaching its peak abundance in summer (Smith and Bourne 2019). With repeated removals, a 43% reduction in summer canopy height in removal plots was achieved in Arthur Bay compared to control plots, even given four months of regrowth (Figure 3.5).

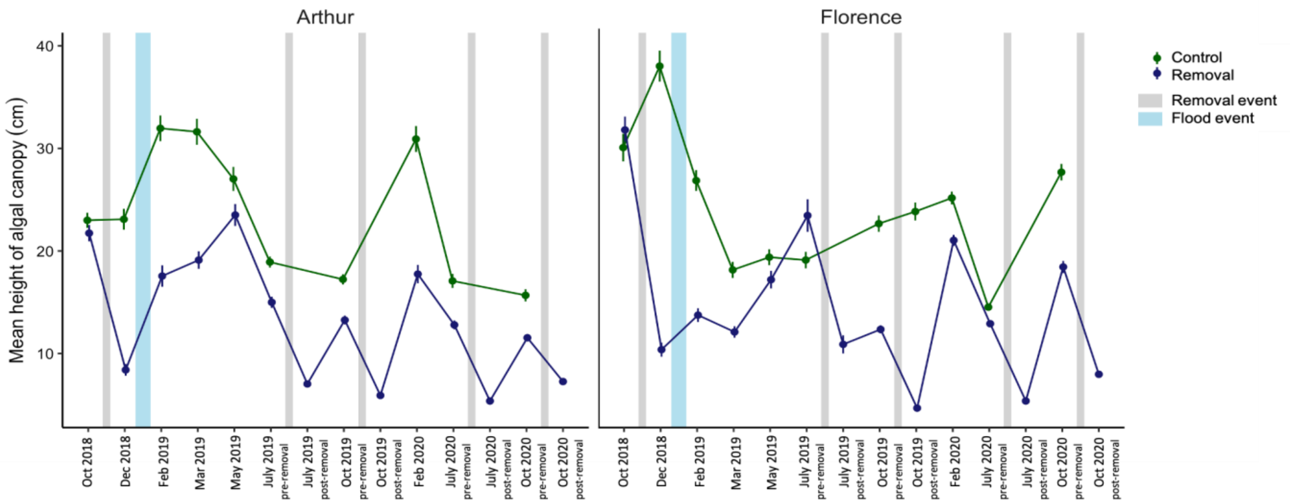


Figure 3.5: The mean height of macroalgae canopy over time in Arthur Bay and Florence Bay. Grey bars indicate removal events; blue bar indicates the Townsville Flood (February 2019).

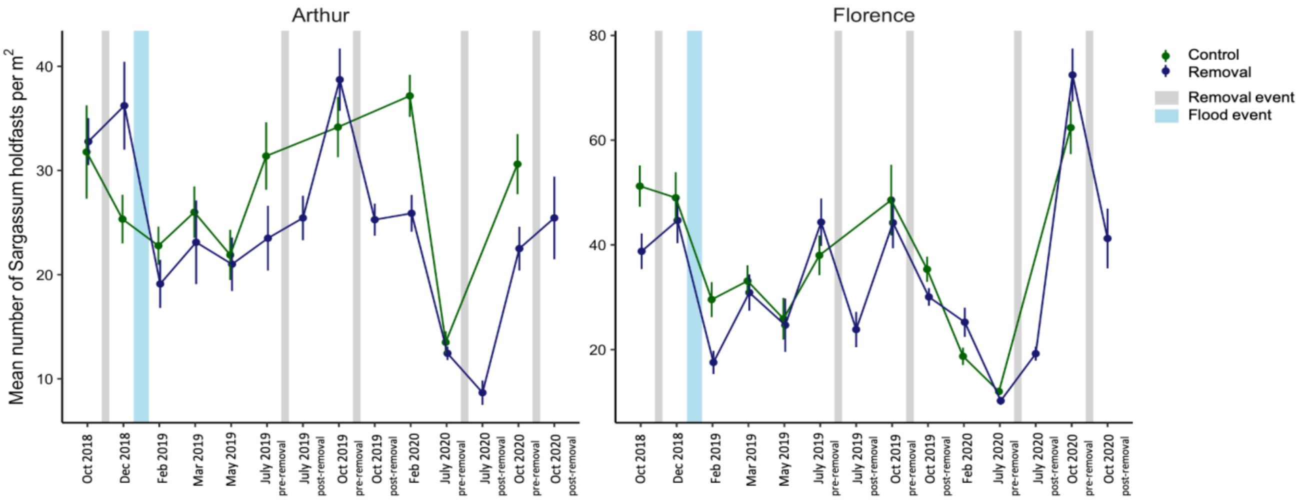


Figure 3.6: The mean number of *Sargassum* spp. holdfasts per square meter over time in Arthur Bay and Florence Bay. Grey bars indicate removal events; blue bar indicates the Townsville Flood (February 2019).

Other studies (summarised in Ceccarelli et al., 2018) described the importance of removing holdfasts to reduce macroalgal regrowth. In our study, there were significant reductions in the number of holdfasts following some, but not all removal events (Smith and Bourne 2019). Despite the variation in successful removal of holdfasts, given the significant reduction in canopy, it may not be necessary to fully remove holdfasts to gain the desired effect. Further monitoring is required to determine how the number of holdfasts changes with repeated removal events, and how this impacts coral recovery dynamics.

Terracotta settlement tiles are often used to quantify coral recruitment through soaking field-deployed tiles in bleach solution and counting resulting coral skeletons. Here, we installed such tiles to test for the effect of macroalgae removal on natural coral recruitment. In the first year of the project, we observed a significant increase in the number of coral juveniles on tiles from Florence Bay plots where macroalgae had been removed following the 2018 coral spawning event, particularly to the bottom surface of settlement tiles (Figure 3.7). However, the pattern was not as distinct in Arthur Bay, with the highest number of settlers recruiting to the upper surfaces of the settlement tiles in control plots. There was no difference in the size of juvenile corals between removed and control plots, suggesting there is no benefit to growth of settlers; however this will be monitored into the future. At the time of writing, time-consuming data collection is still in progress to examine settlement tiles deployed prior to the 2019 spawning event. These tiles were retrieved in two lots, in February and April 2020 to assess recruitment, survival, and growth of coral juveniles. Initial *in situ* observations have detected increased numbers of coral recruits in removal plots, however ongoing monitoring is planned.

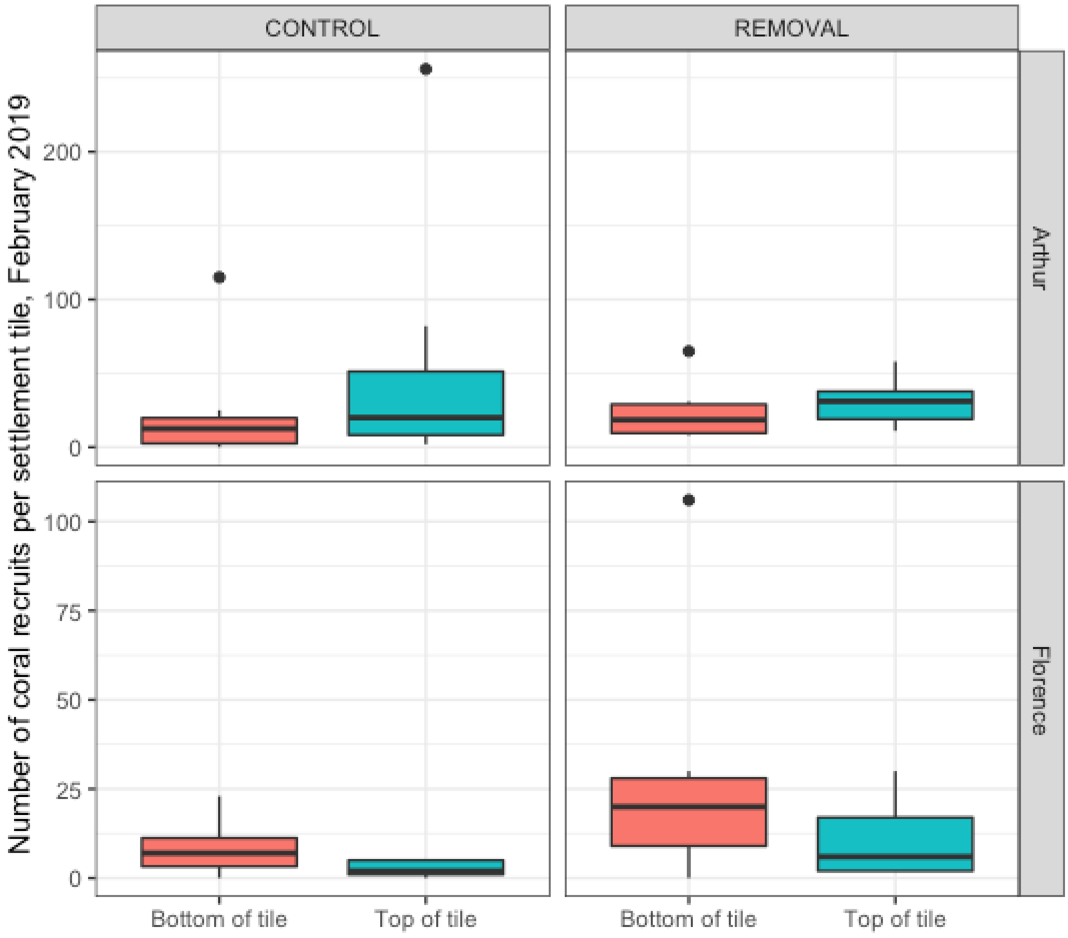


Figure 3.7: Total number of natural coral recruits per settlement tile surface in control and removal plots across Florence and Arthur Bays, Magnetic Island, following the 2018 spawning event.

One of the known benefits of macroalgae is providing shade to corals living below algal canopies, as such it is possible that removal of algae may stress cohabiting corals by increasing harmful UV penetration to the benthos. During the mass bleaching event of March 2020, the opportunity arose to assess the relationship between bleaching severity in plots with and without macroalgae removal. Unfortunately due to Covid-19 related travel restrictions, field data collection was limited to target only those colonies that bleached, rather than a full community census. Nonetheless, surveys found that bleaching incidence was greater in the macroalgae-removed plots compared to the control plots. Despite this result, recovery was significantly higher in the macroalgae-removed plots compared to the control plots four months following the bleaching event. The absence of a dense macroalgal canopy in the removal plots may, therefore, allow corals the opportunity to expend more energy on recovery as opposed to competition. If further acute thermal events arise in the future, a more thorough examination of these processes will be undertaken in the experimental plots at Magnetic Island.

In addition to quantifying coral recruitment, which is seen as a major indicator of restoration success, current work by JCU, and AIMS is also investigating the impact of macroalgae removal on sediment deposition, resuspension and turf algae dynamics, which are likely to be important factors influencing coral settlement and recruitment. Planned future work will aim to quantify coral host genetic parameters and changes to benthic microbial biofilm communities. Importantly, citizen science forms a critical part of this project through ongoing partnership with

Earthwatch Institute Australia. A range of activities are completed by citizen scientists, with the goal to develop the best way to incorporate local community action into macroalgae removal-based projects into the future, should results support wide-scale implementation. To date, four Earthwatch partnered expeditions have been conducted with citizen scientists participating in a range of activities including removal of macroalgae and data collection.

A related project led by GBRMPA focused on testing logistics and feasibility of larger-scale removal by removing macroalgae from three 20m x 20m plots in Florence Bay on Magnetic Island by hand in 2018 and again in 2019 using hand removal and a suction device (Figure 3.2h, N. Mattocks *pers. comm.*). Pre-removal assessments of coral and fish populations were undertaken, with further surveys planned.

3.5 Coral larval propagation

Coral larval propagation aims to increase the rates of larval settlement and recruitment on damaged reef areas using large numbers of coral larvae, thereby increasing the rate of recovery (dela Cruz and Harrison 2017). The methods are designed to exploit the high fecundity of corals and maximise fertilisation and larval rearing rates for increasing larval supply on damaged reefs, mimicking the natural pulses of high larval supply and recruitment following major spawning events on healthy reefs. Larvae are either reared in water within floating enclosures on reefs or in laboratories or aquaculture facilities to optimise production and retain them for restoration, rather than allowing them to be dispersed in currents away from target reef areas. When larvae are visually assessed as competent to settle they are released onto reef areas using various methods, including temporarily contained under mesh sheets for small scale manipulative experiments, or released as larval clouds directly onto damaged reef areas at larger scales.

Initial larval propagation trials in the GBR began on Heron Island reef patches in 2016, using three densities of *Acropora* larvae settled in replicate 2m x 2m plots and larvae reared from wild spawn slicks. In 2017, larval enhancement experiments were initiated on replicated 10m x 10m patch reefs at Heron Island and One Tree Island reefs using multispecies mixes of *Acropora spp.* and *Diplora spp.* coral larvae, with significantly increased larval settlement in larval propagation reef plots compared with controls reliant on low natural larval settlement rates (Harrison 2018).

More recently, larger-scale reef trials were successfully initiated on reefs in the central and northern GBR using combinations of larger floating spawn catchers and floating larval pools to contain multispecies coral spawn slicks, and rearing millions of larvae in floating pools and laboratory culture tanks that were settled onto degraded reef areas with low coral cover (Harrison 2018, Harrison et al. 2019, and unpublished data). For example, over 150 million larvae were successfully reared in larval nets moored on Moore Reef, off Cairns (Harrison et al. 2019).

An experiment at Moore Reef included larval propagation and the inoculation with heat tolerant *Symbiodinium*. Twelve 30 m^2 experimental plots with four plots for larvae without symbionts, four plots for settlement of larvae co-cultured with symbionts, and four plots as controls. In addition to the planned project laboratory and reef experiments, they also successfully deployed ~5.5 million 7-day old larvae over a patch reef using a newly trialled gravity fed and diver-controlled larval release method (Harrison et al. 2019). Monitoring of longer-term recruitment and coral restoration outcomes is ongoing for all of these projects.

Recently, macroalgae removal and larval propagation have been combined in a fully crossed field experiment, building on the algal removal experiments at Magnetic Island. Within the 12 established quadrats, three quadrats are assigned to each of four treatments (control, algae removal only, larval propagation only, and combined algae removal with larval propagation). Adult colonies of *Acropora tenuis* were removed from the reef and allowed to spawn in the National Sea Simulator at AIMS. Gametes were fertilised, larvae cultured, and then approximately 3 million larvae were returned to the reef in specially-designed 5m x 5m mesh tents to target delivery of larvae onto the experimental plots. This process was completed during the 2019 spawning for Arthur Bay, and repeated in 2020 for both Arthur and Florence Bays. In February 2020 (following the 2019 spawning), live coral recruits were counted on settlement tiles from Arthur Bay, with significantly increased numbers of recruits in the combined treatment quadrats (i.e. larval propagation with algal removal), however all three other treatments (control, larval propagation only, algae removal only) had similar numbers of recruits. Recruit counts were repeated in September 2020, with the combined treatment again showing most recruitment, followed by algae removal plots, followed by larval propagation plots, followed by control. Monitoring is ongoing for this project.

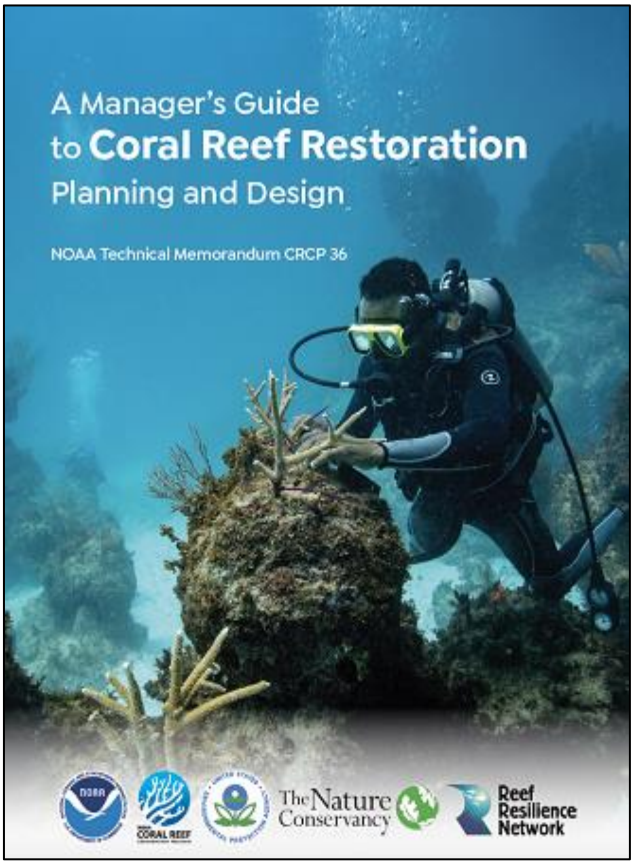
4.0 BEST PRACTICE CORAL RESTORATION

One of the primary goals of this project was to produce best-practice guidelines for GBR coral restoration projects. Our team worked with a broad team of national and international collaborators drawing on global expertise to produce these guidelines. The main relevant outputs included:

- Producing content to update the Reef Resilience Network's restoration section on their website, including providing a case study about coral bommie repositioning, and content to update the substrate stabilisation and macroalgae removal website sections (to be incorporated in early 2021). https://reefresilience.org/restoration/
- Producing content for the Reef Resilience Network's online restoration course and helping to facilitate the mentored version of this course. https://reefresilience.org/online/
- Co-authoring the major global report 'A manager's guide to coral reef restoration planning and design' and mentoring teams from Guam and the Northern Mariana Islands local governments to plan restoration in their waters using the guide
- Co-authoring the major global report with UNEP and ICRI 'Coral reef restoration as a strategy to improve ecosystem services. A guide to coral restoration methods' (to be released in January 2021)
- Producing webinars and consolidating the best available best practice guidance to create a 'GBR toolkit for local-scale coral restoration' in partnership with GBRF and RRAP.

A summary of two of the most important global reports that this project contributed to, and the GBR toolkit for local-scale coral restoration follows:

4.1 Coral restoration planning and design

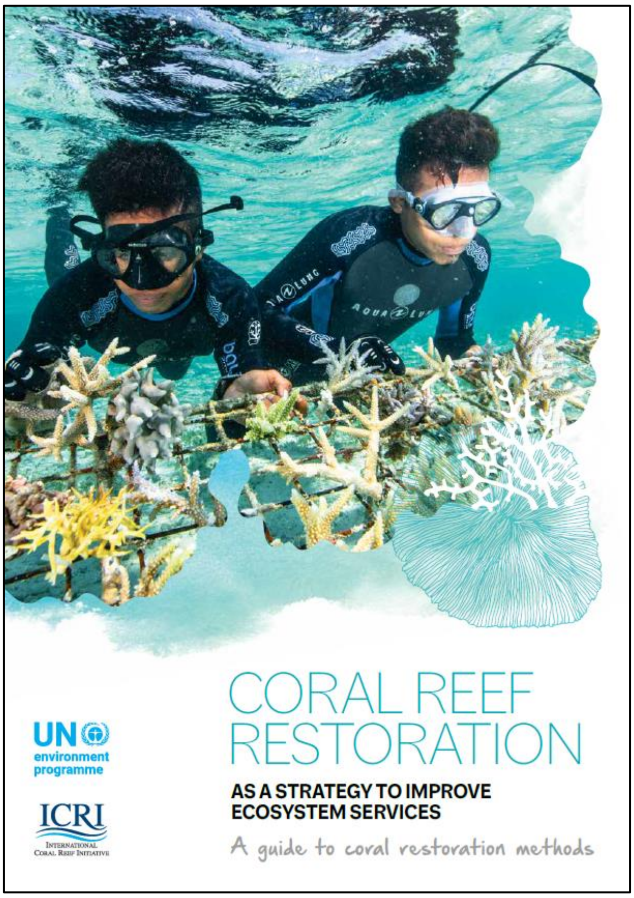


A manager's guide to coral reef restoration planning and design (Shaver et al. 2020) supports the needs of reef managers seeking to begin restoration or assess their current restoration program. Based on global best practices - and tested with managers from Hawaii, Guam, American Samoa, and the Commonwealth of the Northern Mariana Islands - the guide was developed for reef managers and practitioners and anyone who plans, implements, and monitors restoration activities. From this project, Ian McLeod, Margaux Hein and Lisa Boström-Einarsson were authors of the report and Ian McLeod helped mentor the teams from Guam and the Northern Mariana Islands.

As managers embark on restoration activities to combat reef degradation and enhance resilience, careful planning is required to improve the chances that restoration will be successful. Effective planning includes working with local experts, stakeholders, and decision-makers to determine how, when, and where restoration will be conducted, and how it can complement existing coral reef conservation and management strategies.

Together with a suite of tools and templates, the guide maps out a six-step, iterative process to help users gather relevant data, ask critical questions, and have important conversations about restoration at their location. Use of the guide culminates in the creation of a Restoration Action Plan to enhance reef resilience and recovery.

4.2 Coral reef restoration as a strategy to improve ecosystem services: A guide to coral restoration methods



In anticipation of the coming UN Decade on Ecosystem Restoration, and as a response to the UNEP Assembly resolution 4/13 adopted in 2019, the UNEP assembled a team of experts to produce a report on coral reef restoration as a strategy to improve ecosystem services. This team was led by Margaux Hein (Margaux was employed as a UNEP consultant to lead this report) and Ian McLeod along with collaborators from around the world. The report (Hein et al. *In Press*) presents an overview of current methods, and the best-available knowledge in the field of coral reef restoration. A set of recommendations are also provided to assist key actors such as managers, practitioners, policy makers, and funding agencies to make informed decisions in applying coral reef restoration more broadly as an integrated reef management strategy. Specifically, the report includes two comprehensive recommendation tables, one method and one goal-based, highlighting expert views on strengths and weaknesses of existing methods, and key recommendations and challenges depending on the overarching goal of a restoration project. A suitability-index matrix was also created to match specific methods to goals and assist the decision-making process in the early planning phases. The report along with a policy brief and an animated video are expected to be released in January 2021. A peer-reviewed publication highlighting key concepts of the report (Hein et al. *In Review*) is in-review in the journal Frontiers in Marine Science as part of a special issue on *Coral Reef Restoration in a Changing World: Science-based Solutions.*

4.3 GBR toolkit for local-scale coral restoration

This toolkit is hosted on the RRAP website with the following text and content:

"*RRAP's aim is to create an innovative suite of safe, acceptable interventions to help the Great Barrier Reef resist, adapt to, and recover from the impacts of climate change. The Program supports the eventual deployment, if required, of at-scale integrated restoration and adaptation interventions. We recognise that local engagement in restoration work has the potential to enhance and be an innovative scaling approach for intervention deployment.*

But what is available now? The resources listed here provide users with quick access to a range of key Great Barrier Reef coral restoration guidance material and links to find out more about coral restoration efforts around the world "

The toolkit will be published mid-December 2020 and can be accessed at:
https://gbrrestoration.org/resources/coral-restoration-toolkit/

The toolkit will include the following sections when launched and all website links will be available through the web address above:

<u>GBR Restoration</u>
Background Reading
- Best practice coral restoration for the Great Barrier Reef: Synthesis of results (McLeod et al. 2020)
- Tourism and restoration – motivations, opportunities and challenges (Hein et al. 2020)
- Infographic - what is coral gardening ?
- Great Barrier Reef blueprint for resilience (GBRMPA, 2017)

Watch and Learn
- Webinar: Overview of NESP products and findings
- Webinar: Coral gardening in Australia
- Webinar: Permitting processes for GBR coral restoration projects
- Webinar: Why do tourism operators engage in coral restoration?

Guides
- GBRMPA permitting processes

<u>Global Coral Restoration</u>
Background Reading
- Coral restoration: A review
- Coral restoration and adaptation: Mapping current and future priorities
- Motivations, success, and cost of coral reef restoration
- Coral reef rehabilitation through removing macroalgae
- Supporting coral reef recovery with small structures and substrate stabilisation

Guides
- A manager's guide to coral reef restoration planning and design
- Coral reef restoration monitoring guide

- Reef rehabilitation manual
- A guide to coral restoration methods
- Reef resilience network – coral restoration training course
- Guide to ecological engineering: The restoration of coral reefs and associated ecosystems

Resources

- Global coral restoration database
- Coral restoration image library

5.0 SUMMARY AND FUTURE DIRECTIONS

Since 2017, there has been a rapidly growing field of research into coral restoration and adaptation, and a growing number of in-water projects. This project has systematically reviewed restoration techniques used around the world to date, and synthesised the results and recommendations into three book chapters, nine peer-reviewed journal articles, and six reports. These outputs have already been cited 68 times in the scientific literature (as of 15 September 2020 Google Scholar) and read over 4000 times (as of 15 September 2020, ResearchGate). The legacy of this project not only comes from these and subsequent publications, but from the broad collaboration and engagement through the process including hundreds of phone calls and meetings, and scores of presentations and media and social media posts. Through co-creating an online training course with the Reef Resilience Network and an in-person Coral Restoration and Leadership Workshop with Reef Ecologic (four workshops of up to four days during 2018-2020), we also shared the learnings of this project with hundreds of people. Many of the co-investigators have moved into leadership roles in the field of restoration, for example senior leadership roles in RRAP, and the CRC. As coral restoration is a long-term process, only interim results can be included in this report. As the NESP ends in December 2020, these experiments have been handed over to collaborators or funded through other sources to continue monitoring and reporting.

The heightened interest in coral restoration and adaptation over the three years of the project has been supported by increased funding. For example, Australia's first Restoration Hub has been launched in the Cairns-Port Douglas region with AUD 1.1 million in funding for projects in the initial round. The RRAP R&D Phase was launched with AUD 130 million in dedicated funding for the first four years. These efforts and investments reflect an increasing sense of urgency for action to confront the coral reef crisis and management appetite for implementation, including a new GBRMPA Policy on GBR Interventions being developed (https://elibrary.gbrmpa.gov.au/jspui/retrieve/1a949699-19b8-4aee-8b73-271feb19eab1/v0-Interventions-Great-Barrier-Reef-Policy.pdf). Generally, there has been a collaborative, positive spirit, and coral restoration has brought together stakeholders who rarely work together (Burrows et al. 2019). However, many of these projects are new and will experience challenges, and some may not meet their objectives as there are few examples of large-scale success through existing coral restoration techniques around the world (Boström-Einarsson et al. 2020).

In general, there has been a shift in the use of coral restoration. Projects are becoming less focused on assessing the feasibility and efficacy of individual restoration techniques and more focused on developing practical, scalable solutions with specific objectives linked to long-term outcomes in a changing climate. This approach requires research partnerships that extend beyond the coral research space to include engineers, social scientists, modellers, economists, infrastructure development experts, and project managers (Anthony et al. 2020). The RRAP is the largest investment in restoration and adaptation of a marine ecosystem globally. RRAP aims to deliver an integrated, properly governed and executed 10-year R&D program to provide a level of health insurance for the GBR by developing safe and effective new interventions before they become critically needed. The R&D Program is designed to be responsive to the range of possible climate outcomes and the range of the Reef's ecological responses to this changing environment. It aims to reduce critical uncertainty, improve understanding of the system and quickly narrow a set of optimal interventions. These interventions would provide an integrated, three-point approach:

- Cooling and shading reefs to help protect them from the impacts of climate change
- Assisting reef species to adapt to a changing environment
- Assisting recovery of damaged and degraded reefs

The envisaged final phase of RRAP would be an implementation phase which could overlap with the R&D Phase as early as five years from commencement depending on the specific intervention in question. This would include commercial transfer of the reduced set of candidate measures, including the construction and deployment of scaled-up systems.

Currently, considerable effort, including RRAP, is focused on developing methods and testing efficacy with the goals of increasing the scale and reducing the costs of interventions. While there is an urgent need to scale-up interventions to match the scale of threats and degradation, there is also value in small scale interventions. If project objectives include increasing community engagement, then approaches that allow for hands on participation may be the most appropriate. Between 2017 and 2019, ten tourism organisations were actively involved in coral restoration projects on the GBR (Hein et al. 2020). Since then many more organisations have become involved and interest is growing rapidly across the sector (J. Lodder, *pers. comm.*). This involvement is often motivated by the desire to be proactive in improving the condition of the reefs they use. For example, crown-of-thorns starfish control, macroalgae removal, or coral restoration using *corals of opportunity* may be appropriate to be applied at small scales to improve the health of local reefs, such as at popular dive sites. Tourism operations also recognise the value of coral restoration programs in educating the general public and providing opportunities for reef stewardship (Hein et al. 2020). Until very recently this type of hands-on reef stewardship would have been difficult or impossible due to strict permitting requirements. However, a shift in appetite for active interventions by management agencies has now opened a pathway for these kinds of reef stewardship activities.

5.1 Conclusion

Australia has thousands of hectares of coral reef area, and none of the current coral restoration techniques are able to be scaled up towards even a fraction of this area (nor do they claim to). Coral restoration and adaptation is new in Australia and the novelty of the concept has in some instances led to a narrative that these approaches can ‘save our reefs’. This mismatch in the scale of the problem, the scale of existing restoration techniques and the expectation set by such misleading messages can be damaging to the trust in restoration practitioners and managers. Therefore it is critical to stress that restoration is (1) not a quick fix, but rather a long-term investment, and (2) not a solution on its own, but rather one of the tools in a reef manager’s toolbox to assist the recovery and adaptation of reefs to current and projected climate conditions.

Coral restoration using existing methods in Australia is therefore best applied at the local reef scale where there is sufficient evidence of successful outcomes in terms of coral growth and survival. The RRAP is focused on producing an innovative suite of safe, acceptable, and cost-effective interventions to help protect the GBR from climate change, and increase the scalability of options. However, it is important not to discount techniques and methods with a local focus as even small-scale actions can support socio-cultural and economic benefits valuable to local livelihoods and communities. Further, while existing methods may not match the scale of the crisis facing coral reefs in a climate impacted future, restoration and adaptation techniques could be key to maintain remnant live reefs, effectively buying time as the world takes urgent global action on climate.

Such a multi-pronged approach is likely to be the best strategy for maintaining resilient reefs in a complex future. The rapid progress in trialling coral restoration in Australia builds on decades of overseas experience. Australia is at the cusp of investing considerable time and money into developing new interventions and are an emerging leader in this space. There are great advantages to continuing to actively collaborate with researchers internationally and with other sectors not currently involved in coral reef management as this can save on costs and bring in new ideas. This could be facilitated through coordinating communication with practitioners through organisations and networks such as the Coral Restoration Consortium, and the Reef Resilience Network, scientific collaborations through RRAP, and the International Coral Reef Society, and outreach to governments and funding agencies though the United Nations, and the International Coral Reef Society.

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APPENDIX 1: PUBLICATIONS

Book chapters

1. **McLeod, I.M.**, **Hein, M.Y.**, Babcock, R., Bay, L., **Bourne, D.G.**, **Cook, N.**, Doropoulos, C., **Harrison, P.**, van Oppen, M.J.H., Mattocks, N., **Smith, A.**, **Smith, H.**, Suggett, D., Taylor, B., Wachenfeld, D., **Boström-Einarsson L**. (In Press). Coral restoration in Australia: An overview. Advances in Marine Biology. Volume 84.

2. **Smith, A.**, **Hancock, B.**, **Cook, N,** Vaughn, D (In Press). History and overview. In 'Active coral restoration: techniques for a changing planet' (Ed. David Vaughan).

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1. **Hein, M.**, Mohammed, A., **Boström-Einarsson, L.**, Grimsditch, G., Pioch, S., Shaver, E., Vardi, T., **McLeod, I.M.** (In Review) Perspectives on the use of coral reef restoration as a strategy to support and improve reef ecosystem services. Frontiers in Marine Sciences

2. **Ceccarelli, D.M.**, **McLeod, I.M.**, **Boström-Einarsson, L.**, Bryan S.E., Chartrand, K.M., Emslie, M.J., Gibbs, M.T., Gonzalez-Rivero, M., **Hein, M.Y.**, Heyward, A., Kenyon, T.M., Lewis, B., Mattocks, N., Newlands, M., Schläppy, M., Sugget, D.J., Bay, L. (2020). Supporting coral reef recovery with small structures and substrate stabilisation: State of knowledge, considerations for management and implementation. PLoS ONE.

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4. **Boström-Einarsson, L.**, Babcock, R.C., Bayraktarov, E., **Ceccarelli, D.M.**, **Cook N**., Ferse, S.C.A., Hancock, B., **Harrison, P.**, **Hein, M.**, Shaver, E., **Smith, A.**, Suggett, D., Stewart-Sinclair, P.J., Vardi, T., **McLeod, I.M.** (2020) Coral restoration – A systematic review of current methods, successes, failures and future directions. PLoS ONE 15(1): e0226631. https://doi.org/10.1371/journal.pone.0226631 [19, 506]

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6. Burrows, D.W., Purandare, J., Bay, L., **Cook, N**., Koopman, D., Long, S., Lundgren, P., Mead, D., Morris, S., Newlands, M., Roth, C., Wachenfeld, D., **Smith, A.K.** and

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4. **McLeod IM**, Newlands M, **Hein M**, **Boström-Einarsson L**, Banaszak A, Grimsditch G, Mohammed A, Mead D, Pioch S, Thornton H, Shaver E, Souter D, Staub F. (2019). Mapping Current and Future Priorities for Coral Restoration and Adaptation Programs: International Coral Reef Initiative Ad Hoc Committee on Reef Restoration 2019 Interim Report. 44 pages. Available at icriforum.org [1, 167]

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Report to the National Environmental Science Program. Reef and Rainforest Research Centre Ltd, Cairns (63pp.). [11]

6. **Cook, N.**, **Smith, A.**, **McLeod, I.M.**, **Boström-Einarsson, L.**, Christie, S., McKenna, G. (2018). Fitzroy Island coral installation and baseline report. Report to the National Environmental Science Program. Reef and Rainforest Research Centre Limited, Cairns, Australia. 26 pp. [0, 578]

Thesis

1. Mastroianni, E. (2019). Macroalgal removal on inshore reefs of the Great Barrier Reef. Honours Thesis (1st Class). Supervisors **DG Bourne**, **HA Smith**, **L Boström-Einarsson**, **P Harrison**

APPENDIX 2: NESP TWQ HUB PROJECT 4.3 INVOLVEMENT IN GBR CORAL RESTORATION PROJECTS

Project	NESP TWQ Hub Project 4.3 Involvement
Fitzroy Island coral gardening	Assistance and funding with establishment of first coral nurseries, assistance with monitoring and project evaluation.
Agincourt Reef rubble stabilisation	Advice and assistance with planning and monitoring
Whitsundays Islands coral gardening	Advice and assistance with planning and monitoring
Magnetic Island macroalgae removal and coral larvae propagation	Co-leadership and co-funding with Earthwatch Institute Australia, Southern Cross University and the Australian Institute of Marine Science
Coral Nurture Program (coral gardening and direct transplantation, six reefs in the Cairns/ Port Douglas region)	Assistance with monitoring and data management planning
Mars Inc. Reef Star Installations	Early discussions and advice
Reef Restoration and Adaptation Program	Collaboration and co-funding of global coral restoration review
Manta Ray Bay coral bommie redeployment	Assistance with monitoring as publishing results

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