INVESTMENT CASE

A report provided to the Australian Government from the Reef Restoration and Adaptation Program

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1 EXECUTIVE SUMMARY

Australia's Great Barrier Reef is now under imminent threat from climate change. Warming oceans are causing more frequent and serious bleaching events, which kill coral. Recent events have hit the Reef hard. More bleaching events are predicted in the coming years. Nevertheless, the Reef remains, for now, a vibrant ecosystem of great natural resilience, beauty and economic value.

While the world works to bring global greenhouse gas emissions under control, we need new ways to help the Reef adapt and remain resilient to climate change. This Reef Restoration and Adaptation Program (RRAP) Investment Case sets out a long-term vision and workplan for how this could be achieved, at scale, affordably and within the window of opportunity for action that now exists.

The findings clearly show that investing in RRAP will be good for Australia and the world. To make it happen, major investment in research and development (R&D) is needed now to secure options that could be used, if needed, within the next decade. Earlier interventions could be possible if we start now and work together. RRAP provides hope for the Reef.

The Great Barrier Reef – a natural wonder at risk

Over 2300km long and covering some 344,400km^2, the Great Barrier Reef (the Reef) is the largest living reef structure on Earth[1]. It is home to more than 12,000 macroscopic marine species and is one of the most biodiverse places in the world[2]. In 2015/16, the Reef contributed more than 66,000 full-time jobs and $6.4B to the Australian economy; with an estimated economic, social and icon asset value of at least $56B[3]. But, as discussed below, the Reef now faces an existential threat climate change[4–8].

Most of the Reef is within the Great Barrier Reef Marine Park. In 1981, the United Nations (UN) bestowed the Reef with World Heritage status for its outstanding universal value. At that time, the UN stated: *"The major portion of the reef is in a reasonably pristine condition"*[1].

But over the next three decades, the Reef's condition deteriorated, primarily due to the combined effects of declining water quality from land-based runoff [9,10], marine pests[11,12] and cyclones[13–15]. Between 1985 and 2012, the Reef lost almost half its coral cover[13].

A new, emerging threat

Coral bleaching is caused by sustained periods of warmer-than-usual reef waters[16] and can result in extensive coral mortality and ecosystem disruptions[5,17]. Mass coral bleaching on the Reef in 1998 and the early 2000s[18] was a small contributor to coral decline before 2012[13]. However, in 2016, an unprecedented mass coral bleaching event resulted in the temporary loss of an average of 30 percent of shallow water corals, mostly in the northern region where heat exposure was most extreme. In 2017, the central region was mainly affected by a second major bleaching event, causing further decline across the northern two-thirds of the marine park[5,19]. Similar declines have been observed in Western Australian reefs[20], as well as globally[6]. During these events, decades-long efforts to build the Reef's resilience through best-practice management were overwhelmed in a few short weeks of sustained, high sea temperatures. Many of the world's reefs have now bleached twice in the past decade[5,6]. This is significant because reef recovery from such disturbances may take a decade to occur[21–23].

New interventions are needed

Continued climate change will mean a continued decline of coral reefs[5,24–27]. Conventional management methods will no longer be enough to protect coral reefs under any projected climate change scenario[28–30]. A new set of on-reef management options is needed now if we are to give coral reefs the best chance to survive and prosper in a warmer future, and to build resilience while the causes of climate change are being addressed.

The Great Barrier Reef has already lost half its natural capital. Without stabilisation of global temperatures in the coming decades, the health of the Reef is expected to continue to decline[5,24–27].

A window of opportunity still exists 20 to 30 years at most for the coordinated and integrated actions needed to sustain the Reef and coral reefs globally: keep warming below 2°C[31], continue to strengthen conventional management techniques and help reefs become more resilient to the effects of climate change through the introduction of new and effective interventions[28–30].

First response

Recognising this opportunity, the Australian Government provided $6M to an integrated consortium of Australian institutions, led by the Australian Institute of Marine Science, to undertake a concept feasibility study for RRAP. The result is a comprehensive suite of reports, including this investment case.

Before this study, there had been little rigorous scientific investigation of the prospect for at-scale reef intervention[30,32]. Efforts to repair reefs in the Caribbean, the Philippines, Hawaii and other locations (with varying levels of success) have been at the scale of metres only.

A national mission

RRAP is envisaged as a multi-decadal national mission to develop, test and, if necessary, deploy solutions to help keep the Reef resilient and sustain critical ecosystem services and values in the face of climate change.

The high-level objectives of RRAP are:

1. Provide decision-makers with scientifically-proven, ecologically-effective, socially-acceptable, technically-feasible and economically-viable options to successfully intervene at scale on the Reef. Effective and time-critical solutions will be available to reef managers and policymakers to enhance the resilience and adaptive capacity of reef corals to climate change.
2. Determine and communicate the environmental, ecological, economic and social implications of alternative intervention strategies.
3. Resolve regulatory and stakeholder complexities around intervention choices to help pave the way for their deployment, if needed.
4. Work with, not replace, conventional Reef management and climate change mitigation.
5. Support and guide the eventual deployment, if required, of at-scale integrated restoration and adaptation intervention solutions, as directed by reef managers and policymakers.

This document explains why Australia needs RRAP and how this ambitious mission can and must be achieved by an integrated consortium of partners aligned around a shared mission. It presents the results of the concept feasibility study into new innovative approaches that can deliver benefits for the Reef, and Australia, in a race against time.

RRAP Concept Feasibility Study objectives

The objectives of the RRAP Concept Feasibility Study were to:

1. Assess the range of likely trajectories of coral reef health and condition under different climate change scenarios.
2. Conduct a preliminary evaluation of the widest possible range of new intervention techniques that could, alone and in combination, complement existing management approaches to help protect the Reef's ecological functions and economic and social values.
3. Recommend a comprehensive R&D program to develop and test the underlying knowledge needed to successfully intervene on the Reef, at scale.
4. Develop a business case for investment in the R&D and its integration and coordination required to move from concept to successful on-reef intervention.

This report provides a high-level summary of the 32 detailed reports covering every aspect of the feasibility study. It integrates them into a case for investment in a comprehensive RRAP R&D Program. Accompanying reports cover technical assessments of prospective interventions. These include modelling the predicted effectiveness of different intervention strategies and the associated analysis of the state-of-reef modelling, economic value and cost-benefit analysis, surveys of social attitudes and regulatory capacity, detailed design and costings of the proposed R&D program, and a broad survey of international and domestic funding opportunities.

There is scope to protect the Reef

The feasibility study examined a wide range of intervention options from large-scale cooling and shading, to coral reproduction and recruitment to enhanced climate resilience and adaptation. It concluded that with the right R&D effort and strategy, and with the right integration and coordination, new interventions developed under RRAP would have good prospects of sustaining Reef coral condition under climate change. Helping corals (the climate-sensitive reef engineers and habitat builders) adapt and remain resilient will help protect critical reef functions, rich biodiversity and valuable ecosystem services. Models estimated that effective intervention strategies could increase the likelihood of sustaining high coral cover (greater than 20 percent areal abundance) on the Reef from 25 to 79 percent in 2050 under strong carbon mitigation and from 13 to 66 percent in 2050 without mitigation (Table A5, **R3: Intervention Analysis and Recommendations**). While modelling results are associated with uncertainty, the R&D program would aim to maximise this chance of success. The degree of success will depend on a suite of factors including appropriate funding, Traditional Owner and stakeholder support, regulatory capacity-building, collaboration of key agencies and research providers, inclusion of private sector capability and, ultimately, global action on climate change.

Analyses showed that no single *silver bullet* can protect the Reef. Instead, a multi-pronged strategy will be critical. First, integrated packages of interventions designed to reinforce each other in space and time could add new levels of coral resilience. These would consist of approaches to *protect* the Reef from the most damaging temperatures, *assist adaptation* to warming and *restore* damaged sites of key functional importance and value (Figure 1). Second, intensified conventional management efforts, including control of outbreaks of the native coral-eating crown-of-thorns starfish and pollution management, must be part of the integrated strategy. Third, the degree to which new interventions offer protection and enhance resilience will depend upon the extent to which climate change and greenhouse gas emissions will be mitigated. The closer the world gets to achieving the goals of the Paris Accord, the greater the chance we can preserve the Reef, as we currently know it, and sustain its functions and values. Critically, it would be cheaper, faster and ultimately more effective to help the Reef adapt to climate change than to try to help it recover *after* it has been damaged or destroyed.

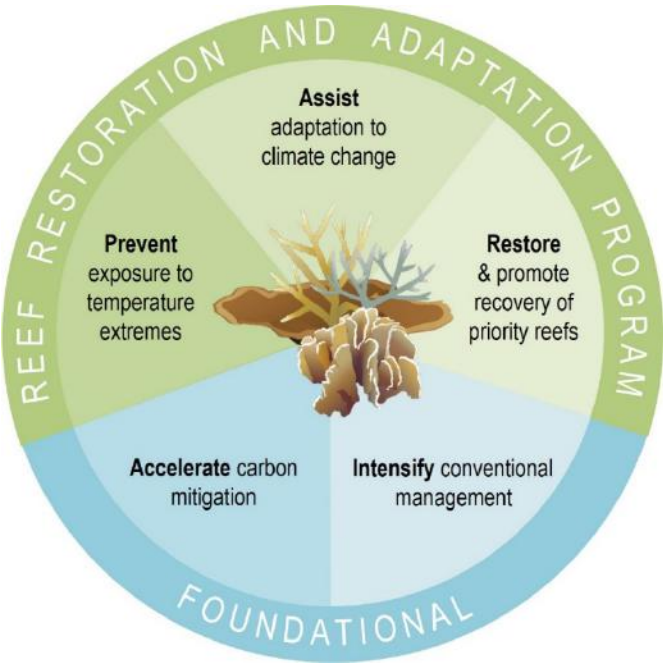

Figure 1. Multi-pronged strategy needed to protect the Reef. This forms part of the philosophy, strategic approach and guiding principles of the recommended RRAP R&D Program.

A race against time

RRAP will be in a race against time to produce solutions. Global carbon emissions continue to increase[33]. This trend, combined with current climate mitigation commitments, would see the world warm 2.6°C to 3.1°C above pre-industrial levels[34,35], with significant risk for the survival of reefs worldwide.

Early on-reef intervention may help stem the decline. Delaying action will almost certainly mean the loss of critical Reef value. Under best-case emissions scenarios, RRAP interventions could provide an opportunity to even reverse the decline and grow the natural capital of the Great Barrier Reef. Under business-as-usual emissions and continued climate change, successful RRAP interventions will buy time for Reef survival. A key challenge will be to identify and develop robust solutions that provide the best chance of positive outcomes under the widest range of climate scenarios.

Significant potential benefits for Australia

The engagement and economic analyses undertaken as part of the feasibility study predicted the economic, social and environmental benefits of Reef intervention for Australia were likely to be significant. This would be especially so under strong carbon mitigation (scenario RCP 2.6 of the Intergovernmental Panel on Climate Change [IPCC], which would globally meet the Paris Agreement targets, IPCC 2014). Under this scenario, estimates of gross, undiscounted damage avoided (or benefits achieved) from implementing new interventions (compared with best-practice conventional management only), ranged from $10.7B over 60 years when using the most conservative assumptions developed for this study to between $200B and $773B when using published ecosystem services-based value estimates for coral reefs[37,38] and assuming values increase in proportion to coral condition. Total Reef benefits were predicted to decline under the IPCC unmitigated emissions scenario of RCP 8.5 in the long term. However, the net benefits of RRAP interventions may be sustained under RCP 8.5 until around 2050, as opportunities to avoid damage in the near term will be substantial.

In all cases, direct benefits from RRAP to, and involvement of, regional economies and Traditional Owners would be significant. This is in terms of economic activity and jobs and involvement in activities to sustain the Reef, as well as the more intangible community development and capacity-building. Cost-benefit analyses conducted for this study show potential returns to the nation many times greater than the investment Australia may choose to make.

Technically possible, but not yet

The RRAP Concept Feasibility Study shows conclusively that new interventions at scale could help the Great Barrier Reef remain resilient in the face of climate change, but not yet.

An exhaustive, comprehensive, multi-disciplinary and multi-organisational assessment considered a total of 160 interventions across multiple scales (micro = a few square metres; small = key reef sites, a few hectares to a single reef; medium = 50 reefs or more and large = 200 or more reefs to all of the Reef). These were evaluated against defined criteria including the ability to deliver functional Reef benefits (via modelling of ecological impact and benefits), risk, technology readiness and development requirements, feasible deployment scale and cost.

Many of these interventions show promise (across a spectrum of feasible deployment scales), but none are ready to deploy at anything other than the micro-scale. A significant, concerted R&D effort is required to make any new scalable intervention technically-feasible, safe, acceptable to the public and regulators, and affordable. Of the 160 interventions assessed, 43 are recommended to progress for further assessment and development.

It is estimated that selected small-scale interventions (a few hectares to a single reef) could be made investment-ready within two to five years, and could be deployed shortly thereafter, if deployment funding became available early (within the first few years of an R&D program commencing). These could include rubble stabilisation, coral seeding and small-scale shading methods working in combination. Effective large-scale interventions would take longer to develop, test and make deployment ready.

Informed choices to drive optimal strategies

Once developed, the effectiveness and efficiency of interventions will be strongly dependent on the quality of decisions guiding their deployment. Factors such as climate future, which interventions, which reefs, which locations on a reef, deployment densities, timing, intervention combinations and risk trade-offs need to be considered. Early indications show there are potentially several orders of magnitude difference in outcomes between average and high-quality decisions informed by a decision-support system. Therefore, emphasis must also be placed on developing next-generation reef models and the reef knowledge required to drive these models and decision-support systems.

Both modelling and decision support will depend heavily on proper functioning and resourcing of the planned Reef 2050 Integrated Monitoring and Reporting Program (RIMReP), currently being developed as a separate activity by the Great Barrier Reef Marine Park Authority.

Strong public support

The enormity of the threat faced by the Great Barrier Reef has sparked the Australian public's interest and imagination (see Figure 6). Public surveys conducted as part of the feasibility study showed strong in-principle support throughout Australia for science-based intervention to help keep the Great Barrier Reef resilient and support adaptation.

Engagement is key

Traditional Owner and community engagement and acceptance are fundamental requirements for any viable intervention option to be deployed. Ongoing engagement, consultation and alignment with community values are essential for building trust, especially as options are developed and move closer to deployment. Traditional Owners have a unique and critical role to play in the formulation and implementation of any intervention options. This must be reflected in the governance of RRAP and the implementation and management of the R&D and deployment phases. Principles of co-design will need to be embedded in the program.

Manageable risk

There are risks associated with the delivery of RRAP outcomes. These include lack of social acceptance, technical feasibility and financial viability, unexpected shifts in the external environmental factors or threats, ecological risks, lack of funding for critical management and coordination of activities within RRAP, and meeting and maintaining appropriate regulatory approval in a novel operating environment.

The program will actively manage risks using an integrated and systematic approach. First, it will minimise the likelihood of any event that prevents the program from meeting its key objective: to help sustain or grow Reef values safely. Second, it will help mitigate or manage unintentional consequences that may have a negative impact on the Reef or the people of Australia.

To achieve this, a comprehensive, multi-tiered risk-management plan will be developed early in the RRAP R&D Program. At the program governance level, the plan will lay out mechanisms to minimise and mitigate all strategic risks. Lower-level tactical and operational risk management will be nested within strategic risks via RRAP's Decision Support Framework.

The current regulatory regime does not preclude on-Reef intervention. However, it will be challenged by novel interventions and will need to adjust to ensure it continues to balance the risks of intervention with the risk of no action. The proposed program will help this adjustment via an open and transparent process of risk analysis and decision support.

Do it, but do it right

The feasibility study demonstrates that success will depend on a planned, integrated, coordinated, long-term program. Doing it right will mean much more than developing specific intervention technologies. If, for example, interventions are to be deployed at scale, they will require extensive production and deployment systems and capability to be developed in parallel. Equally, success will depend on developing key underlying knowledge and systems to guide their development and deployment including building improved ecological models and decision-support systems to deal with the uncertainty inherent in such a complex and changing system, managing a range of risks, overcoming regulatory challenges and managing the perceptions of stakeholders who may be confronted by the idea of large-scale Reef interventions. Further, it requires transparency, inclusiveness and ongoing consultation. To achieve this, a multi-phase program is proposed, commencing with an R&D program, which will progressively deliver interventions for deployment as required.

Details of the proposed next phase, the RRAP R&D Program, including an integrated technical work plan, cost estimates, risk management and proposed governance are provided in this investment case and the supporting reports.

Required investment

The RRAP R&D Program will be the world's largest and most ambitious effort to develop and test at-scale restoration and adaptation interventions for coral reefs. An integrated, properly governed and executed 10-year R&D program will provide a level of health insurance for the Reef by developing safe and effective new interventions before they become critically needed.

The estimated cost of the minimum recommended R&D program, described in detail below and in the accompanying reports, is $326M over the first five years, with an additional $216M required from years six to 10. While the overall R&D effort required to take large-scale interventions to deployment may require a decade or more, smaller-scale interventions may be ready to deploy in the first few years.

This level of funding would provide the drive and flexibility to deliver novel, practical and stakeholder-informed research to solve complex challenges, engage with international organisations and experts and attract additional R&D funding. In addition, adequate funding would give the program the ability to take risks and rapidly identify investment-ready interventions, to examine previously untested solutions, and to test interventions on-Reef and deploy prospective interventions at small scales within the first few years.

The $100M from the Australian Government, for reef restoration and adaptation science, through the Reef Trust Partnership, bolstered by contributions from the research consortium partners, would provide an important start to the recommended R&D program and real hope for the future of the Great Barrier Reef.

The RRAP R&D Program represents significant value for the Reef and Australia, in its own right. Effective R&D provides access to intervention options otherwise out of scope. It helps navigate decision pathways that can maximise benefits and minimise risks and costs at strategic, tactical and operational levels. Without effective R&D, new interventions on the Reef will be unguided, risky and less likely to produce return on investment. Conservative value of information analyses for only one intervention type (development and small-scale deployment of warm-adapted corals) showed the likelihood of positive returns (via new options) increased 20-fold with early R&D investment (first five years).

What can be ultimately achieved, and how fast, will be a function of the final investment profile. Fast tracking of intervention R&D and the parallel development of prototype deployment systems could reduce the timeframes to implementation by five or more years. Whatever investment profile is ultimately chosen, we now have a window of opportunity to start the journey.

Real hope for the Great Barrier Reef

Innovation Science Australia called saving the Great Barrier Reef from climate change a “national mission”[39]. The RRAP mission is ambitious. Successful intervention on the Reef, along with ongoing conventional management, would help to protect and retain the core environmental, social and economic values of the Reef in the future. The program can help achieve this mission indefinitely under strong carbon mitigation and for 20–30 years without mitigation.

With a bold, long-term, breakthrough R&D program, what may have once seemed impossible can now be achieved. Australia has the scientific ability, know-how and engineering capability to deliver such a program. The proposed investment in the RRAP R&D Program would place Australia in a position of global leadership in strategic coral reef resilience support and adaptation. This would open opportunities to partner internationally and export our know-how to other countries whose reefs face similar challenges.

Right team at the right time

In a recent interview with *Time*, when asked about the future of the planet’s environment and the emerging impacts of climate change, 92-year-old Sir David Attenborough said:

“*The question is are we going to be in time, and are we going to do enough? And the answer to both of those is no. We won’t be able to do enough to mend everything. But we can make it a darn sight better than it would be if we didn’t do anything at all.”*

The RRAP R&D Program would bring together the best and brightest from Australia and around the world, built around the current consortium of leading Australian institutions, in the largest-ever coordinated effort to help a significant global ecosystem in its fight to survive climate change. The RRAP mission is not a piecemeal one; success will require an all-in strategy, the equivalent of a space mission. At this point, we have the opportunity, the people, the ideas and the wherewithal to succeed. Many might feel the task is too great, the scale too large and the complexities too bewildering to even contemplate. But we can’t succeed if we don’t try. If we do succeed in the RRAP mission, the positive economic, social and environmental implications for Australia, and the world, will be enormous. And even if we are only partially successful, at least we will have made it ‘a darn sight better’ than it would have been if we had done nothing at all.

2 A GUIDE TO READING THIS REPORT

The Reef Restoration and Adaptation Program (RRAP) Concept Feasibility Study acknowledges the ongoing spiritual and cultural connection of Traditional Owners to the Great Barrier Reef (the Reef). We acknowledge native title and the diversity of Indigenous values, rights, interests and aspirations. There are more than 70 Aboriginal and Torres Strait Islander Traditional Owner groups with connections to the Reef, and approximately one million people who live in the 424,000km^2 catchment of the Great Barrier Reef World Heritage Area.

2.1 Overview

This investment case provides policymakers and senior government officials with a high-level summary of the findings and recommendations of the 18-month, $6M study into the feasibility of intervening at scale on the Great Barrier Reef to help it adapt and remain resilient to climate change.

This report provides a synthesis of six summary reports (*what we found and what we should do*), 13 detailed technical reports on different aspects of the feasibility study (*what we did, how we did it and what we found*) and detailed research and development (R&D) planning (*what needs to be done and how*).

Appendix C provides a schematic of the full suite of reports and how they link, along with a guide to authorship and the names and affiliations of reviewers of each document. Details on how these reports can be accessed are available at http://www.gbrrestoration.org/reports.

2.2 Report structure

This investment case contains:

- **The need for action:** Why we should examine options for intervening on the Great Barrier Reef. The slow decline of a splendid natural treasure. The existential threat of climate change to the future of the Reef. Economic, social and environmental value at risk. What we can do about it.
- **The opportunity** for Australia, and the world, if R&D can unlock the ability to intervene effectively on the Reef at scale. An open window, for now. How integrated and coordinated action will help the Reef, Australia and the world.
- **The scope and objectives of the concept feasibility study:** The overarching mission of RRAP, of which the concept feasibility study is the first phase. The concept feasibility study objectives: Is intervening on the Reef at scale feasible? What do we know? What don't we know? How can we fill the knowledge gaps through R&D? What would be the costs, benefits and risks of intervening vs not intervening?
- **Summary of key findings and recommendations of the concept feasibility study:** The possibility of intervening at scale. Views of the Australian public. Regulatory capacity. The R&D needed to inform decision-makers about workable, safe and economically viable options. How an R&D program should be delivered to achieve the best results possible.
- **Benefits of intervening at scale:** What does Australia stand to gain from helping the Reef adapt and remain resilient to climate change? Estimates of economic, social and environmental value to be gained from intervention are compared with initial, high-level

estimates of what it might cost. What would be the benefits to regional economies and Traditional Owners from intervening at scale?

- **Proposed RRAP R&D Program:** How to best deliver the required R&D. Technical focus areas. Cross-cutting essential research. Intervention development. Governance and management. International links. Detailed costing.
- **Risk management:** A high-level summary of the key strategic risks to the RRAP R&D Program and how they would be managed, including proposed risk management processes.
- **Summary:** What is the case for significant investment in a coordinated R&D effort?
- **Appendix A:** synthesis of the RRAP Concept Feasibility Study: More detail on each of the key aspects of the study.
- **Appendix B:** Details on governance and investment requirements.
- **Appendix C:** RRAP Concept Feasibility Study document map and list: Details of authorship of each document and the names and affiliations of reviewers of each document.

3 THE NEED FOR INTEGRATED AND COORDINATED ACTION

3.1 The slow decline of a splendid natural treasure

The Great Barrier Reef and the coral reefs of the world have long been recognised as some of the most precious places on Earth. Sir David Attenborough called the Reef *"one of the greatest and most splendid natural treasures that the world possesses".* Millions of people rely on reefs for their food and livelihoods. Millions more each year enjoy the beauty and complexity of these ancient ecosystems as tourists. Coral reefs are the rainforests of the sea and home to the richest biodiversity in the world's oceans[40,41]. Traditional societies worldwide hold deep cultural connections to these places of beauty and meaning. Australians see the Great Barrier Reef as an essential part of their national identity[3].

The scale of the Great Barrier Reef is staggering: over 2300km long, covering some 344,400km^2, it contains more than 2900 reefs and 1050 islands, and is home to some of the planet's most unique species. Most of it is protected within the Great Barrier Reef Marine Park (Figure 2).

In 1981, the United Nations (UN) bestowed the Great Barrier Reef with World Heritage status for its outstanding universal value: *"cultural and/or natural significance which is so exceptional as to transcend national boundaries and to be of common importance for present and future generations of all humanity"*[42]. In the original nomination for World Heritage status in 1981, the UN stated that *"the major portion of the reef is in a reasonably pristine condition".*

But as the next 30 years passed, the Reef's condition deteriorated with the combined effects of declining water quality from land-based runoff[9], marine pests[11,12] and cyclones[13–15]. Between 1985 and 2012, the Great Barrier Reef lost almost half of its coral cover, largely due to the impact of cyclones and mass outbreaks of the native, coral-eating, crown-of-thorns starfish[13]. Multiple lines of evidence point to nutrient run-off as one driver of crown-of-thorns starfish outbreaks[43,44], potentially exacerbated by warming[11]. Coral bleaching was recognised as a small contributor to the observed decline during this period, mainly as a result of global bleaching events in 1998 and the early 2000s[18]. Mass coral bleaching is caused by sustained periods of warmer-than-usual reef waters[16] and can result in extensive coral mortality and ecosystem disruptions[5,6,45,46].

In 2015, the Reef 2050 Plan[42] was developed, setting out Australia's commitment to protecting the Great Barrier Reef's outstanding universal value for the future. The plan focused on actions to reduce pressure on the Reef and build its resilience, including improving water quality and fisheries management and battling crown-of-thorns starfish. The original plan was largely silent on climate change.

Despite all the stresses on the Reef, it has remained an incredibly diverse, resilient and valuable asset. A report on the value of the Reef, based on data from 2015/16, showed the Reef contributed more than 66,000 full-time jobs and $6.4B a year to the Australian economy[3]. The same report identified the economic, social and icon asset value of the Great Barrier Reef was at least $56B. Estimates of the Reef's ecosystem services value developed as part of the RRAP Concept Feasibility Study were as high as $800B.

Figure 2: The Great Barrier Reef Marine Park. Source: The Great Barrier Reef Blueprint[47].

3.2 The existential threat of climate change

This extraordinary natural asset now faces a new, more potent threat. In 2016 and 2017, the Great Barrier Reef was hit with back-to-back major bleaching events, which resulted in the temporary loss of an average of 30 percent of the remaining shallow-water corals on the Reef in 2016 alone[5]. Other reefs in Western Australia and worldwide were also affected[6,20,48]. Strikingly, the 'reasonably pristine' northern Great Barrier Reef was worst hit (Figure 3)[45]. The decades-long efforts to build the Reef's resilience were overwhelmed in a few short weeks of sustained, unprecedented, high sea temperatures, two years in a row, driven by climate change.

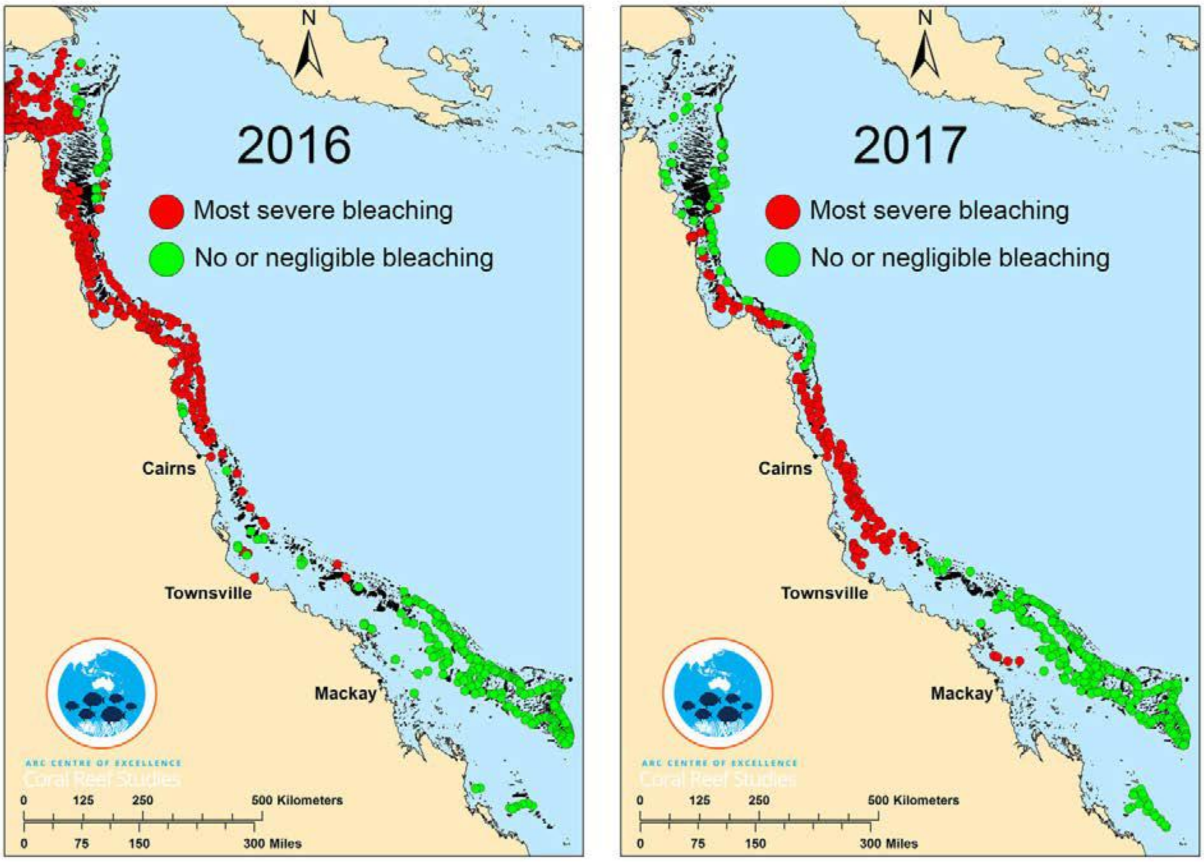

Figure 3: Results of aerial surveys undertaken by the ARC Centre of Excellence in response to the 2016/17 bleaching event Figure from Hughes et al., 2017[49].

The scale and severity of the damage in 2016 and 2017 highlighted the critical threat climate change poses to all reefs already in a 1°C warmer world, including the Great Barrier Reef. If the world remains on its current greenhouse gas emissions trajectory, reefs globally are projected to suffer catastrophic decline by mid to late century[6,27,50,51]. Even if the world manages to stabilise global warming at 1.5°C above the pre-industrial average, mass bleaching events are predicted to increase in frequency and severity in the coming decades[27,52]. Critically, the Reef's resilience may already be significantly impaired. Rates of coral recruitment in 2018, following the recent back-to-back bleaching events, were reduced by 89 percent, compared with rates during 1996–2016[53]. Other recent studies have shown that coral recovery now takes longer[54] and may be reduced by up to 80 percent[55]. In short, we are facing the very real prospect that, within a generation and without concerted action to reduce emissions and help drive adaptation and faster recovery from damage, the Great Barrier Reef as we have known it will cease to exist. This calls for urgent support to enhance resilience beyond that achievable by any conventional intervention. There is a growing realisation that in this warming world, no matter how much we refine and improve current management approaches, on their own they will not be enough to protect coral reefs[28–30,56].

While mass bleaching events were first observed in the 1980s[57], many of the world's reefs have now bleached twice in the past decade[5,6,48]. This is significant because reefs may take a decade to recover from disturbances[21–23]. Without a significant stabilisation of global temperature increases in the coming decades to below 2°C, reef health is expected to continue to decline[5,24–26,55]. Conventional management methods will not be enough to protect coral reefs[28,30]. A new set of effective on-reef management options is needed now if we are to give coral reefs the best chance to be sustained and prosper in a warmer future, and to buy time while the causes of climate change are addressed. A window of opportunity still exists 20 to 30 years at most for the dual action needed to sustain the world's coral reefs: keeping warming below 2°C[31] and helping reefs stay resilient[4,28,29,58,59]. The R&D program will help Australia take advantage of this opportunity for the Great Barrier Reef.

3.3 Prospects for solutions

For coral reefs to survive and prosper in the 21st century, three actions are required:

- Curbing global warming to below 2°C; the Paris target[60]
- Best-practice conventional management
- New interventions to support reef restoration and adaptation.

Along with emissions mitigation, Australia needs to find ways to help Reef corals, the key habitat providers for thousands of fish and invertebrate species, remain resilient, adapt at scale to warming conditions and recover more quickly when they are damaged. The Reef 2050 Plan update[1] incorporated support for innovative approaches to reef restoration, protection and management, and identified local climate resilience actions. The RRAP mission will add a critical new set of strategy options to the Reef 2050 Plan. Options include interventions that build resilience and adaptive capacity under climate change and will be part of a portfolio of interventions that are developed ahead of the curve of climate change[61], which represent no regrets and are safe for Reef and people.

Modelling studies show that even if we are successful in limiting global warming to 2°C relative to pre-industrial levels, reefs will still be severely affected[50,62]. At-scale resilience and adaptation action, if feasible, could make the difference between highly degraded reefs or sustaining reefs that are fully functional, biodiverse and able to provide benefits to the community and economy for decades to come. Under more severe, unmitigated emissions trajectories, the prospects for the world's reefs are much gloomier[7,27,63–66].

To date, there has been very little rigorous scientific investigation of the prospects for at-scale reef restoration and adaptation[30]. While very small-scale (a few square metres) efforts to repair reefs have been undertaken in the Caribbean, the Philippines, Hawaii and other locations (with varying levels of success), no larger-scale projects have occurred. The methods that have been used at small scales are not suitable for larger-scale efforts and the scale of the scientific endeavour has, until now, been inconsistent with the magnitude and complexity of the challenge.

Reducing global emissions will take time and commitment[34,67–69]. Acting now on effective adaptation measures can help reefs stay resilient and may buy time for the necessary emissions reductions to occur. This will maximise the chances of sustaining viable reef systems in the future. Under more pessimistic and potentially more realistic emissions scenarios, integrated and coordinated resilience and adaptation action, if successful, could extend the functional life of the Reef while global warming is brought under control.

The Reef is tremendously valuable to Australia and that value is under threat. Current conventional methods for building reef resilience, on their own, have proven insufficient in the face of repeated mass bleaching[28,30,45]. If we want to safeguard the Great Barrier Reef for the future, we need to begin developing options for intervening on the Reef to help it adapt and be resilient to climate change, should we choose to use them.

4 THE OPPORTUNITY

4.1 An open window, for now

While many reefs worldwide may have already declined beyond their ability to recover[70], substantial areas of the Great Barrier Reef still show resilience in their ability to recover from the combined threats of invasive pests, changes in water quality and impacts from extreme weather events[14,71–73]. Substantive work has been undertaken to address these threats[1], but there has been limited opportunity to tackle the challenge of building reef resilience in the face of global warming[30,59,74,75]. RRAP is the first program to tackle this challenge at scale.

The time to begin a restoration and adaptation R&D program is now, while there is still enough diversity to preserve and enough intact ecosystem functions to support reef resilience. Climate models predict that the window of opportunity to reduce global emissions to a level that can keep global warming below 2°C is closing very rapidly[34,68,76]. Coordinating early actions on climate change and adaptation can secure a future for the Reef and other sensitive ecosystems. While 2°C warming may exceed the tolerance levels of some sensitive coral species[62,77], proactive restoration and adaptation represent the opportunity to build critical resilience in the remaining Great Barrier Reef fauna, which will produce ecosystem benefits for Australians into the future.

Figure 4 conceptually illustrates this opportunity. As the oceans continue to warm, Reef condition is expected to continue to decline and the likelihood that the Reef can be sustained in a good condition (high state) declines[5,27]. The greater the warming, the less effective conventional management techniques will be on their own[28,29]. By investing in measures to help reefs remain resilient and able to adapt to the effects of climate change, we open the prospect of real hope for the future of our reefs. But if we wait too long, the window will close. Long-term solutions beyond 2°C warming would be for reef ecosystems that are functionally different from those today and will unlikely be at scale or with ecosystem benefits characteristic of today's reefs.

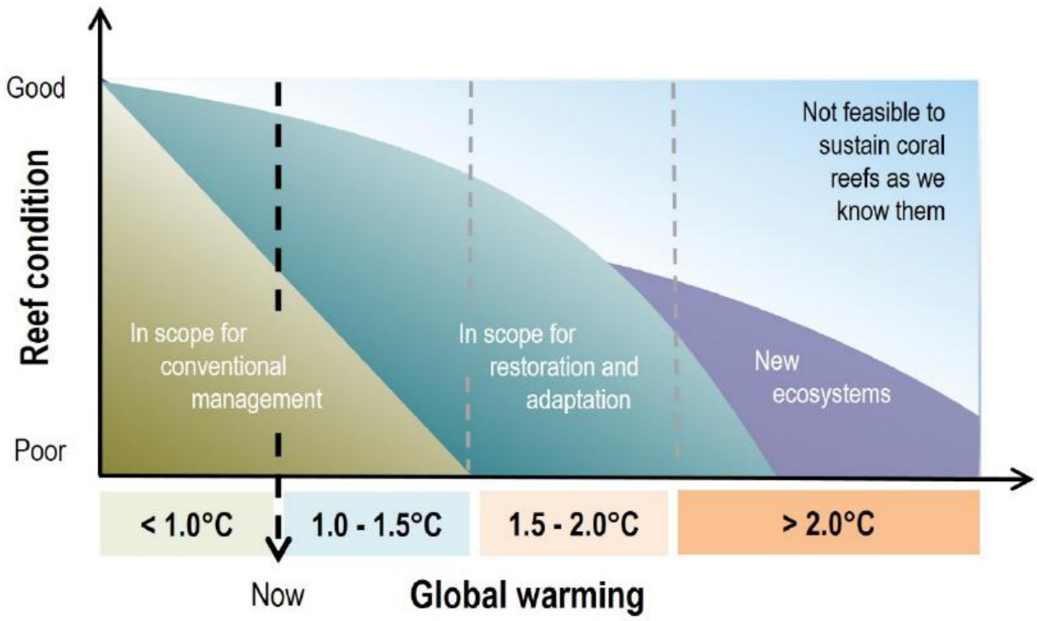

Figure 4: The opportunity provided by at-scale reef restoration and adaptation in a race against time. The diagram conceptually illustrates the need for a three-pronged strategy to sustain coral reefs this century: (1) mitigation (reducing global warming), (2) best-practice conventional management and (3) timely and effective restoration and adaptation. The bold, vertical dashed line represents present condition (1°C warming above pre-industrial levels), indicating the scope for conventional management to sustain coral reefs is already compromised. Restoration and adaptation can build resilience in concert with best-practice conventional management, but within a limit set by severe climate change. Beyond that limit, reefs as we know them will be inviable and their loss may give rise to new or altered reef ecosystems. Note that boundaries between management regimes are illustrative only. Source: modified from Anthony (2016)[26].

Good for Australia, good for the world

The need for urgent action to protect the Great Barrier Reef, and reefs globally, presents unique opportunities for Australia. If we begin the strategic R&D now, we can stay ahead of the curve and develop feasible options to help protect the Great Barrier Reef (and other reefs) from some of the impacts of climate change. This opens the possibility of preserving a significant part of the Reef's economic, environmental, social and cultural value for generations to come. Under worst-case scenarios of unabated global emissions and the resultant warming, timely restoration and adaptation measures offer the opportunity to extend the life of the Reef as we know it; to help the world buy time to reduce emissions, potentially allowing us to retain a more functional Reef over the longer term. Without undertaking the necessary R&D in search of effective and safe solutions, we will not be able to intervene successfully and the Reef will be left to its fate. The results of the feasibility study demonstrate significant scope to intervene and minimise damage to a unique Australian asset.

As one of the few developed nations hosting coral reefs, Australia has the expertise, capability and wherewithal to take a leading global role in the emerging field of reef restoration and adaptation. This, in turn, will present opportunities for Australia to export knowledge and expertise to the rest of the world. Developing and deploying restoration and adaptation methods will also open significant regional economic development opportunities for Reef communities and Traditional Owners.

Based on the analysis of the RRAP Concept Feasibility Study (described in more detail below and in the accompanying RRAP reports), the broader opportunities for Australia of at-scale reef restoration and adaptation include:

- **Value preservation and creation:** Best case maintaining or growing Reef values over the long term; worst case life extension for the Great Barrier Reef to buy time for emission reductions to take effect.
- **Regional economic development** including substantial opportunities for Traditional Owners and Indigenous communities.
- **Development of skills and know-how** across the Australian R&D community and in the Australian private sector.
- **Global leadership** in a new, emerging field, with the associated potential to export knowledge, tools, systems and technologies to help the rest of the world (including less-developed nations) preserve their reefs.

5 RRAP CONCEPT FEASIBILITY STUDY: SCOPE AND OBJECTIVES

5.1 Mission and context

Recognising the need for action, and the opportunity that currently exists, a consortium led by the Australian Institute of Marine Science (AIMS) proposed a long-term, multi-phase approach of research, development, testing and implementation: the Reef Restoration and Adaptation Program (RRAP).

In January 2018, the Australian Government provided $6M for the first phase: an 18-month concept feasibility study. The RRAP mission: to provide decision-makers with scientifically-proven, ecologically-effective, socially-acceptable, technically-feasible and economically-viable options for intervening at scale on the Great Barrier Reef, and other Australian reefs, to help them adapt and remain resilient to climate change and to help guide implementation if required. Figure 5 shows the proposed phases of RRAP.

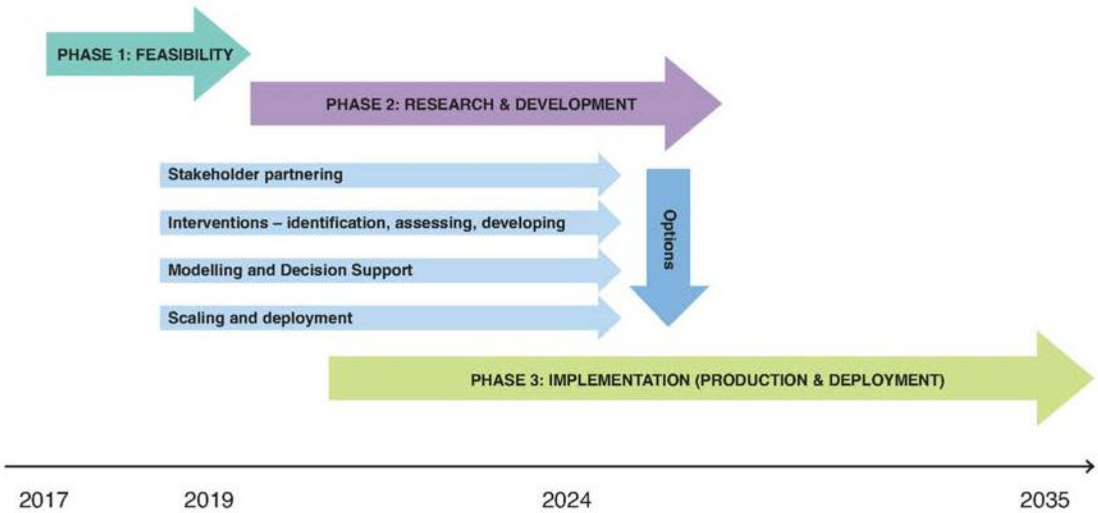

Figure 5: RRAP—a long-term, multi-phase program.

5.2 Feasibility study scope and objectives

The scope and objectives of the RRAP Concept Feasibility Study were:

1. Examine the overall feasibility of undertaking restoration and adaptation interventions to protect key ecological functions and economic and social values of the Reef. *Can such interventions help keep the Reef resilient under climate change? At what scale? At what cost? To what benefit for the nation?*
2. Conduct a preliminary evaluation of the widest possible range of intervention options and techniques, alone and in combination, to achieve this. *What restoration and adaptation techniques could be used? What is their state of development? Given what we know now, what is their likelihood of success, as single interventions or combinations?*
3. Recommend a comprehensive R&D program to develop and test the underlying knowledge and techniques needed to achieve the mission. *What R&D needs to be done? What will it cost? What are the risks? What is the business case for investment in R&D? How should it be implemented and governed?*
4. Subsequent to the development of RRAP, the Australian Government committed $100M to the Reef Trust Partnership in the 2018 Budget for Reef restoration and adaptation science activities over five years (to be supplemented with $100M each from philanthropy and research providers). The RRAP reports will be key guiding documents for investment in these activities.

5.3 Feasibility study execution

5.3.1 Team

The RRAP Concept Feasibility Study was conducted by a partnership that included AIMS, the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Great Barrier Reef Foundation (GBRF), James Cook University (JCU), The University of Queensland (UQ), Queensland University of Technology (QUT), the Great Barrier Reef Marine Park Authority (the Authority) and a dozen other specialist research, private sector and international organisations. More than 150 scientists and engineers from four countries were involved. The $6M investment from the Australian Government was supplemented by significant additional co-investment from the partner organisations.

5.3.2 Approach

The planning of the RRAP Concept Feasibility Study, selection of key tools and methods and constitution of the core team commenced in October 2017. Key scientists involved in the core team are listed in Appendix C. The establishment of multi-institutional sub-teams was driven by selecting lead scientists from across the consortium partners based on their expertise and availability.

The following primary technical activities were conducted in parallel:

- Characterise, understand and engage with stakeholders.
- Determine regulatory implications and response pathways.
- Review existing, and determine potential, intervention types.
- Scope and define deployment methods and scaling options.
- Assemble, refine and apply existing ecological, bio-physical and hydrodynamic models, and use these to examine the prospective performance of selected interventions, alone and in combination.
- Estimate the impacts of interventions on Reef values and economic benefits and costs.

5.3.3 Intervention identification and screening

In dealing with such a complex subject, a clear and standardised nomenclature is required. For RRAP, the following definitions are used:

- **Intervention**: Achieving a specific *intervention objective*, delivered to the Reef through a specified *delivery method,* applied at a certain *scale*.
- **Intervention objective**: One of seven identified types of functional objectives. Some are aimed at preventing coral bleaching by removing the heat stress or by helping the system adapt to future conditions. Others would be applied to help the system recover after damage.
- **Delivery method**: A specific technique used to achieve the required objective.
- **Scale**: *micro*: A few square metres; *small*: tourist sites (a few hectares, a single reef); *medium*: 20 or more reefs and *large*: 200 or more reefs up to all of the Great Barrier Reef.

Seven potential **intervention objective types** were identified, encompassing both restoration and adaptation (each is described in more detail in Appendix A):

- *Cooling and shading* reducing exposure of coral reefs to heat and light stress during heatwaves.
- *Stabilisation* adding reef structures and stabilisation to increase substrate quality and facilitating improved coral recruitment and recovery following disturbances.
- *Coral seeding* using natural stock of coral larvae to enhance coral reproduction and reef recovery following disturbances.
- *Biocontrol* managing coral predators and competitors to enhance coral survival.
- *Application of field treatments* promoting coral survival and health following disturbances with probiotics, feeding, medicines or other treatments.
- *Seeding enhanced corals from existing stock* supporting the resilience of local coral populations by seeding with specimens from existing stock that are warm-adapted.
- *Seeding enhanced corals bred from engineered stock* supporting the resilience of coral populations by seeding with corals that are warm-adapted, derived from synthetic biology and gene editing approaches.

Several possible *delivery methods* were identified and assessed for each intervention objective, at various scales. The criteria for assessment included technical feasibility, development requirements and scale applicability, based on estimates of deployment costs and logistical constraints. Delivery methods are described in more detail in Appendix A.

This was achieved through a combination of international expert workshops and assessments of current global restoration practices.

A total of 160 possible interventions were considered across the four scales (micro, small, medium and large) and evaluated against defined criteria. These included the ability to deliver functional Reef benefits (via modelling of ecological impact and benefits), risk, technology readiness and development requirements, and feasible deployment scale and cost. Synergies and redundancies between delivery methods were identified and those deemed infeasible were eliminated from further consideration. A more detailed summary of the interventions considered is provided in Appendix A.

5.3.4 Social, economic and regulatory dimensions

A comprehensive study of stakeholder perceptions was undertaken to test the sentiment of the Australian public to intervening on the Reef. This was complemented by an analysis of the current regulatory regime.

The RRAP Concept Feasibility Study also developed estimates of the benefits of adaptation and restoration, the likely costs of intervening and a business case for investment in the R&D required to move from concept to actual on-Reef intervention.

Ongoing social and regulatory acceptability is a fundamental requirement for the success of any at-scale reef adaptation and restoration implementation activity.

5.3.5 Peer review

All aspects of the feasibility study were extensively peer reviewed to ensure the process adopted, and the options identified, were reasonable in the context of the current scientific, social and community understanding of the challenge. Internal peer review was conducted on an ongoing basis within the program, involving three tiers: core RRAP science team, RRAP Steering Committee and RRAP Executive Committee. All program assessment areas were established as multi-institutional collaborations, with consensus outcomes required. International expert workshops provided independent input and helped guide the effort. This included RRAP participation in two studies by the US National Academy of Sciences, Engineering and Medicine: (1) *Review of Interventions to Increase the Persistence and Resilience of Coral Reefs*[30] and (2) *A Decision Framework for Interventions to Increase the Persistence and Resilience of Coral Reefs*[32]. In areas with limited internal expertise, third-party technical peer review was undertaken. Specialist external consultants were employed to oversee critical assessments such as the modelling of benefit streams and cost-benefit analysis. To improve and validate future deployment cost and scalability estimates, industry was contracted to develop concept designs and cost estimates.

Finally, fully independent peer review of this investment case was undertaken by two high-level international experts with experience in applying large-scale multi-disciplinary science to major challenges prior to submission to the Independent Expert Panel for final assessment. A summary of authorship and review of each of the RRAP Concept Feasibility Study documents is provided in Appendix C.

6 RRAP CONCEPT FEASIBILITY STUDY: SUMMARY OF TECHNICAL FINDINGS AND RECOMMENDATIONS

The concept feasibility study produced a significant documented body of information and understanding about our current state of knowledge of reef adaptation and restoration, and our ability to predict and influence the Reef's responses to change and intervention[a].

The key technical findings and recommendations of the study are discussed below, grouped into the following categories:

- **Social acceptability and regulatory environment**: Public perceptions and attitudes towards restoration and adaptation, and implications for regulatory processes.
- **Intervention objectives and delivery methods**: Restoration and adaptation techniques considered, how they could be delivered to the Reef and preliminary screening of options.
- **Scale considerations and modelling results**: The ability of interventions to produce the required results at different scales, based on modelling results.
- **International partnerships and investment**: How Australia's current effort relates to the global reef challenge under climate change.

The study concluded that with the proper R&D effort, there was scope to build resilience and help the Reef recover from, and adapt to, the effects of climate change, under a wide range of climate futures. Effective RRAP intervention strategies, combined with best-practice conventional management, could double the likelihood of sustaining the Reef in good condition by 2050 (see Table 7 in R3: Intervention Analysis and Recommendations). Success would depend on a wide range of factors including appropriate funding, stakeholder and Traditional Owner support, capacity building in the regulatory regime, collaboration of key agencies and research providers, inclusion of private sector capability and, ultimately, global action on climate change.

6.1 Social acceptability and regulatory environment

Achieving social license would require strong stakeholder and Traditional Owner engagement, including participation in the co-design of intervention programs. Public sentiment (measured through a major survey of 4000 representative Australians) was generally accepting of the types of technologies and interventions proposed in RRAP. Coral reproduction and recruitment-related strategies were associated with the highest positive sentiment. Addressing emissions and other threats to the Reef, while outside the scope of RRAP, were important to the perceived credibility of the program. Figure 6 shows results from the survey on a subset of questions that probed public attitudes on the value of the Reef, the perceived need for action, the role of science and support for the idea of large-scale restoration action. Responses from the sample of Reef residents and the national sample were very similar. Ongoing engagement and monitoring of community attitudes and issues are essential for maintaining this support, especially as options develop and move closer to deployment. Results shown in Figure 6 should be considered as early indications of in-principle support only.

[a] Here, we present headline results; more details are provided in Section 7 (costs and benefits) and Appendix A.

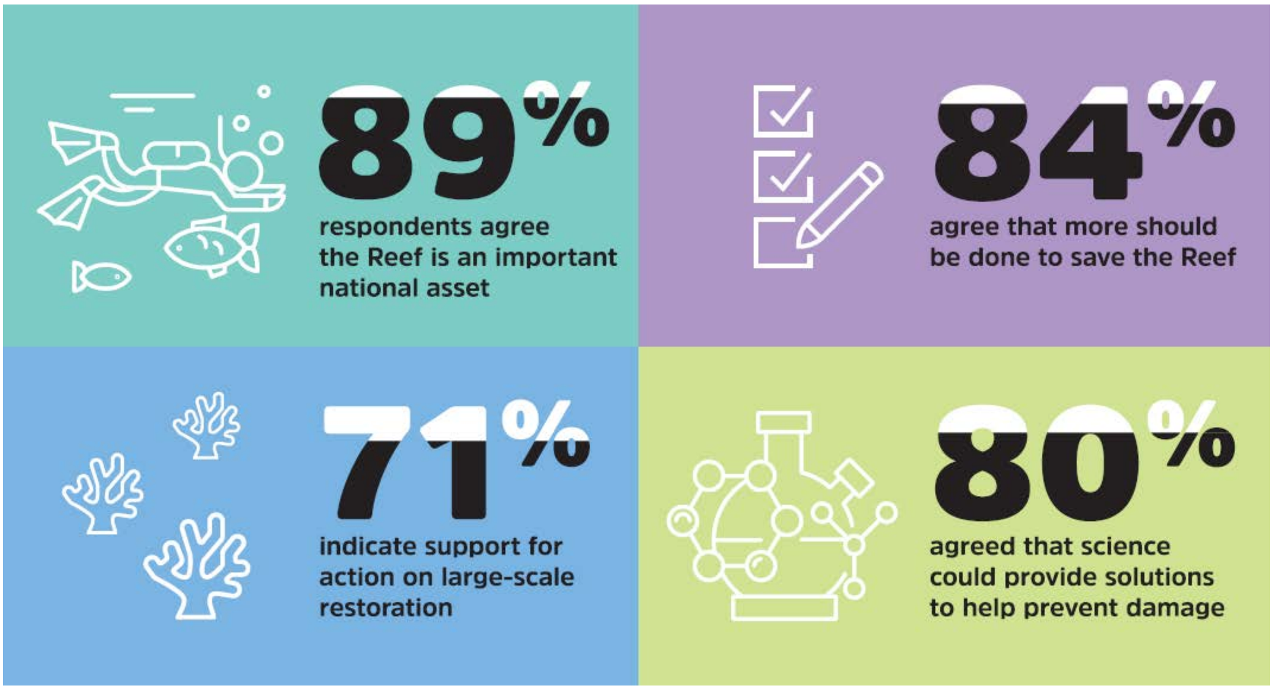

Figure 6: Findings from the national survey of Australian and Great Barrier Reef residents that indicated support for action to protect and restore the Reef and in-principle support for large-scale restoration and the role of science.

The Reef stakeholder engagement and Traditional Owner context is complex and engagement strategies tailored to RRAP R&D needs will require detailed planning. Traditional Owners have a unique and critical role to play in the formulation and implementation of any intervention option. Traditional Owners should have a prominent place in the RRAP governance structure. These communities must be included in decision-making that involves proposed restoration or adaptation activities on their sea country and in the R&D program and deployment activities.

The feasibility and viability of RRAP interventions will depend on the regulatory environment in which they are developed and deployed. The existing Great Barrier Reef regulatory and policy environment, as it relates to proposed RRAP interventions, is robust; however, it is not entirely fit-for-purpose. The current regulatory framework was devised in a different operating environment, where the need for large-scale adaptation and restoration interventions was not widely contemplated. While the current framework does not preclude on-Reef intervention, the system will be challenged by new interventions and, as such, will need to be reviewed and updated to ensure it continues to balance the risks of intervention action and no action. Some of the interventions pose an unprecedented challenge to the existing regulatory system to address novel risks and impacts, high levels of uncertainty and untested mechanisms for observation and monitoring. These aspects will need to be considered in RRAP governance and the regulator (Great Barrier Reef Marine Park Authority) will need to develop the capacity to consider, approve and, if necessary, fast-track on-Reef interventions.

6.2 Intervention objectives and delivery methods

A total of 160 possible interventions across four scales (micro, small, medium and large) were evaluated, based on their ability to deliver functional Reef benefits, risk, technology readiness and development requirements, feasible deployment scale and cost. Of these, 43 interventions showed promise and were deemed worthy of further exploration in the R&D program.

A significant and coordinated R&D effort is needed before any new on-Reef interventions can be made feasible, affordable, safe and acceptable to the public, at small, medium or large scales. This would include on-Reef pilot trials within the first few years. The larger the scale of intervention, the greater the potential for positive impact on the Reef, but also the greater the intervention risk. Risk of large-scale intervention is driven by the following factors:

- Social license would be more difficult to obtain.
- The level of regulatory scrutiny would be higher.
- More significant R&D effort would be needed.
- It would take longer to make the intervention ready for implementation.

6.3 Scale considerations and modelling results

Micro-scale intervention: Interventions focusing on a few square metres of reef were deemed ineffective at achieving the 'at-scale' requirement of the RRAP mission and were eliminated from further consideration.

Small-scale intervention: Helping multiple small, high-value areas, such as tourism sites, adapt and remain resilient to climate change is highly feasible. Given tourism is one of the largest benefit streams on the Reef, the ability of RRAP to help safeguard key tourism sites could provide multi-billion dollar returns for Australia. Active intervention at this scale could begin within two to five years of focused R&D and could form the early stages of the RRAP Implementation Program. This would require early investment in the required infrastructure and operational systems that enable a new implementation program.

Medium-scale intervention: Restoring, adapting and preventing bleaching at the scale of tens of reefs is feasible, but not yet proven. Success at this scale would require a combination of interventions working together to form an optimised strategy in space and time. Focused R&D, including advanced modelling and decision support, will be required to develop, test and select such strategies against multiple performance criteria: maximum benefits, minimum risk and minimum cost.

Large-scale intervention: Great Barrier Reef-scale adaptation and resilience support (i.e. applied to more than 200 reefs) may be feasible, but a broad range of risks need further exploration. A comprehensive and coordinated R&D program would be required to refine and guide such an effort. Large-scale adaptation and resilience support would involve interventions that work with natural processes (e.g. reef connectivity) to build system resilience beyond their scale of deployment and would need to be socially acceptable.

All scales: In general, it would be cheaper, faster and, ultimately, more effective to help reefs adapt to climate change than to try to help them recover *after* they had been damaged or destroyed. Therefore, the RRAP R&D Program will prioritise interventions that build resilience by supporting multiple processes in a hierarchy of (1) preventing exposure to temperature extremes, (2) assisting adaptation to climate change and (3) restoring and promoting recovery at priority sites (Figure 1).

All scales: Achieving impact at medium- and large-scales may not require interventions on all reefs if intervention strategies are designed such that benefits spill over from reef to reef.

Targeting a subset of 100 to 200 reefs that represent key nodes in the reef network—connected by flows of coral larvae[72]—could achieve impacts at a larger scale.

All scales: Model analyses conducted in the feasibility study showed that benefits arising from multiple interventions are likely to be compounding and synergise with conventional management efforts. These results are consistent with those of the parallel National Academy of Sciences Engineering and Medicine (NASEM) study[32]. The impact of some combinations of multiple interventions in this RRAP feasibility study was greater than the sum of the parts (Figure 7). See **R3: Intervention Analysis and Recommendations** for detailed analyses.

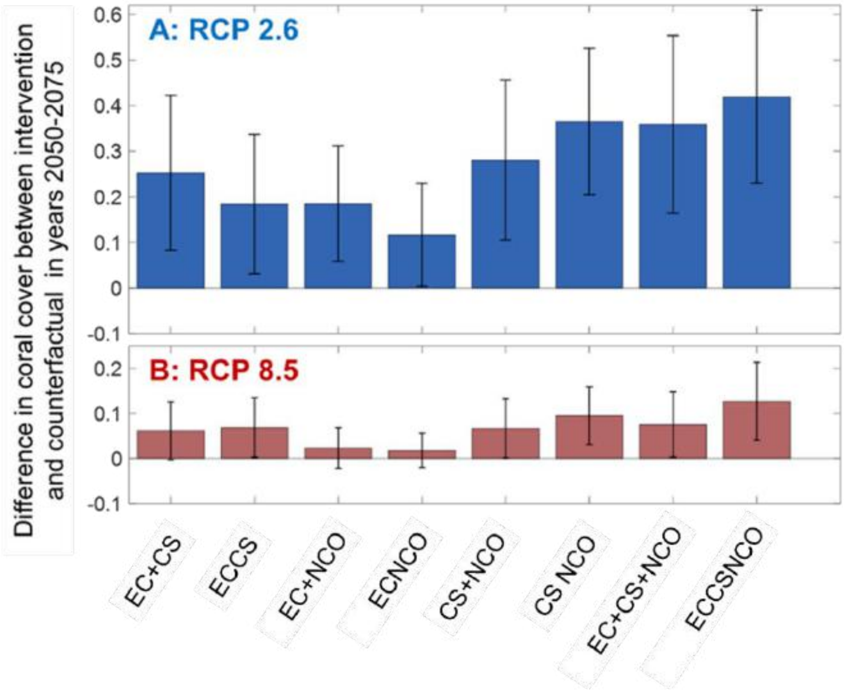

Figure 7: Interactions between selected RRAP interventions. Key to symbols: EC: enhanced corals; CS: cooling and shading, NCO: no crown-of-thorns starfish outbreaks via enhanced starfish control in years 2050–2075 for (A) RCP 2.6 and (B) RCP 8.5. Projections are for the entire Great Barrier Reef (2096 largest reefs). Data are differences in coral cover in areal proportion (means and standard deviations of 2096 reefs modelled) compared with the base case: no RRAP intervention and business-as-usual crown-of-thorns starfish control. Best-practice water quality management is assumed for all interventions and the base case. The + sign indicates the results of single interventions added to allow for assessment of whether combined interventions were better than additive outcomes. For example, EC+CS (enhanced corals and cooling and shading) is the additive outcome of the individual actions of EC and CS, whereas ECCS is the result of running both intervention strategies in combination.

All scales: Development and application of a decision-support system, based in part on data from the Reef Integrated Monitoring and Reporting Program (RIMReP) will be critical to success at any scale. RIMReP is being developed under a separate activity, led by the Great Barrier Reef Marine Park Authority. Significant effort will be needed to develop the next generation of ecosystem models, comprehensively incorporating social and economic dimensions, and including regulatory, risk and safety considerations. Such a decision-support system should be developed early in the R&D program and used to guide intervention strategy development, testing and implementation. The system would help RRAP maximise benefits, minimise risks and costs and manage trade-offs.

All scales: Continued best-practice conventional management to improve water quality would be essential for the success of the RRAP mission. Modelling performed as part of the feasibility study showed that intensified control of crown-of-thorns starfish would be a critical factor in improving the efficacy of RRAP interventions. A separate, continuing R&D effort is thus needed to prevent crown-of-thorns starfish outbreaks.

All scales: In the idealised, best-case scenario of moderate climate change (RCP 2.6[31]) with highly effective crown-of-thorns starfish and water quality management, interventions would be more effective and could result in significant improvement in current coral cover across the entire Great Barrier Reef (see Figure 8A).

All scales: Such projected improvement in coral condition to beyond 50 percent coral cover under RCP 2.6 is not unrealistic, given the modelled intervention effort and assumptions involved for both new and conventional interventions. These levels of coral cover reflect historical highs and are currently seen on some of the best-preserved reefs[20]. Importantly, as the RCP 2.6 scenario is projected to see global temperatures stabilise by around 2050[31,36], surviving coral populations that become adapted to the additional 0.5°C warming will by then be expected to recover and increase in abundance. A key caveat here is that such a projected increase in coral cover may come at the expense of reduced diversity of coral species and, in turn, a risk of losing key reef functions and ecosystem services[78]. Such losses of species and functions are not reflected in the projection of coral cover in Figure 8A.

All scales: Under unmitigated climate change (RCP 8.5[31]), and assuming highly effective crown-of-thorns starfish control and water quality management, substantial intervention efforts would be required, involving multiple interventions to sustain coral cover at or above 20 percent. Successful intervention, however, could forestall eventual Reef decline by a few decades the latter indicated by the dashed line and grey envelope in Figure 8B. Interventions would thus largely buy time for emissions to be brought under control and for society to adapt to the changing ecosystem.

All scales: Model results suggest successful intervention under RCP 8.5 would produce a less positive impact in the long term compared with the results under RCP 2.6, with the average coral cover on the Reef marginally exceeding 20 percent by mid-century (Figure 8B). Ocean acidification, which is not accounted for in these results, may further lower projections under both intervention and no-intervention situations. RRAP interventions offer an opportunity to delay coral decline by 20–30 years under RCP 8.5, which is a significant window of opportunity for climate adaptation measures to produce solutions and for global initiatives to curb emissions. Under RCP 8.5, without RRAP interventions, even best-practice conventional management would have limited scope to prevent rapid, systemic decline (dashed line with grey envelope in Figure 8B).

Local and regional scales. Results indicate large variation in projected coral cover among reefs, with some reefs expected to reach 40 percent coral cover (0.4 areal proportion) under RCP 8.5 while others expected to decline to less than 10 percent (Figure 8B). This variation among reefs represents an opportunity for RRAP. If the program can identify reefs that have the best chance of responding positively to intervention, RRAP can help these priority reefs sustain critical ecosystem services and values for people and industries.

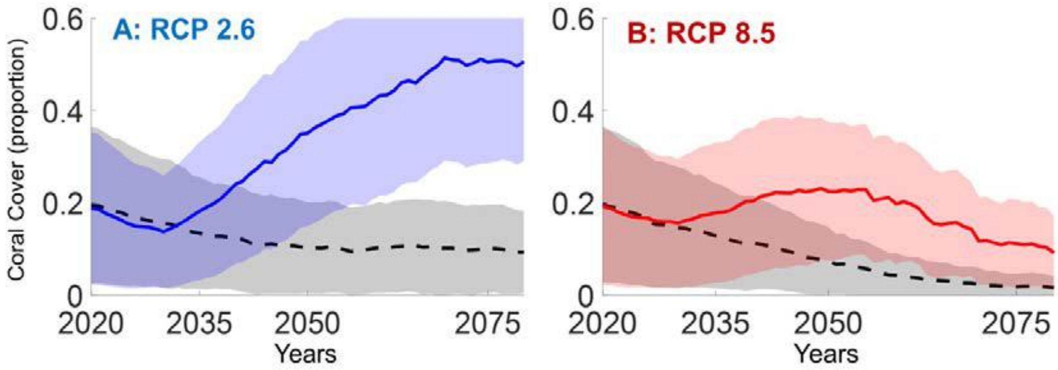

Figure 8: Modelled projections of coral cover (areal proportion of Reef with live corals) for two new example interventions combined with idealised conventional management practices. RRAP interventions comprise (1) deployment of enhanced corals and (2) regional cooling and shading using cloud brightening. Conventional management interventions are (1) effective water quality management and (2) no crown-of-thorns starfish outbreaks. All are simulated under contrasting climate change scenarios (A: RCP 2.6: blue—moderate climate change and B: RCP 8.5: red—unmitigated climate change). Data shown are means (lines) and standard deviations (envelopes for n = 2096 reefs modelled) on the Great Barrier Reef. For comparison, projections of the no-intervention situation are also shown for each climate change scenario (dashed line, grey envelopes), assuming that best-practice water quality management is sustained. Note these projections represent one of multiple, possible scenarios and assume optimal performance of the interventions. They represent best-case estimates. The 'no-intervention' projections should also be considered optimistic because ocean acidification was excluded from model simulations. Note that the low range of the grey envelopes in both climate scenarios reaches zero coral cover before 2050, highlighting the extreme risk the Reef now faces. More details are available in Appendix A.

6.4 International partnerships and investment

There is strong interest from international peers to partner with an Australian R&D effort. Funding constraints will limit the capacity of most potential collaborators to contribute materially, but mechanisms for collaboration and information-sharing are being established.

Most effort and expenditure outside Australia focus on restoring highly degraded reef systems, with limited investment in assisting reefs to adapt to current or expected future conditions. Australia is different in that the Great Barrier Reef has retained comparatively more resilience and structure than most other major reef systems worldwide. Australia has an opportunity and imperative to direct significant new funding to help a functioning ecosystem adapt and remain resilient to climate change. Undertaking large-scale restoration of degraded reefs is a much more difficult and expensive task.

Of the known international government and private sector investments in reef adaptation and recovery, most are directed at micro to small-scale restoration projects rather than 'large-scale' method development with long-term missions.

Global concern about the decline of coral reefs has yet to translate into the funding of step-change restoration and adaptation programs such as RRAP in other parts of the world. Australia now clearly leads the way. The opportunity exists to promote these efforts and attract significant international interest, and future investment, as methods that show promise are developed and trialled on the Great Barrier Reef.

In raising awareness of the potential benefits of reef restoration and adaptation, RRAP will encourage increased international government investment in large-scale resilience-building efforts. Of the potential mechanisms explored, the International Coral Reef Initiative (ICRI) looks to be the most promising forum to promote the work on the Great Barrier Reef.

More details on findings and recommendations are provided in Sections 7 and 8, as well as in Appendix A. Appendix C provides a road map to the relevant RRAP Concept Feasibility Study reports.

7 BENEFITS OF INTERVENING AT SCALE

The RRAP Concept Feasibility Study examined the potential benefits of intervening at scale on the Great Barrier Reef to help coral reefs adapt and remain resilient to climate change. These include avoiding the loss of direct and indirect economic benefits to Australian businesses and communities that rely on a healthy Reef; avoiding loss of broader ecosystem services; economic benefits to Traditional Owners and regional communities associated with implementing at-scale interventions; and translation of know-how and technology from Australia to the rest of the word, in the event that the Great Barrier Reef interventions are successful.

Following is a synthesis of this substantial body of work undertaken in the feasibility study. This is summarised in **R3: Intervention Analysis and Recommendations** and underpinned by several technical reports (**T5: Future Deployment Scenarios and Costing**, **T9: Cost-Benefit Analysis** and **T10: Benefit Streams**).

7.1 Approach

Environmental, ecological and economic models and analyses were integrated to address three central questions: What is the potential for restoration and adaptation interventions to sustain coral condition on the Great Barrier Reef? How will these impact on economic values for Australians? Will benefits exceed costs?

A set of broad, concept-level interventions were examined for their potential to sustain Reef coral condition and the economic values it underpins from 2016 to 2075, under different climate change scenarios. Four elements were considered: environmental and ecological modelling results, economic benefit streams, deployment scenarios and costs, and a cost-benefit analysis. Projections of environmental conditions and responses by coral communities on the Great Barrier Reef were simulated using the best available bio-physical models, advanced further for this program.

Estimates of triple-bottom-line economic, social and environmental benefits to Australia resulting from different intervention strategies were developed using two different methods. One method directly calculated quantifiable economic benefit streams representing the current monetary value of eight specific benefits derived from the Great Barrier Reef (see Section 7.2). The second method estimated aggregated ecosystem service benefits generated by the Reef, using published values of reef published values of reef ecosystem services per hectare and with UN guidance (see Section 7.3)[b].

Two key intervention objectives were simulated at large-scale (greater than 200 reefs across the Great Barrier Reef domain): (1) cooling and shading (local or regional solar radiation management) and (2) strategic seeding with warm-adapted (enhanced) corals. These were explored under two scenarios of crown-of-thorns starfish control (business-as-usual vs no outbreaks) and under two climate change scenarios (unmitigated: RCP 8.5 and strongly mitigated: RCP 2.6, the latter being representative of meeting Paris Agreement targets). Benefits of RRAP interventions were estimated by comparing modelled coral condition on the Great Barrier Reef with and without interventions. Best-practice conventional management of water quality was used as a baseline for all scenarios.

A discussion of the potential regional and Traditional Owner economic benefits is provided in Section 7.4 and a summary of the RRAP cost-benefit analysis is presented in Section 7.5.

7.2 Directly quantifiable economic benefits

Benefits were estimated for tourism, commercial fishing, coral harvesting, medicinal option values (reflecting some biodiversity/gene pool values), storm surge protection, recreational fishing and Indigenous cultural values. Present-day estimates of the measurable benefits of the Great Barrier Reef to Australians amounted to at least $3.4B per year. This corresponds to a net present-day value of approximately $100B, assuming a 3.5 percent discount rate applied over 60 years. The Deloitte Access Economics study (2017)[3] estimated economic benefits of $6.6B a year and an economic, social and icon asset value of $56B (at 3.7 percent discount rate over 33 years).

Ecological modelling presented in **R3: Intervention Analysis and Recommendations**, and summarised in Appendix A, estimated the likely effect of various combinations of interventions on coral cover, compared with the no-intervention scenario. Improvements in coral cover (damage avoided) from the intervention were then translated into value. Under the RCP 2.6 moderate climate change scenario, estimates of undiscounted damage avoided (or gains achieved) from implementing new interventions (compared with continued, best-practice conventional management only), ranged from a total of $10.7B to $17.5B over 60 years. Under RCP 8.5 unmitigated climate change, the scope for new interventions to prevent economic damage ranged from $3B to $29B over 60 years (Table 1). The higher upper range of estimated benefits for RCP 8.5 ($29B) compared to RCP 2.6 ($17.5B) is because of the greater opportunity for RRAP to prevent economic damage in the near term (until around 2050) as the reef would lose resilience to unmitigated climate change under the no-intervention scenario (counterfactual).

These estimates are conservative, represent a bottom-up approach and are based on how people currently use and appreciate the Reef. Also, they assume a high capacity for people and industries to adapt to a change in the Reef's condition, i.e. a relatively low economic sensitivity to changes in ecological state. Further, several key value streams are not incorporated in these estimates, including broader ecosystem services values. Benefits for people outside of Australia are excluded, as is the possibility that new future values of a sustained Reef may grow as other

[b] Estimates of economic value are based on annual streams of benefit. Summing these annual streams over several years provides total benefits over that period. Applying a time value of money (discount rate) results in a present value estimate of total benefits. Undiscounted totals are simply the gross aggregate of annual flows summed over a specified number of years.

reefs decline. For these reasons, the values in Table 1 can be considered as lower-bound estimates of potential benefit.

Table 1: Estimated economic benefits of implementing large-scale cooling and shading, out-planting of warm-adapted corals and intensified crown-of-thorns starfish control under climate change scenarios RCP 2.6 and RCP 8.5. Data are predicted, undiscounted damages avoided and totalled over 60 years.

			Predicted undiscounted damages avoided via RRAP in $M (range)		
Benefit Stream	Current value in $M per year (range)	Mechanisms by which RRAP can impact	RCP 2.6 (fewer estimates)	RCP 8.5	Considerations
1. Commercial fishing	5.6 (2–8)	Maintenance of habitat and complexity	67 (50–78)	66 (8–111)	Some adaptive capacity (location)
2. Recreational fishing	10.6 (5–15)	Maintenance of habitat and complexity	11 (0–17)	11 (0–16)	Moderate adaptive capacity (location, target species)
3. Coral harvesting	0.25 (0.02–0.60)	Maintenance of habitat and species	6 (5–7)	3 (1–6)	Some adaptive capacity (location and species)
4. Medical options for the future	174 (20–1000)	Support of biodiversity	2557 (1833–3028)	2209 (254–3608)	Biodiversity most important
5. Coastal protection	26 (10–50)	Support of reef structure	612 (416–725)	439 (67–791)	Choice of coral species will be critical
6. Reef tourism	1543 (1200–1800)	Biophysical state and 'image'	4877 (3240–5705)	6214 (999–10,517)	Adaptive capacity within regions; image crucial; worldwide competition
7. Non-use (bequest, existence, identity)	1015 (490–1200)	Holistic including 'image'	2409 (1782–2835)	3382 (647–5192)	Rarely place-specific; perceptions crucial
8. Indigenous cultural placeholder values	>629 (179–2000)	Unknown, but likely holistic	4450 (3340–5157)	5332 (1045–8887)	Highly place-specific. No capacity for substitution
Total	**3404 (700–8000)**		**14,962 (10,650–17,500)**	**17,657 (3021–29,128)**	

7.3 Estimated benefits of protecting ecosystem services

Another set of estimates of the extent to which successful interventions might reduce the loss of ecosystems service values on the Great Barrier Reef was also developed, using a different approach. The key underpinning assumptions were based on the mid to lower range of published ecosystem service values for coral reefs globally: $90,000/ha/year[38] and $352,000/ha/year[37]. In the low estimate, coastal protection from storm damage was excluded, which was based on the rationale that the loss of live coral cover on the outer Great Barrier Reef may not substantially reduce the capacity of a degraded Reef to protect the Queensland coast from storm waves until late this century, when reef erosion and sea-level rise may prevail[26,79]. Contrary to the benefit-stream analyses above (normalised to people), per hectare analyses assumed that ecosystem service values were proportional to coral condition (i.e. high sensitivity). While these analyses do not directly reflect how Australians value the Reef ecosystem services today, they enable comparison with global assessments of reef ecosystem service values.

The same combination of interventions used in the estimates of economic benefits above yielded undiscounted benefits of between $200B and $773B over 60 years under the RCP 2.6 scenario. A discount rate of 3.5 percent reduced the estimated benefits under this scenario to between $46B and $177B. Under the RCP 8.5 scenario, estimated benefits fell to approximately half of those under RCP 2.6 (for both undiscounted and discounted values).

These results represent upper-bound estimates of the benefit of successful at-scale intervention on the Reef when anchored in global base estimates of ecosystem service values. Importantly, while RCP 2.6 represents an opportunity for growing current Reef values in the long term, benefits of interventions were projected to diminish over time under RCP 8.5 as pressure from climate change eventually overwhelms the capacity of any intervention to support reef resilience and associated ecosystem services.

7.4 Traditional Owner and broader regional community benefits

The Great Barrier Reef is valued by the international community. In Australia, the Reef is critical to the cultural, economic and social wellbeing of more than one million people who live in its catchment. Work on at-scale intervention on the Reef may yield additional specific benefits for Traditional Owners and the regional communities in the 424,000 km^2 catchment of the Great Barrier Reef World Heritage Area (**T10: Benefit Streams**).

Benefits for Traditional Owners

The RRAP Concept Feasibility Study acknowledges the ongoing spiritual and cultural connection of Traditional Owners to the Great Barrier Reef. We acknowledge native title and the diversity of Indigenous values, rights, interests and aspirations. There are more than 70 Aboriginal and Torres Strait Islander Traditional Owner groups with connections to the Great Barrier Reef. RRAP would engage and involve relevant sea country groups in restoration activities and support aspirations related to traditional knowledge being recognised and Traditional Owners caring for country. The Reef is a place that is highly significant for sustaining cultural celebration and community wellbeing for Traditional Owner groups. The Indigenous Reef Advisory Committee at the Great Barrier Reef Marine Park Authority noted in the Great Barrier Reef blueprint for resilience (2017)[47]:

> *We the first nations people of Australia send an urgent call to all people of the world to please give us your help to turn back the clock of deterioration.*
>
> *We believe it is no longer a question of resilience but a desperate need for intervention. With deep respect, we call out to all global citizens and international storytellers who have, in the past, and wish to in the future, experience the majesty of the Reef, to walk with us on this journey of courage, to give back her dignity, by nursing her back to health…*

The Great Barrier Reef Marine Park Authority's Aboriginal and Torres Strait Islander Heritage Strategy for the Great Barrier Reef Marine Park (2019)[80] articulated a vision where Traditional Owners and other Reef managers manage the Reef together to keep sea country and Indigenous heritage strong, safe and healthy. Both tangible and intangible benefits have been shown to support or improve Indigenous wellbeing, although there are relatively few empirical studies that have converted documented improvements in wellbeing into monetary estimates. Information from relevant studies was used to draw inferences about potential values.

A study by Social Ventures Australia Consulting (2016)[81] examined the social return on investment in the Girringun people's Indigenous protected area north of Townsville and their associated ranger programs. Collectively, the programs were estimated to have generated returns for members of the Indigenous community amounting to approximately $2902 per person per annum but, more importantly, they were helping to close the gap and build a resilient community. These benefits included increased skills through training and experience, increased confidence, better health and wellbeing, increased pride and sense of self, better caring for country and benefits accruing to the community at large such as more role models for young people, rangers and families living on country, additional funding and economic opportunities, increased respect from the non-Indigenous community, strengthened connection to country, conserved culture and language, more burning using cultural practices, less weeds and fewer feral animals. No studies were found that attempted to measure, in monetary terms, the aesthetic/amenity/lifestyle values of the Great Barrier Reef for Indigenous people. The analysis in **T10: Benefit Streams** suggested that for the entire Reef catchment area, the best estimate of Indigenous cultural value was $629M per annum.

No studies were found that estimated, in monetary terms, the potential impact of reef degradation on Indigenous cultural values. However, given the deep spiritual connection between peoples and their country, the impacts are likely to be substantial. Even relatively small changes in just one small part of the system (e.g. Reef health) could be associated with large changes in Indigenous wellbeing and cultural values. For any given fall in Reef health, we have assumed a larger fall in Indigenous values than in non-Indigenous non-use values. This reflects the absolute non-substitutability of Indigenous place-based values. If a Traditional Owner's country is degraded, they cannot make up for that by connecting to someone else's country.

Reef restoration outcomes are critically important to Traditional Owners' economic, social and cultural wellbeing and for sustaining healthy communities. RRAP has the potential to deliver a range of Traditional Owner and Indigenous community benefits including:

- Improving the health of Traditional Owners because the health of individuals is inextricably linked to Reef health, making successful adaptation and restoration fundamental.
- Leadership, partnering, employment and other community and economic opportunities arising from sea country management and Reef-based industries engagement in a growing Australian marine rehabilitation industry; Traditional Owner stewardship activities that contribute to Reef health and resilience.
- Closing the gap and increasing community resilience through employment, skills capability development opportunities and building Indigenous capacity: co-design and joint implementation of reef research, development and management offer a range of opportunities for employment and development of high-value skills and capabilities that will be globally relevant, with some core skills applicable across other industries. A healthy Reef will maintain or open new employment or business opportunities, including eco-enterprises associated with land and sea management activities.
- Implementation of at-scale adaptation and restoration efforts resulting in significant economic opportunities for Traditional Owner communities.
- Efforts to maintain Reef functionality and health will retain at least some of the benefits currently derived from the use and management of cultural landscapes for current and future generations.
- New and valued resources (physical, financial, organisational, technical and intellectual) will be available to better understand and manage places of significance to Indigenous communities.
- Healthy ecosystems are known to contribute to educational outcomes. Visits to sea country provide appropriate forums for cultural knowledge exchange.

Benefits for regional economies

The longitudinal data were obtained from the Social and Economic Long-Term Monitoring Program for the Great Barrier Reef and the latest Deloitte Access Economic[3] study report on the value of the Great Barrier Reef to Reef users, communities and industries. More specifically, at-scale implementation of reef adaptation and restoration measures will significantly boost the economies of communities along the Great Barrier Reef coast. Much of the required R&D activity would take place in institutions based in Queensland. Implementation would require significant involvement of local shipping and fabrication industries, as interventions are constructed and delivered to the Reef. Local engineering contractors would benefit through the design and commissioning of various intervention components. Much of what must happen to deploy at scale would require significant amounts of local labour and would offer significant training and upskilling possibilities, especially in rural and Indigenous communities. In Section 7.5, estimates are provided of the likely economic impact of investment in medium to large-scale implementation to regional economies. New knowledge and data generated by RRAP will also inform and in some cases better enable culturally, socially and economically responsible action of communities, industries and government agencies.

The RRAP Implementation Program expenditure analysis presented in Section 7.5 outlines the potential range of flow-on effects to the Australian economy. Over the anticipated life of full-scale RRAP implementation, there is the potential for expenditure in Australia, including flow-on effects, of between $1.2B and $28B (present value in 2016 dollars, at 3.5 percent discount rate), depending on the option chosen. Much of this will likely be directed towards regional economies. This could translate into the creation of several thousand permanent and many more part-time jobs for regional reef communities over the first 20 years of active intervention.

7.5 Cost-benefit analysis

Approach

The costs and benefits of intervening at scale on the Great Barrier Reef were compared. Estimated benefits (compared with continued, best-practice conventional management) are described in Sections 7.2 and 7.3 for two different climate change scenarios. Detailed cost estimates were developed for the R&D and deployment of two example intervention strategies (**T5: Future Deployment Scenarios and Costing**). Costs were for the restoration and adaptation components only and did not include costs associated with concurrent efforts on water quality improvement and crown-of-thorns starfish control. This resulted in the assessment of 14 options, based on different levels and combinations of crown-of-thorns starfish control, deployment of warm-adapted (enhanced) corals and alleviation of heat stress via cooling and shading interventions. The cost-benefit analysis was integrated over a 60-year horizon (2016 to 2075) to provide insight into the likely range of net benefits of successful intervention at scale.

Environmental, ecological and economic models and analyses were integrated as part of the analysis to address three questions:

1. What is the potential for new restoration and adaptation interventions (separately or in combination) to improve the outlook for the Great Barrier Reef under climate change compared with best-practice conventional management only?

2. If the potential of these interventions could be realised, what would be the likely net economic benefit for Australia?

3. Are there circumstances where investment in RRAP is favourable, thus allowing decision-makers to determine whether the program should progress to the next stage?

The analysis involved the wider RRAP Concept Feasibility Study team to ensure a robust outcome. Input to the cost-benefit analysis was provided by modelling, engineering, estimating, economics and engagement teams. Details of the cost-benefit analysis, including details on the assumed timing of capital spend and starting points for interventions within the 60-year period, are provided in **R3: Intervention Analysis and Recommendations**.

Results

If we decide to intervene on the Reef, choices will have to be made: How much do we spend? When and where do we act? How aggressive do we need to be? What specific short- and long-term goals do we want to reach? The answers to these questions will determine which combinations of interventions we use and at which scales. The 14 at-scale options assessed in detail ranged in cost from $0.24B over three years in capital (with operating costs of $30M a year) to $2.7B over three years (with operating costs of $240M a year). Ranges account for modelled uncertainties of intervention efficacy (likelihood of success), benefits and costs.

The cost-benefit analysis found that not all 14 options assessed resulted in a positive net benefit. Those options would not be deployed. However, the best option realised a significant potential economic upside from successfully intervening at scale on the Reef. Using the more conservative economic Reef value estimates discussed in Section 7.2, the base-case present value of the net benefit to Australia was estimated at $4.1B per annum (2016 dollars, 3.5 percent discount rate), equivalent to $28B undiscounted over 60 years. Taking a 90 percent probability interval for 1000 iterations of sensitivity parameters, the potential present value of net benefit is $14.5B (2016 dollars, 3.5 percent discount rate) for the base case. Using higher ecosystem services-based Reef value estimates (per hectare estimates), the net benefit for successful intervention is considerably higher. It is acknowledged that monetary estimates of the value of the Great Barrier Reef are insufficient to capture its total ecological, social, cultural, economic and existence values. This analysis should therefore be considered as a conservative estimate of the real potential value of successful intervention.

Conclusions – A good deal for Australia

Given the range of uncertainties that currently exist, the results of the cost-benefit analysis indicate:

1. If integrated and coordinated intervention at scale could be done successfully, the likely total benefit to Australia is considerable, conservatively in the tens of billions of dollars.

2. RRAP is likely an investable proposition despite a broad range of uncertainty. The cost-benefit results are robust across a wide range of possible future conditions and assumptions.

3. The R&D program can unlock these potential benefits by identifying and developing integrated and coordinated intervention strategies that produce maximum ecological, economic and social gains, safely and at minimum cost. Without the required R&D, these benefits cannot flow.

4. On this basis, investing in R&D at the proposed level (approximately $326M in total over the first five years and a further $216M over the following five years) to unlock that potential is a good deal for Australia and a good proposition for the world.

5. Purely from a cost-benefit perspective, developing and implementing a suite of novel, at-scale restoration and adaptation interventions is a valid new management strategy for the Reef and should be invested in.

7.6 Limitations of the analysis

This analysis was based on the best available information, estimates and models. The RRAP Concept Feasibility Study highlighted the considerable gaps in our understanding of the Reef system, and hence our ability to predict the success of any program of intervention. The recommended RRAP R&D Program would reduce uncertainty and risk, drive down implementation costs and improve the certainty of outcomes. With this achieved, the program will likely deliver considerable benefits to Australia and the world.

The following modelling assumptions are important to consider when interpreting these findings:

1. Benefit estimates do not formally account for risks such as intervention system failure, unintended consequences of eliminating crown-of-thorns starfish outbreaks and the spread of disease, or other ecosystem disruptions associated with moving or introducing warm-adapted corals on the Great Barrier Reef. Understanding, minimising and managing these risks will be a priority of the R&D program. Great care will be taken to fully manage risks before any field testing and implementation.

2. Benefit estimates assumed, conservatively, that assisted coral adaptation methods could only enhance thermal tolerance by 0.4°C. The R&D program is expected to deliver significantly higher levels of thermal tolerance.

3. Estimates of changes in benefit streams, or prevention of the loss of ecosystem services driven by interventions, pertain only to the monetary gain for Australians based on current behaviour and realisation of ecosystem services; they do not consider benefits realised by the international community. Also, they are conservative as they assume a relatively low sensitivity of people and industries to ecological change.

4. Economic analyses did not consider potential increases in Great Barrier Reef values that would inevitably occur if the Great Barrier Reef could be sustained in better condition than other reefs worldwide.

Comparisons of coral health trajectories under RCP 2.6 and 8.5 illustrate that the RRAP R&D Program would need to race against time to produce solutions. Climate uncertainty means interventions could provide an opportunity to grow the natural capital of the Great Barrier Reef under RCP 2.6 or buy time for survival under RCP 8.5 and continued climate change. A key challenge for RRAP would be to identify and develop robust solutions that provide the best possible chance of positive outcomes under the possible range of scenarios, while identifying high-gain opportunities in each possible climate change scenario.

The next section provides details of the proposed RRAP R&D Program, which is designed to deliver on the potential of reef restoration and adaptation.

8 PROPOSED RRAP R&D PROGRAM

8.1 R&D program design

8.1.1 Approach

The concept feasibility study concluded that successful intervention on the Reef is possible and could deliver significant benefits for Australia. However, many uncertainties and knowledge gaps remain. The RRAP R&D Program needs to reduce critical uncertainty, improve our understanding of the system and quickly narrow a set of optimal interventions, i.e. those that maximise benefits against multiple objectives, minimise risks and minimise costs. Importantly, for solutions to be effective and safe, they will need to be fully integrated and coordinated within the RRAP mission ad hoc or unaligned interventions are unlikely to deliver benefits.

A key principle of structured decision-making that seeks to identify effective solutions for nature conservation, medicine or business is to begin with as many options as possible. Eliminating options too early, with the rationale of reducing costs at the outset, could lead to risks of losing the best options before they were identified[82,83]. On the other hand, retaining the full suite of options for too long under limited resources means the program would be weighed down by non-viable options[84]. The optimal situation is to apply a fast but rigorous filter to interventions, measured against four key criteria:

- Expected capacity to deliver against one or more objectives
- Scale of operation and impact
- Costs and risks of the associated delivery method
- Duration of R&D and time until full deployment, relative to the rate of decline in the absence of intervention.

The feasibility study started that process, filtering 160 intervention-scale combinations to 43.

8.1.2 Principles

The R&D program must be designed to deal with the inherent uncertainty associated with such a new endeavour and strike an appropriate balance between risk, time and investment requirements. To achieve this balance, the RRAP R&D Program was developed based on the following principles:

1. Drive early deployment of smaller-scale interventions as soon as feasible, to help protect high-value reefs. This is consistent with the no-regrets options recommended for ecosystem conservation broadly under climate change[61].
2. Quickly identify and focus on interventions with the highest likelihood of success. Reduce uncertainty around the benefits, risks and costs of those interventions.
3. Respond to key collaboration challenges, or challenges of integration or coordination, through the shared principles set out in the governance framework.
4. Deploy the required R&D expertise in a flexible and cost-efficient way, through a mix of cross-cutting and specific intervention-focused R&D teams.
5. Prioritise prevention over repair.
6. Identify and capitalise on synergies between new interventions, with natural processes and patterns of dispersal and adaptation, and with existing conventional management.

Genuine collaboration will be fundamental to RRAP delivering on its ambitious goals. Collaboration will need to be centred on project integration, full partner alignment and coordination of activities within a focused, outcomes-driven mission. The RRAP consortium partners' agreement recognises that RRAP is a mission-directed venture to deliver investment-ready reef restoration and adaptation interventions in a race against time. The program needs to focus on development and delivery, follow an engineering development approach and employ fit-for-purpose teams. The consortium partners accept that not all ideas would proceed to fruition indeed, most would not. Success must be shared across partner organisations.

During the first five years of the recommended R&D program, focus would be on delivering the underlying cross-cutting research (support and engineering research sub-programs that underpin the success of all, or groups of, interventions) and moving smaller-scale interventions to the deployment stage. As the program progressed, focus would shift to the deployment of larger-scale interventions. The R&D program evolution is shown in Figure 9, including progressive elimination of intervention options as research findings improve knowledge of feasibility, risks, efficacy, social acceptance and regulatory compliance.

Details of the R&D program design principles are provided in **R4: Research and Development Program** and **R6—Governance and Program Delivery**.

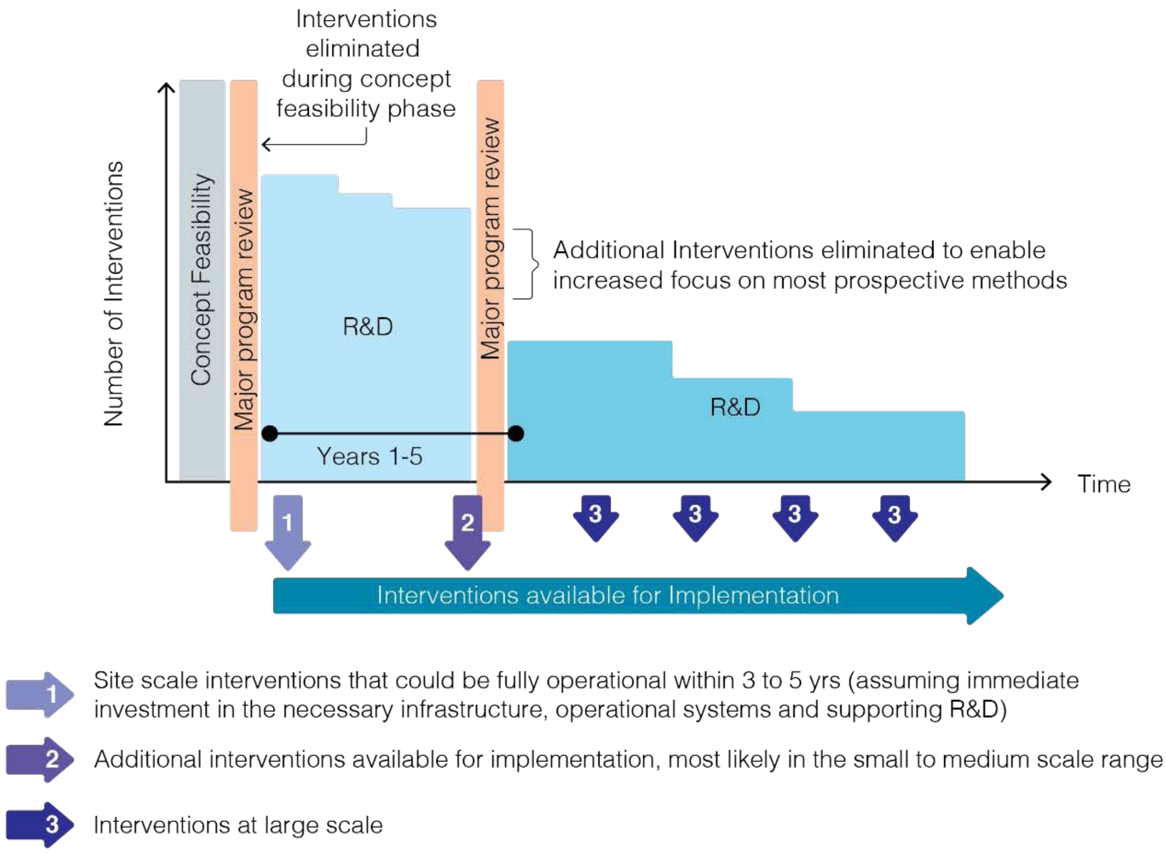

Figure 9: RRAP strategy to progressively deliver interventions and refine the focus of the R&D program as research findings improve knowledge of feasibility, risks, efficacy, social acceptance and regulatory compliance.

8.1.3 Design

The R&D program would involve a series of complementary sub-programs designed to deliver targeted outcomes, as shown in Figure 10. Cross-cutting support and engineering sub-programs would support a suite of intervention-focused teams ([R4: Research and Development Program](#)).

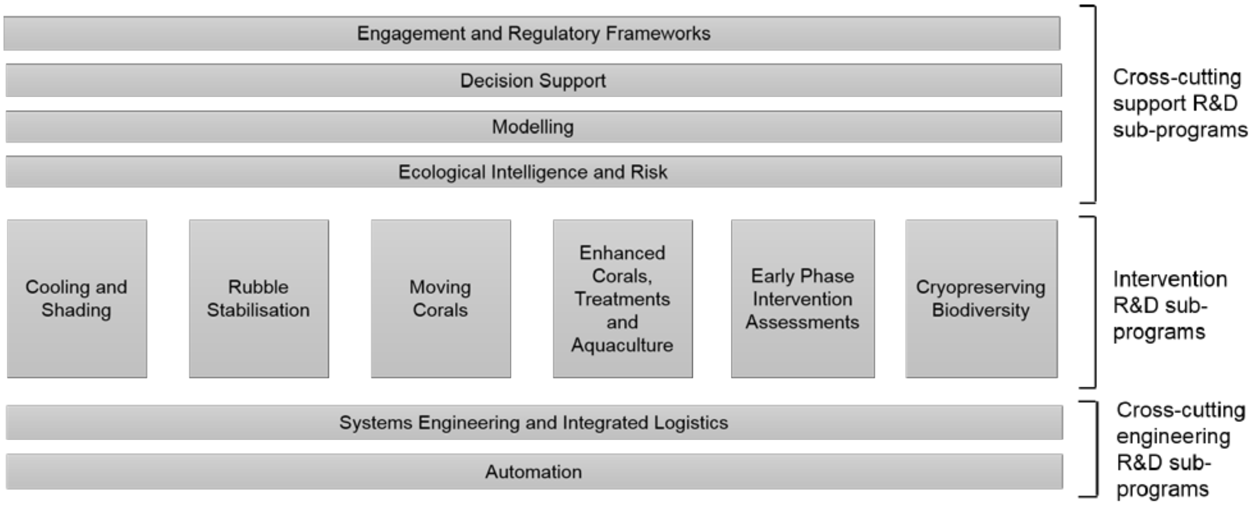

Figure 10: RRAP R&D Program structure. Six cross-cutting science and engineering sub-programs, supporting six intervention sub-programs.

The R&D sub-programs would work together as follows:

- The Engagement and Regulatory Frameworks Sub-Program would facilitate and guide the required interaction and engagement between the program, Traditional Owners, key stakeholders and regulators.
- The Decision Support Sub-Program would provide the framework within which to assess different intervention options and strategies, and R&D investment prioritisation and focus.
- The Modelling and Ecological Intelligence and Risk sub-programs would help examine the functional benefits and risks of interventions and consider aspects such as scale, efficacy and integration with other types of interventions that may be deployed in parallel. Ecological Intelligence refers to filling the core ecological knowledge gaps required to reduce uncertainty in critical process understanding.
- The Cooling and Shading; Rubble Stabilisation; Moving Corals; and Enhanced Corals, Treatments and Aquaculture sub-programs would each consider a set of interventions, progressively eliminate infeasible options and develop interventions to investment-ready status.
- The Early Phase Intervention Assessments Sub-Program would conduct desktop reviews of new and emerging interventions to determine whether R&D investment was warranted. It would also assess new ideas as they emerge.
- The Cryopreserving Biodiversity Sub-Program would develop specific enabling-capability to increase the rate of R&D in areas linked to annual coral spawning cycles. It may potentially enable productivity improvements in coral seeding interventions. It would also provide a capability to biobank endangered coral species on the Reef for future breeding and re-deployment.
- The cross-cutting Systems Engineering and Integrated Logistics Sub-Program would guide the progressive refinement and development of each intervention concept design. It would

design the integrated deployment systems needed for interventions to work together and develop shared infrastructure and systems. It would evaluate centralised vs distributed production and deployment models and identify ways for industry and communities to engage in the deployment program.

- The Automation Sub-Program would aim to develop technology that can substantially increase the efficacy and productivity of interventions developed in RRAP. Even small-scale interventions on the Great Barrier Reef are major undertakings due to the massive size of the system. Most terrestrial automation requirements could likely be procured from existing automation providers; however, underwater and offshore marine automation is a niche area and development would be required.

More background on the rationale and scope of the sub-programs is available in Appendix A2.4, while a detailed description of the sub-programs is provided in **R4: Research and Development Program.**

8.2 R&D program minimum investment requirements

The budget for the first five years of the R&D program as a minimum investment case is provided in Table 2, broken down to the level of sub-program. The total cost estimate is $326M over five years, with the largest two sub-programs (enhanced corals, cooling and shading) accounting for roughly half that amount. A forward estimate for years six to 10 is $216M, reflecting the tapering of effort illustrated in Figure 9.

The forecasts in Table 2 were based on current information, the required expertise of teams, assumptions regarding the results of stage-gate assessments and the reduction of the number of interventions being developed. An outline of the underlying budgeting principles and assumptions is provided in Appendix B, while details on how individual project budgets were developed, key underlying assumptions and procedures for stage-gating are provided in **R4: Research and Development Program.**

Table 2: Projected costs for the minimum investment case RRAP R&D Program.

Sub-program (Refer to Figure 9)	Projected costs, first five years, RRAP R&D Program ($M)						Second five years estimate ($M)
	2019/20	2020/21	2021/22	2022/23	2023/24	Total	Total
Engagement and Regulatory	2.1	2.8	2.7	2.7	2.6	12.9	7.3
Decision Support	0.9	1.3	1.2	0.8	0.6	4.8	2
Modelling	1.8	2.8	3	1.9	1.2	10.7	4.2
Ecological Intelligence and Risk	2.4	4.4	4.6	3.9	2.8	18.1	8.8
Enhanced Corals, Treatments and Aquaculture	7.7	17.7	22.6	23.1	22.3	93.4	36.8
Moving Corals	2.9	4.8	5.2	4.6	4.4	21.9	11.3
Rubble Stabilisation	2.1	5.9	6.3	4.8	3.3	22.4	29.1
Cooling and Shading	5.7	12.3	15.4	14.9	14	62.3	26.3
Early Phase Assessments	0.6	0.5	0.4	0.4	0.4	2.3	2.4
Cryopreserving Biodiversity	1.1	1.9	2.1	2.4	2.1	9.6	4.7
Systems Engineering and Integrated Logistics	1.6	2.7	3	3.7	3.9	14.9	10.4
Automation	1.7	2.5	1.3	0.6	3.7	9.8	26.2
International	0.4	0.35	0.35	0.35	0.35	1.8	1.75
Program Management (incl. contingency)	3.4	7.3	10	10.2	10.4	41.3	44.4
Total per year	33.7	66.5	77.4	73.6	71.3	326.2	215.6

8.3 Research infrastructure investment requirements

Delivery of the R&D program is linked to appropriate research infrastructure access. This includes research vessels, monitoring equipment including Integrated Marine Observing System (IMOS) infrastructure, research aquaria and other specialist equipment and facilities.

Where equipment is not available, the cost of purchase was included in the R&D investment budget described in Section 8.2. Not included in this budget are the required enhancements for major research infrastructure platforms.

Currently, the only major required platform enhancement is the planned expansion of the National Sea Simulator, purpose-built for restoration and adaptation research. It has unique capabilities fundamental to the R&D of the interventions being assessed. The expansion is funded within the National Research Infrastructure Road Map; however, there is a timing mismatch with RRAP. A separate process is underway to secure the earlier release of this investment and align the timing of the new capacity with that required by the RRAP R&D Program.

9 FUTURE INFRASTRUCTURE REQUIREMENTS

9.1 Overview of future requirements

Intervention deployment will depend on establishing and operating production and deployment facilities and systems. Some interventions, if only being deployed at small scales, may be feasible to operate on a project-by-project basis using leased infrastructure. However, most (all medium- to large-scale deployments) require dedicated infrastructure to be developed and operated.

During the concept feasibility study, these requirements were assessed as part of an initial estimation of future deployment costs. Details of these assessments are in **T5: Future Deployment Scenarios and Costing** and **T11: Automated Aquaculture Production and Deployment**. Final requirements will be dependent on the specific interventions progressed and target deployment scales.

In general, it is too early to consider investing in production and deployment systems. Actual needs will only become clear over time, once decisions are made as to which of the available interventions are to be deployed and at what scale. However, there is an emerging case for early investment in carefully selected prototype systems that form part of the testing regime of the R&D program (see Section 9.2).

9.2 Prototype infrastructure investments

Assessment of required deployment and operating infrastructure identified that while large-scale interventions may take five to 10 years of development before being ready for initial deployment, selected smaller-scale interventions could be deployed much earlier in the R&D program.

Subsequent implementation of these interventions will require the development of dedicated production and deployment systems. Even smaller-scale deployments are several orders of magnitude beyond those achievable using current research and/or leased infrastructure systems. Dedicated facilities and systems will be necessary to achieve the required production volumes and unit cost rates. Additionally, several of the larger-scale interventions will reach a point during the first five years of the R&D program where the development of dedicated infrastructure would aid larger-scale proof-of-concept testing.

Developing the required production and deployment systems will take an estimated three to 10 years, depending on the specific intervention and the deployment scale being targeted. Factoring in a delay while funding is secured, this shifts the likely earliest deployment even at modest scales to five years post the completion of R&D.

One option to reduce the delay is to commence the development of deployment systems in parallel with undertaking R&D. This would allow well-designed, high-value, small-scale deployments to occur much earlier. Early wins are critical as the urgency to build climate resilience on the Reef grows. For example, protecting or restoring high-value areas such as tourism reefs could safeguard the industry. However, these benefits need to be balanced against investing too early in deployment systems and the associated sunk cost risk.

In reviewing the proposed interventions and their development programs, several areas were identified where early investment in production and deployment infrastructure could occur at low risk.

By focusing on intervention delivery methods that are both more evolved and support multiple interventions, risks of sunk costs can be reduced. By developing these at a prototype scale where the facilities are large enough to be useful, initial costs would be minimised and the investments would fill an important role in the engineering development process. These initial systems would need to be researcher-led, with appropriate engineering and industry partners. They would be designed for training, production systems testing and technology transfer to industry.

The areas currently considered the most prospective include production prototype systems to support aquaculture, larval movement and testing of rubble stabilisation and cooling and shading. It is recommended that over the next 12 months, further assessments to refine and validate this strategy and determine investment requirements are undertaken.

10 GOVERNANCE AND MANAGEMENT

10.1 Key considerations

The RRAP mission can only be delivered through a program that:

- Is managed through a highly adaptive approach to prioritising technologies proposed for intervention.
- Delivers an R&D program that embeds the design principle that technological interventions need to be suitable for implementation on the Reef at scale.
- Brings to bear diverse multi-disciplinary science and skills—including social science and economics—to enable delivery of the objective and, for this purpose, maintains this intellectual base throughout the program.
- Integrates and coordinates strategic, tactical and operational activities within a focused and outcome-driven mission.
- Collaboratively pools and organises the intellectual capital of many organisations to create and maintain a ‘hybrid vigour’ that drives the program and engenders a fundamental sense of shared purpose and commitment.
- Allows for the necessary brave decisions in managing the risks inherent in deploying new intervention technologies (even at pilot-test scale) into the environment.
- Builds societal confidence in the utility of proposed interventions, through transparent, high-quality science and engineering.

10.1.1 Governance model

A range of possible governance models and alternatives were considered in detail by the RRAP Executive Committee and assessed against a list of criteria considered essential for the success of the R&D phase. Key considerations were:

- Ability to take risks and move quickly to identify prospective interventions
- Need to include a wide range of diverse stakeholders
- Ability to bring in new partners and drive effective collaboration
- Ensure strong engagement and alignment of partners
- Ability to raise additional funding

- Make decisions quickly in response to changing conditions.

Details of this process are available in **R6: Governance and Program Delivery** and a graphical representation of the proposed governance structure is provided in Appendix B.

It is recommended the RRAP R&D Program be executed by a consortium of partners, operating through an unincorporated joint venture. This governance structure and culture with the commitment of the participants to the purpose of the program would enable the consortium to deliver the required results in a highly adaptive and prioritised manner. With the ability to marshal the right resources to accomplish this mission, technical risks could be managed and real outcomes for the Reef could be delivered, under conditions of rapid change and uncertainty.

An integrated consortium model (Figure 11A) will be critical for the program's capacity to deliver on what will be a highly complex, ambitious and time-bound mission. The success of this mission will require an unprecedented degree of project integration and coordination, partner alignment and time-critical delivery of strategic, tactical and operational products, both for the R&D and deployment programs. Opting for a traditional governance model driven by an internal competitive process (Figure 11B) would undermine such coordination and, ultimately, prevent the delivery of a successful program.

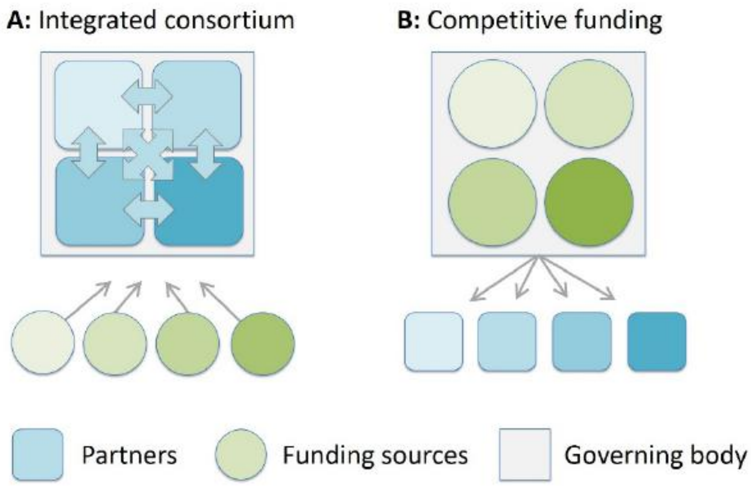

Figure 11. Conceptual representations of contrasting governance models.

A: Recommended model for RRAP, which will require an unprecedented level of project integration and coordination, and partner alignment, and, **B:** classical competitive funding model. While model **B** can produce science excellence, model **A** will be necessary for mission-driven program delivery.

The unincorporated joint venture would be governed by a board with an independent chair, supported by an independent peer review panel and a Traditional Owners advisory sub-committee. A steering committee run by an executive director would be responsible for directing the implementation of the R&D program. The R&D effort would be managed by a program director. A summary of each structural component is provided below, with further detail in **R6: Governance and Program Delivery**.

Board

The independently-chaired joint venture board would be the ultimate decision-making body for the RRAP R&D Program, noting that for activities funded via the Reef Trust Partnership, the Great Barrier Reef Foundation Board makes decisions about the appropriation of these funds, but will do so informed by the advice of the collaborative board. In addition to ensuring focused program delivery, the collaborative board would manage issues including the societal mandate for the program, maintenance and growth of the consortium, changing stakeholder expectations and the required resourcing for the scale-up of demonstration sites for interventions.

The board would comprise an independent chair, senior executives from the six partner organisations, at least two independent members (selected on a skills basis), a Traditional Owner representative and observers from the Great Barrier Reef Marine Park Authority, the Department of Industry Innovation and Science and the Department of Environment and Energy. The board would meet quarterly and be directly advised by a Traditional Owners advisory sub-committee. AIMS and GBRF would be permanent members of the collaborative board.

International peer review panel

The board would ensure all aspects of the R&D program including plans, results, deliverables and key strategic decisions were scrutinised and peer reviewed by a panel of independent international scientific experts at an appropriate level of detail. The panel would consist of core members chosen exclusively from international ranks. Their advice would be received at the board level and referred to the steering committee for consideration. Given the Great Barrier Reef focus, the relatively limited pool of key senior specialists in Australia and the involvement in RRAP of most Australian institutions with capacity in reef-related science and engineering, this approach would help limit conflict-of-interest and heighten credibility. The panel could call upon other experts, as required, to ensure the highest level of peer review.

Steering committee

The steering committee, led and chaired by the Program executive director, would be the senior technical decision-making body of the venture, responsible for executing the board’s strategic direction and charting the critical path to accomplish the mission. The steering committee would be responsible for overall program formulation, prioritising the intervention options actively pursued, ensuring an adaptive approach was applied through the appropriate use of stage gates (critical decision points), allocating resources among partner organisations and managing the ongoing working relationships between R&D partners. If required, it could form sub-structures and/or engage independent specialists to provide technical advice. It would also be advised by a stakeholder sub-committee.

The executive director role would be vital to the success of the program as an interface between the collaborative board, the partners and the governance and program delivery structures. Reporting to the chair and collaborative board, the executive director would lead this complex research and development consortium and provide strategic oversight of the program in accordance with the RRAP guiding principles. For this, the executive director would work closely with the managing entity and other partners in the development and implementation of the R&D program.

The executive director would ensure alignment between the UJV partners and funders, and with Traditional Owners and key stakeholders. The executive director would have a responsibility to maintain strong productive relationships internally (board, steering committee, program management team, partner representatives) and externally (government representatives, funders, Reef 2050 and international committees, strategic collaborators and partners).

Program management team

The management team, led by the program director, would be responsible for the day-to-day management and delivery of the R&D effort. The program director would report directly to the executive director and steering committee and be responsible for all day-to-day development and operational program management activities such as budget management, scheduling, oversight, program integration and sequencing, quality control, planning and execution of on-Reef pilot trials, and use of decision-making protocol to sequence and plan R&D activities.

Managing entity

The unincorporated joint venture agreement, program management and administration functions will require an organisation(s) to host them. These could be outsourced or split among the partners; however, hosting by a single entity is more efficient and is the selected model. It is proposed that AIMS undertake the role of managing entity for the unincorporated joint venture partnership.

10.1.2 Intellectual property management

The intellectual property arrangements for RRAP would be included in the unincorporated joint venture contractual agreement and tiered down through subsidiary contracts for the program. Designing the intellectual property arrangements in terms of the rights required for the implementation of intervention options arising from RRAP would ensure these arrangements do not limit the options for on-Reef implementation.

The need for management of intellectual property underpins the long-term role of facilitating the transfer of intervention and deployment technology. Below are the preferred arrangements:

- RRAP intellectual property would be publicly available for reef restoration and adaptation a requirement for public funding investment.
- Rights to background intellectual property would be sought for reef restoration and adaptation.
- Rights to use of RRAP intellectual property for applications that do not overlap with reef restoration would reside with the inventing institution, with the intention that inventing institutions would be encouraged to attract additional resources, including from industry, to independently further develop those technologies.
- Standard arrangements for approvals for the publication of scientific outcomes in the scientific literature (subject to coordination arrangements regarding RRAP communication).

10.2 International links

If the Australian Government's $100M commitment to Reef Restoration and Adaptation Science via the Reef Trust Partnership were to go towards the RRAP R&D Program, along with the commitments of other investors and the consortium research partners, this would make RRAP the world's largest single investment in helping reefs adapt to climate change. It has the potential for global impact and puts Australia at the forefront of this new and important emerging effort. To maximise impact, the program would seek to engage, coordinate and collaborate through international partnerships, consortia and funding structures.

The proposed strategy would be to:

- Establish an Australian partnership with the Coral Restoration Consortium/Reef Resilience Network to facilitate best practice and research exchange, and commence globalisation of the Coral Restoration Consortium.
- Encourage international governments, through Australia's role as co-chair of the International Coral Reef Initiative (ICRI), to invest in R&D programs in their countries, enabling international researchers to collaborate and engage with the work progressing in Australia. This includes establishing an ICRI working group in 2019 to explore areas of common R&D need and opportunities for collaboration.
- Target international and domestic philanthropy and industry with co-investment opportunities.
- Engage with, and guide, global challenge and prize initiatives in coral reef restoration, to encourage innovation and collaboration and leverage the Australian Government funding.

Opportunities for international engagement and partnering are documented in greater detail in the **R5: International Engagement and Partnering**.

10.3 Capacity to respond

Over the past two years, the RRAP consortium has established a unique capability. The concept feasibility study brought together a wide range of more than 150 experts from the core consortium partners (AIMS, CSIRO, James Cook University, The University of Queensland, Queensland University of Technology, Great Barrier Reef Marine Park Authority, the Great Barrier Reef Foundation), augmented by expertise from associated universities (University of Sydney, Southern Cross University, Melbourne University, Griffith University and the University of Western Australia), engineering firms (Aurecon, Worley Parsons and Subcon) and from international organisations (Mote Marine, NOAA, SECORE and The Nature Conservancy).

The partnership formed during the feasibility study has inculcated a strong sense of urgency, common purpose and direction among participants, resulting in an institutionally agnostic and collaborative spirit, based on shared priorities and clear mechanisms for agreement. The RRAP R&D Program would build on this foundation of expertise and commitment, as well as on collaborative relationships that have matured and worked smoothly over the past 18 months, to accomplish the objectives.

The scope of the R&D program warrants additional expertise. Some of this could be sourced by partnering with organisations not formally involved in the feasibility study (e.g. the ARC Centre of Excellence for Coral Reef Studies at James Cook University). Engineering expertise from the private engineering services sector will also be necessary. Partnering with community groups in citizen science and Traditional Owners through RRAP's engagement strategy would broaden capacity, and the intellectual capital and insight available. Preliminary discussions are being held with these groups in preparation for the R&D program.

10.4 Early outcomes of the R&D program (Years 2–3)

The R&D program will be designed to deliver early wins—key outcomes in the first two to three years. These will build program momentum and strategic capacity and enhance the ability to raise additional funds. Outcomes will include:

- Development and deployment of a comprehensive decision-support system, linked with RIMReP (the Reef 2050 Integrated Monitoring and Reporting Program).
- The next generation of integrated reef models.
- At least one on-reef, square-kilometre-scale, intervention trial.
- At least one investment-ready, small-scale intervention, fully costed and designed, ready for on-reef deployment.
- Economic benefits and new jobs in Reef communities, including for Traditional Owners.
- Up-skilling of workers in Reef and Traditional Owner communities involved in pilot-scale field trials and the broader R&D effort.

10.5 Funding of the implementation program

During the R&D program, mechanisms to fund future, at-scale implementation of interventions (should they be needed and prioritised) will need to be developed.

For planning purposes, it was assumed core funding for implementation would come from government. In Australia, the investment required for Reef-scale intervention is beyond any individual stakeholder other than government. While other sources of funding are likely to be forthcoming, core government commitment will be vital. Benefits generated by successful at-scale intervention would accrue across the Australian economy and overseas.

During the R&D program, efforts will be ongoing to work with public and private sector partners to develop options for public-private partnerships. This will supplement a public funding model. Domestically, there are efforts to establish innovative funding mechanisms such as green bonds and reef credits. These may develop to a point where they can help fund large deployment programs.

Internationally, insurance and capital market pressures are starting to generate private sector commercial investment interest in reef restoration and adaptation. Interest from the major philanthropic sector is also mounting, especially as the plight of the world's reefs receives increased global media exposure. The emergence of these potential sources of funding for the deployment phase of RRAP is of great interest and will be actively pursued during the R&D program.

The contribution that RRAP will make to the creation and expansion of a reef restoration and adaptation services market is expected to stimulate higher business investment in reef R&D over time.

11 RISK MANAGEMENT

11.1 Managing risk during the R&D program

Framework

A comprehensive risk management plan will be formulated during the first six months of the RRAP R&D Program. The plan will be consistent with Australian/New Zealand Standards (AS/NZS ISO 31000:2018: Risk Management – Guidelines). Included in the plan will be an outline of the mandate and board-approved risk tolerance statement, the risk management principles and policy, and the relationships, accountabilities, resources, processes and activities employed to manage risks. The plan will include policies, processes and procedures for risk oversight, identification and control.

Two main levels of risk will be managed:

1. **Programmatic risks:** Internal or external factors affecting the program's capacity to deliver against its objectives
2. **Intervention risks:** Potential adverse impacts of one or more interventions on environmental, ecological, economic, social or cultural values.

Expertise

The consortium partners each have established risk-management procedures within their own organisations and senior staff would bring this expertise and experience to the risk management of RRAP. Expert advisors will be engaged as needed to assist in implementing best practice, robust governance, anti-corruption, fraud prevention and audit and risk management policies and procedures.

Philosophy

For a program of such wide-ranging complexity, with a diverse stakeholder community and so much at stake in a future of high uncertainty, it must be recognised that risk will always be present. The RRAP R&D Program, and any future deployment of interventions, must *manage* all risks in the face of complexity and uncertainty. This means developing risk management and decision-making approaches that produce safe and productive solutions across a wide range of possible future conditions and are stable over time, even as the environment changes.

Approach

The program's ability to rigorously test critical issues and decisions will be key to the risk management. In instances of particularly challenging decision-making, specialist methodologies such as 'red team vs blue team' assessments would be deployed. Developed by the US military, the concept involves establishing expert teams who challenge each other to test how robust a plan or proposition is. The blue team defends and the red team attacks the proposition in a simulated exercise. The approach has since been used effectively to manage risks in industry[85]. The RRAP R&D Program could take such a red team vs blue team approach through its governance structure (at the steering committee and project levels), forming multi-institutional red and blue teams, to test critical issues and decisions, and develop risk management and mitigation strategies for both the program and development of intervention strategies.

11.2 Programmatic risks

Material strategic risks for the RRAP R&D Program are outlined below. These are risks that may impact on the program's ability to achieve the intended strategic outcomes. Controls have been incorporated into the structure of the R&D program and governance arrangements to manage and minimise all such risks.

1. **Funding withdrawn or reduced, or the timing of drawdowns hinders progress** **(Likelihood: medium, consequence: high)** Delivery of the first five years of the proposed R&D program is estimated to require a minimum of $326M (combined cash and in-kind funding) and further funds thereafter. If the initial cash funding from the Australian Government (via the Reef Trust Partnership) does not go towards the R&D program or is lower than expected, and any of the funding from partners or other key stakeholders is lower than budgeted, this will affect progress. The timing of funding and allocation of funds to critical path activities are important considerations.

   Risk mitigation: Ensure a high standard of, and regular reporting and consultation on, progress to funding organisations. Ensure a regular two-way dialogue between funders and R&D program leadership to build flexible and adaptive approaches to managing potentially variable funding inflows. **Residual risk = medium**

2. **Inability to deliver intended program results in the time required, due to regulatory or other constraints** **(Likelihood: medium, consequence: high)** As with any major applied R&D program, there is a high level of uncertainty at the early stage. This includes uncertainty of future climate trajectories, future Reef health, natural adaptation rates of corals to climate change, efficacy of novel interventions, unintended impacts (see also below), requirements and likelihoods of achieving regulatory approval for different intervention types and the changing views of society. For example, the existing regulatory and policy environment for the Great Barrier Reef is robust and acknowledged internationally. However, some novel interventions will challenge the existing regulatory framework. Methods for assessing the proposed activities, and monitoring and reporting their impacts, may not currently be established.

   Risk mitigation: Retain broad optionality at the start of the program and refine intervention options and strategies as uncertainty is systematically reduced and/or accounted for. The program's strategy to assess and develop multiple options in parallel will maximise the likelihood of success. Early intervention deployment will be prioritised, but only when and where such an intervention is deemed safe, predicted to deliver benefits with low uncertainty and does not prevent the development or deployment of subsequent and potentially better interventions. The less degraded the Reef, the more likely it will be that adaptation interventions will make a lasting difference. To help ensure intervention deployment at the earliest time, the recommended program was designed to allow for a broad range of interventions and assessments including ecological process studies, scoping of the Traditional Owner engagement context and preliminary stakeholder engagement and regulatory requirements, to be occurring in parallel. Additionally, the suite of interventions is targeted across a wide range of deployment scales, including those that can be delivered more quickly (and target retention of the highest value sites/reefs) and others that may take longer to develop but have higher impact (targeting regional scales). **Residual risk = medium**

3. **Governance and engagement do not meet government, stakeholder or community expectations (Likelihood: low, consequence: medium)** The R&D program will be conducted within a comprehensive governance system that integrates with the management of the Great Barrier Reef Marine Park area and involves many and diverse stakeholders, policies and regulatory frameworks. It will be important that the program appropriately engages in that system to identify issues and opportunities early and ensure complementarity with other Great Barrier Reef programs. Robust and well-functioning governance and management are critical to success. Under-investment in these aspects may result in significant risk of non-delivery.

   Risk mitigation: RRAP will be overseen and supported by a strong governance framework, with leading experts and stakeholders involved in decision-making processes across the program and with independent review panels established to provide 'point in time' assessments. Risk management policies and procedures will be embedded in RRAP governance and operational practices. A strong management team and structure will be established and appropriately funded. This will facilitate early identification, control and appropriate management of risks in accordance with the RRAP Board's risk tolerance and strategic decision-making. **Residual risk = low**

4. **Community support for RRAP wanes (Likelihood: medium, consequence: high)** Maintaining the current high, in-principle support for proposed intervention needs to be based on effective Traditional Owner, community and stakeholder engagement. The balance between the impacts that the short-term intervention may pose to the Reef against the medium- to long-term risks of no action must be clearly understood by the public. Not obtaining social license for interventions that represent effective solutions for Reef and people would represent high risk.

   Risk mitigation: RRAP will establish operational requirements, frameworks and capacities to identify appropriate ways to engage different groups and interests in the co-design, deployment and evaluation of proposed interventions or technologies. This will be informed by an expert social-science capability within the Program. The expectations of Traditional Owners, the general public and stakeholder organisations of the R&D program will be identified and RRAP will provide meaningful and appropriate pathways for participation by all stakeholders. Approaches will be developed with Traditional Owners to ensure their involvement in RRAP governance and R&D activity. These will include subcontracting field research and elements of field testing and monitoring, capacity-building in key areas of deployment activity and field testing, and education and accreditation opportunities. Subsequent to the transition program, RRAP will undertake activities to ensure necessary engagement across five broad activity areas: (1) demonstration sites and citizen science; (2) monitoring public attitudes and social license; (3) participatory technology assessment panels (citizen panels); (4) co-benefit agreements; and (5) coordination, synthesis, and strategy setting. **Residual risk = medium**

11.3 Intervention risks

1. **Ecological and environmental intervention risk (Likelihood: medium, consequence: medium to high)** Strategies that actively incorporate novel and validated interventions in the management toolbox could produce an improved outlook for the Reef. With such new interventions, however, it will be necessary to assess whether the ecological rewards (i.e. benefits) are likely to be greater than the negative consequences (i.e. risks) of inaction. Formal analyses of benefits and risks of intervening early or delay, or not intervening at all, need to guide RRAP decision-making. To fully understand intervention risks, analyses must cover all contingencies of individual and combined interventions and their flow-on effects on the Reef as a whole and on economic, social and cultural values under all scenarios. Uncertainty will be high but must be accounted for in risk analyses. Some proposed interventions aim to alter the environmental conditions of the atmosphere, water column or benthos (flora and fauna on the ocean floor). These may include the application of engineering processes and other technologies at a variety of spatial scales. While the aim is to enhance the resilience of reef corals, these interventions may pose risks to the deeper reef fauna, other biota and terrestrial environments. Other approaches may add biological material, chemicals or structures to the Reef. These may introduce or promote invasive species or altered environmental states that impact negatively on ecological interactions.

   Risk mitigation: All proposed restoration and adaptation interventions and technologies will be assessed against current legislation and regulations, and acceptance will be tested with broad groups of stakeholders. Ongoing assessment of ecological risk and potential adverse environmental impacts will be conducted using a staged series of controlled laboratory and field-testing programs. These will address the requirements for regulatory approval and form control gates as interventions progress from research scale to proof-of-concept and, ultimately, to deployment. Further, risk models will be developed as part of a dedicated RRAP decision-support system, and the ecological, environmental and economic models that underpin that decision-support system. Risk analyses will take full account of known uncertainty such that risk-management decisions are as informed as possible. A 'red team vs blue team' testing regime will be applied here also. RRAP will explore, assess and develop interventions, but none will be deployed unless, or until, the benefits of intervention, as a function of the state of the ecosystem at the time, are expected to outweigh the likely costs and risks (i.e. until the risk/return profile for intervention is acceptable). This approach will again inform the decision-support system, integrated with RIMReP to guide effective decision-making at strategic/program, tactical and technical levels. This work will also be supported by the work of the Modelling, Ecological Intelligence and Risk, Cooling and Shading, Rubble Stabilisation and Emerging Interventions sub-programs. **Residual risk = medium**

2. **Genetic intervention risk (Likelihood: medium, consequence: high)** Several interventions may intentionally or inadvertently alter the genetics of coral reef organisms. This triggers additional risk-management measures[86]. Genetic diversity is a key component of the health, fitness and resilience of populations and could be beneficially (the upside risk) or negatively (the downside risk) impacted at an individual, population or species level. Indeed, this is the actual intent of many proposed interventions, see **T3: Intervention Technical Summary** for a comprehensive discussion. It will be necessary to assess whether any proposed

intervention will have net positive effects on the genetics of populations and species. This will involve cutting-edge genomic analyses of natural populations (before and after R&D), experimental samples combined with evolutionary modelling and theory, to inform risk analysis and guide decision-making. Further, if such interventions favour the performance of one or more species under climate change, could this lead to unintended ecosystem disruptions such as shifts to a few dominant species? Gene editing and synthetic biology approaches introduce novel genes or organisms. They have the dual potential to act to improve the function of genes in processes (such as heat tolerance) and to enhance the trait. These approaches carry a different level of risk to the population genomic risks discussed above and are surrounded by a more stringent regulatory environment.

Risk mitigation: All proposed restoration and adaptation technologies will be assessed against current legislation and regulations. Ongoing assessment of genetic risk and potential adverse environmental impacts will be conducted as part of the R&D sub-programs and as steps to gain regulatory approval (a staged series of controlled laboratory and field-testing programs). It is unlikely R&D with genetically engineered material will be conducted outside quarantine conditions in the foreseeable future. Risk-management will be informed by the RRAP decision-support system. **Residual risk = medium**

12 SUMMARY: THE CASE FOR A RRAP R&D PROGRAM

The recent back-to-back bleaching events of 2016 and 2017 showed that conventional management methods will be insufficient to protect the Great Barrier Reef from the effects of climate change. A new set of options is needed now if we are to give the Great Barrier Reef the best chance to survive and prosper in a warmer future and buy time for global emissions reduction.

The enormity of the threat faced by the Reef has sparked the Australian public's interest and imagination. Surveys undertaken for this feasibility study showed strong levels of in-principle support throughout Australia for science-based intervention to help the Reef adapt and stay resilient.

The economic, social and environmental benefits to Australia of successful intervention to help the Great Barrier Reef adapt and remain resilient in the face of climate change are significant in the tens of billions of dollars. Direct benefits to, and involvement of, regional economies and Traditional Owners, will be significant. The potential returns to the nation will be many times the investment that Australia may choose to make.

The RRAP Concept Feasibility Study has shown conclusively that intervening at scale on the Great Barrier Reef, to help it adapt and remain resilient to climate change, is possible, but not yet. A broad range of techniques are available, but none are ready to deploy. A significant, long-term R&D effort is required to make any intervention feasible technically, safe, acceptable to the public and regulators, and affordable.

With a bold, long-term, breakthrough R&D program, what may have once seemed impossible can be achieved. Australia has the scientific ability, know-how and engineering capability to deliver such a program. The proposed investment in the RRAP R&D Program would place Australia in a position of global leadership in coral reef adaptation and restoration.

Success of the R&D effort would depend on a planned, coordinated, long-term program. The RRAP Concept Feasibility Study has set out a detailed program to deliver the required R&D as a single, coherent package. Doing it right will mean a lot more than developing specific intervention technologies and techniques. Success will depend on developing key underlying knowledge and systems that will apply to any and all interventions. These include building improved ecological models and decision-support systems, managing a range of risks, overcoming regulatory challenges and managing the perceptions of stakeholders who may be confronted by the idea of large-scale Reef interventions.

The proposed initial investment in R&D would provide real hope for the future of the Great Barrier Reef. While the overall R&D effort needed to take large-scale interventions to deployment may require a decade or more, smaller-scale interventions may be ready to deploy in the first few years. Either way, if we start the journey now, we will have good prospects to produce outcomes for the Reef and for Australia.

The RRAP R&D Program would bring together the best and brightest from Australia and around the world, in the largest ever coordinated effort to help a significant global ecosystem in its fight to survive climate change. At this point, we have the opportunity, the people, the ideas and the wherewithal to succeed. And if we do succeed, the positive economic, social and environmental implications for Australia and the world will be enormous.

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APPENDIX A: SYNTHESIS OF RRAP CONCEPT FEASIBILITY STUDY RESULTS

The RRAP Concept Feasibility Study produced a wealth of information and understanding about our current state of knowledge and our ability to predict the Reef's responses to change and intervention. The study findings are documented extensively in 33 separate reports. A document map of how the reports were organised and their specific purpose is provided in Appendix C. The purpose of this appendix is to provide an overview of the approach the study undertook and a synthesis of the key results in support of the key findings summarised in Section 6.

A1 GENERAL APPROACH

The RRAP Concept Feasibility Study planning, selection of key tools and methods and constitution of the core team commenced in October 2017. Key scientists involved in the core team are presented in Appendix C. The establishment of multi-institutional sub-teams was driven by selecting lead scientists from across the consortium partners, based on their expertise and availability to coordinate such teams, and to integrate work packages. Confirmation of scope, key milestones and deliverables, and delineation of critical pathways was completed in time for the study to commence in December 2017.

The main work packages, the work flow and how the work packages related to the critical deliverables are presented in Figure A1. Elements in red denote key technical activities, elements in green denote R&D sub-program descriptions and costings, and elements in blue represent the main synthesis steps and outputs.

The following primary technical activities were conducted in parallel:

- Characterise, understand and engage with stakeholders
- Ddetermine regulatory implications and response pathways
- Review existing, and determine potential, intervention types
- Scope and define deployment methods and scaling options
- Assemble, refine and apply existing ecological and hydro-geochemical models and use to test the prospective performance of selected interventions, alone and in combination
- Translate ecological coral reef metrics to estimates of value.

The findings of some of these technical activities provided direct critical input into two types of study outputs key synthesis and recommendations reports (blue elements, R1, R2, R3; Figure A1) and a suite of R&D strategy reports, outlining research gaps to be addressed, the approach intended and their costs (green element – S reports, Figure A1). The R1, R2 and R3 synthesis and recommendations reports together with the individual R&D sub-program strategy reports formed the main input to the development of the proposed RRAP R&D Program (R4 in Figure A1).

Outputs from the primary technical activities were also aggregated and integrated into the three main analysis steps:

- Feasibility and logistics of interventions
- Social, economic and ecological benefits of reef restoration
- Cost-benefit analysis of reef restoration.

These three components developed and provided critical input into structured decision-making comprising several prioritisation and evaluation frameworks. This formed the basis for assessing risks and prioritising activities to be proposed in the RRAP R&D Program (captured in **R4: Research and Development Program**). Together, the cost-benefit analysis and the R4 report constitute the main input to Sections 7 and 8 of this investment case.

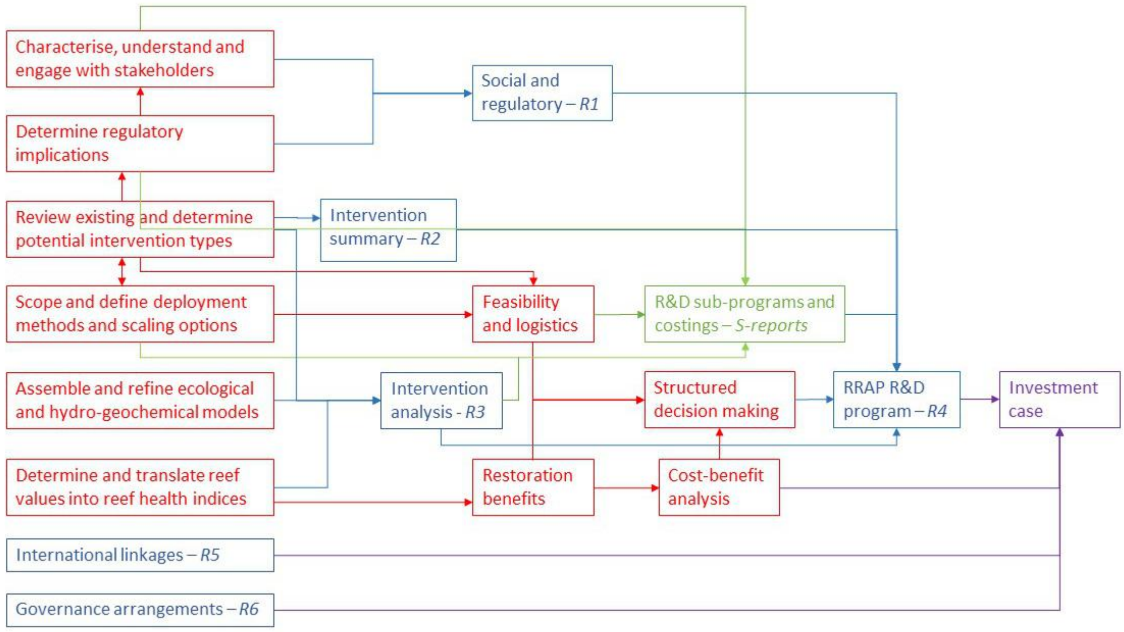


Figure A1: Generalised links and flow between work packages of the RRAP Concept Feasibility Study and key outputs. Elements in red are key technical activities, green are R&D sub-program descriptions and costings, and blue are the main synthesis steps and outputs.

A synthesis of methods, key findings and recommendations emanating from the recommendations in reports R1, R2 and R3 is provided in subsequent sections of this appendix.

Two additional activities investigated international links and scoped a range of governance, intellectual property and program management arrangements. The findings from these were documented in recommendations reports **R5: International Engagement and Partnering** and **R6: Governance and Program Delivery**. High-level results and recommendations from these two synthesis reports provided the base for Section 10 of this investment case.

The RRAP Concept Feasibility Study established a multi-tiered governance structure to guide and oversee the process, comprising a steering committee[c] and an executive committee[d].

[c] David Mead (Chair, AIMS), Dr Britta Schaffelke (AIMS), Dr Christian Roth (CSIRO), Dr Mark Gibbs (QUT), Prof Damien Burrows (JCU), Prof Peter Mumby (UQ), Theresa Fyffe (GBRF) and Dr David Wachenfeld (GBRMPA).

[d] Paul Hardisty (Chair, AIMS), Peter Mayfield (CSIRO), Ian O'Hara (QUT), Iain Gordon (JCU), Bronwyn Harch (UQ), Anna Marsden (GBRF), Margaret Johnson (GBRMPA), Deb Callister (DOEE) and Jane Urquhart (DIIS).

Initially, the executive committee reported to a senior officials committee comprising representatives from the Australian Government's Department of the Environment and Energy and Department of Industry, Innovation and Science. These two committees were subsequently merged into the key decision-making governance body. The role of the steering committee was to provide day-to-day guidance on the execution of the feasibility study, review progress and prepare decision advice to the executive committee.

In addition to the above governance arrangements, ensuring a seamless partnership between the key consortium partners and integration across the various activities was facilitated through bi-monthly RRAP integration workshops throughout the concept feasibility study. In these one- to two-day workshops, all core team scientists and steering committee members jointly reviewed results and ensured the flow of key inputs/outputs between the work packages.

A2 KEY FINDINGS

A2.1 ENGAGEMENT AND REGULATORY ASSESSMENT

A2.1.1 Introduction

The feasibility and viability of the proposed interventions to help preserve and restore the Great Barrier Reef will depend, to a large extent, on their social acceptability and the regulatory environment in which they are developed and deployed.

Critical needs of RRAP include understanding the social acceptability of proposed interventions or specific technologies; assessing how proposed interventions (or non-intervention) may affect the diverse social and cultural values, uses and benefits associated with the Reef and identifying appropriate ways to engage different groups and interests in the co-design, deployment and evaluation of proposed interventions or technologies over time.

The regulatory environment plays a key role in establishing safeguards to protect the environment and enable ecologically sustainable use. It complements social acceptance. The Reef is a highly regulated space, comprising four regulatory and legislative levels (international, Australian Government, Queensland Government and local government). Regulation may facilitate and support agencies and enterprises responsible for developing and implementing restoration best practice, knowledge and research. Conversely, a complex, multi-jurisdictional regulatory environment may hinder intervention, and create confusion and conflict among stakeholders, if it lacks mechanisms for evaluating intervention success and fails to provide regulatory guidance and enforcement.

A2.1.2 Approach

Methods used to understand and assess social acceptability of proposed RRAP interventions and identify appropriate ways to engage different groups and interests, comprised:

- In-depth research interviews with 24 Reef stakeholders.
- A representative national survey in mid-2018 of more than 4000 Australians, including a subset of Reef residents (less than 50km from the coast).
- Sentiment and discourse analysis of Twitter data.
- Review of the suitability of existing engagement arrangements in the Reef.

- Review of international literature on best-practice approaches and principles for engagement in large-scale ecological restoration and adaptation projects.
- Review of existing information about Traditional Owner processes, values and aspirations related to Reef management and governance.

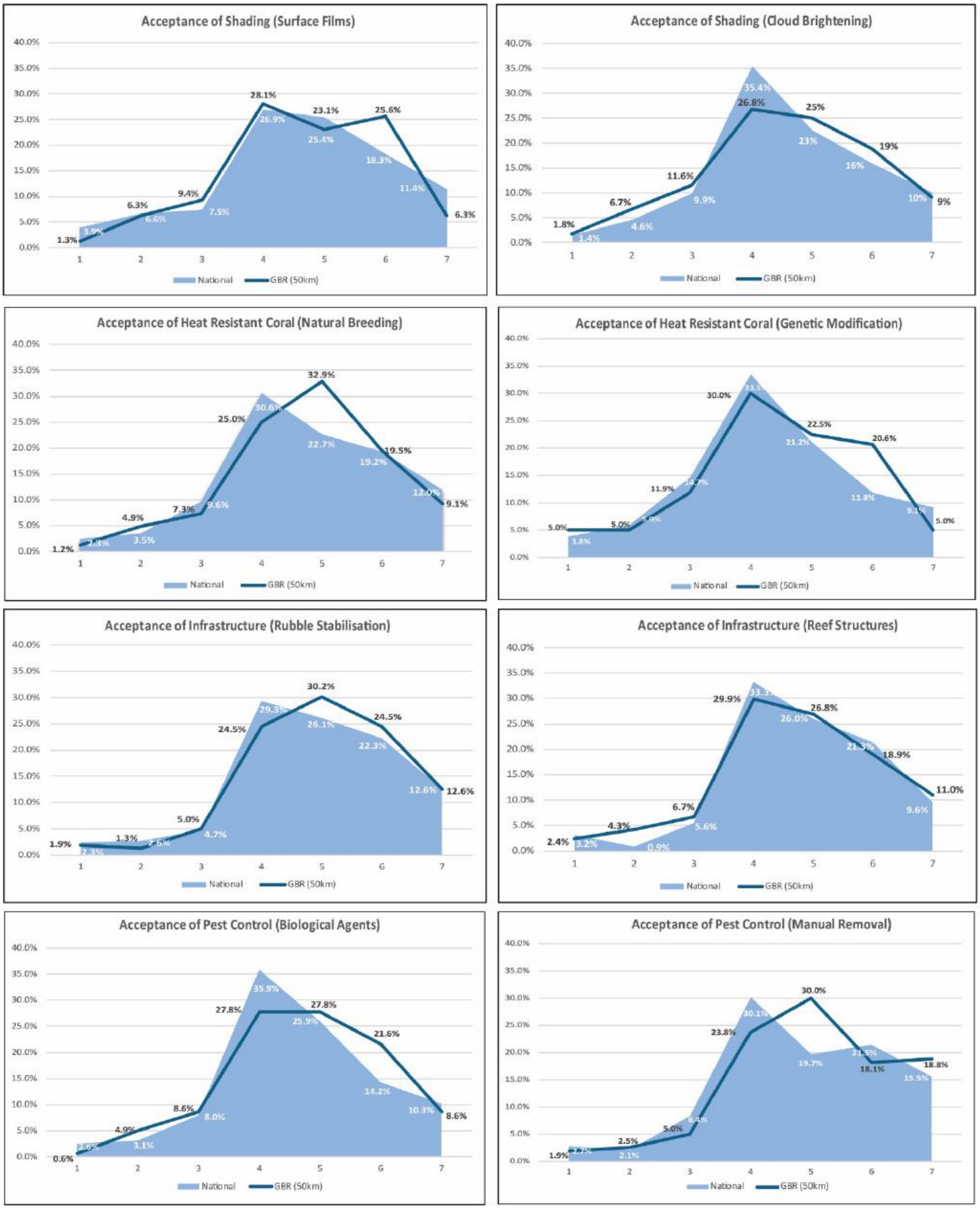
The analysis of the regulatory environment drew on multiple sources of evidence, including documents, peer reviewed literature, focus groups and interviews following standard protocols for qualitative research:

- Desktop review of relevant legislation, policy documents and studies to develop a comprehensive 'map' of the Great Barrier Reef regulatory environment. Sources of documents for the review included legislation databases and government agency websites.
- Interviews and workshops to gain additional information and validate the mapping of the Great Barrier Reef regulatory environment. Interviewees and workshop participants included staff from key federal and state agencies, with expertise in the regulatory environment of the Great Barrier Reef. Interviews and workshops that included RRAP scientists were used to attain a better understanding of the proposed interventions and the extent to which they were captured under existing regulatory arrangements.

A.2.1.3 Analysis and findings – social acceptance

The concept feasibility study identified four headline sets of findings in relation to social perceptions of restoration interventions:

1. There is strong public in-principle support for science-based intervention to restore the reef and, on average, cautious support for specific interventions. However, the datasets revealed complexities and attitude differences towards reef restoration among different groups:
    - The Australian public and Reef residents surveyed were generally accepting of the types of technologies and interventions proposed in RRAP (Figure A2). Separate statistical tests (MANOVA multivariate analysis of variance) were used that indicate some cooling and shading technologies (surface films and cloud brightening), as well as genetically modified, heat-resistant corals, were considered to be riskier than the others.
    - Reef stakeholders (e.g. local government, tourism industry and non-governmental organisations), when interviewed, had more complex attitudes towards reef restoration. Some were sceptical about government motives behind restoration-focused investment and were unsure about the likely effectiveness of interventions. They also identified several ecological, economic and social/psychological risks of the program.
    - Addressing emissions and other threats to the Reef, while outside the scope of RRAP, were important to the perceived credibility of the program.
    - When reef restoration interventions were discussed on Twitter, sentiment was negative in the context of climate change or bleaching. Sentiment was positive when highly innovative technologies were discussed in the context of protecting, repairing and preventing damage to the Reef (both within the Great Barrier Reef region and at a global level). Reproduction and recruitment-related strategies were associated with the highest positive sentiment.
    - Focusing on positive and observable action, there is an opportunity to mobilise significant public support for Reef restoration.



X axis: Level of acceptance or rejection with rated scale from 1 (not at all) to 7 (very much so), midpoint = 4.
Y axis: response percentages from each total number of group data (National and GBR_50km).

Figure A2: 2018 National survey of Australian (n = 2743) and Great Barrier Reef residents (n = 1293), acceptance of specific reef restoration interventions by geography (local and national).

2. Belief about the need to help the Reef, and trust in science and reef managers, were important for social acceptance:
   - People's beliefs about the need for direct intervention to help repair, restore and build the resilience of the Reef, and public trust in reef managers, authorities and research institutions, were strong predictors of acceptance of reef restoration.
   - Overall, the Australian public, Reef residents and stakeholders perceived the Reef to be facing significant threats (from pressures such as climate change, environmental pests and water quality) and there was general agreement on the need to prevent further degradation through restorative actions and supporting adaptation.
   - Public trust in the science community and Reef management agencies was high relative to government and other groups. This suggests the science community and reef managers are well-placed to lead engagement activities.

3. Participation is central to realising the benefits of RRAP:
   - Stakeholders expressed a strong desire to participate and partner in any future R&D program.
   - Traditional Owners and stakeholders strongly asserted that the opportunity to co-design the program was necessary to create and realise potential future benefits (economic, ecological, social and cultural).

4. The Reef Traditional Owner and stakeholder engagement context is complex. Engagement strategies tailored to RRAP R&D needs will require detailed planning:
   - There are more than 100 different organisations, forums or mechanisms that facilitate the involvement of stakeholders and citizens in Reef-related issues, for example local marine advisory committees, regional organisations of councils, industry and peak body processes, education, citizen science and volunteer networks. When multiple cases of the same type of structure (e.g. local councils) are counted, there are more than 380 in total.
   - There are more than 70 Traditional Owner groups with custodial interests in caring for land-sea country across the length of the Reef. Several significant forums or processes support Traditional Owner management and governance of the Reef (such as formal advisory and expert committees, country-based planning and Traditional Use of Marine Resources Agreements). There are well-documented co-research and knowledge-management protocols to guide scientists in working with Traditional Owners and Indigenous peoples that are highly relevant to RRAP implementation.

A.2.1.4 Analysis and findings – regulatory environment

Proposed RRAP interventions may involve different regulatory requirements, primarily depending on:

- If they occur within the marine park/coastal marine park and/or on land
- The nature of the proposed activities.

Many activities within the marine park, including those in the airspace up to 915m, require approval under the *Commonwealth Great Barrier Reef Marine Park Act 1975*.

Overall, permit applications are assessed in terms of the nature and scale of the activities proposed, and the acceptability of the potential impact of these activities on the environment[87]. *The Guidelines for permit applications for restoration/adaptation projects to improve resilience of habitats in the Great Barrier Reef Marine Park*[88] indicate the regulatory requirements and assessment approach to be adopted for interventions similar to those proposed for RRAP. Certain interventions would require additional assessment and approval under other regulations. For example:

- Interventions that may cause a significant impact on the environment of the marine park or other matters of national environmental significance require assessment under the *Commonwealth Environment Protection and Biodiversity Conservation Act 1999*.
- Interventions involving fishery resources (including corals) and activities interfering with fish habitats and marine plants and algae require permission under the *Queensland Fisheries Act 1994*.
- Interventions involving placing structures (e.g. artificial reefs) in the marine park require assessment under the *Commonwealth Environment Protection (Sea Dumping) Act 1981*.
- Interventions involving genetic engineering require permission under the *Commonwealth Gene Technology Act 2000*.

Proposed RRAP interventions (see A2.2) feature different levels of regulatory complexity. Surface films and misting involve regulatory requirements mostly under the *Commonwealth Great Barrier Reef Marine Park Act 1975*, while genetic engineering involves requirements under multiple acts. Further, *Great Barrier Reef Marine Park Authority guidelines for permit applications for restoration/adaptation projects to improve resilience of habitats in the Great Barrier Reef Marine Park*[88] establishes different levels of risk (low to high) to different reef interventions. Overall, interventions considered to be medium risk or higher may require proof-of-concept or supporting rationale for likely success in the marine park. They may also require:

- A pilot study (considered as a research activity) involving tailored assessment and possibly a deed of agreement. If such a pilot study is regarded as successful, a non-research-focused permit to deploy the intervention can be sought.
- Subject to the scale and risk involved, the operational application may require a Tailored or Public Information Package assessment, deed/bond, public advertising and/or an environmental management plan.

The existing Great Barrier Reef regulatory and policy environment as it relates to proposed RRAP interventions is robust; however, it is not entirely fit-for-purpose. It is complex, both fragmented and overlapping, and its capacity to assess novel risks and impacts associated with unconventional interventions is limited. RRAP interventions pose an unprecedented challenge to the existing regulatory system to address novel risks and impacts, high levels of uncertainty and untested mechanisms for observation and monitoring.

A2.1.5 Recommendations

The engagement component of the RRAP R&D Program will need to address the following overarching recommendations:

1. The current engagement architecture in the Reef is generally suitable to support RRAP access to trusted networks to socialise the program, scope interests and values, and plan for future engagement. However, additional, fit-for-purpose engagement activities will be required to meet the more challenging demands of:

    - Deliberation on specific technologies
    - Representation/participation in RRAP decision-making
    - Supporting transparency and co-design of interventions

- Identifying co-benefits from the R&D program
- Exploring broad trade-offs and uncertainties around future Reef states.

2. It is essential the RRAP empowers Traditional Owners to exercise their unique rights and responsibilities. This will require developing approaches to Traditional Owner involvement in RRAP governance; resourcing involvement in R&D activity through co-research, or the subcontracting of field research; and exploring education and accreditation opportunities during the R&D program, amongst others. More work is required to deepen the involvement and engagement of Aboriginal and Torres Strait Islander peoples across RRAP.

3. The complexity and novelty of RRAP, combined with its high dependency on the participation of diverse groups, requires the involvement of social scientists and engagement specialists with expertise in designing, facilitating and evaluating participatory and co-research-based R&D processes that support responsible innovation.

The regulatory component of the RRAP R&D Program aims to help develop a robust and enabling regulatory environment for reef restoration and adaptation. This includes enhancing the capacity of the regulatory system, where needed, to assess the range of risks and impacts associated with unconventional reef restoration and adaptation interventions, and developing a world-leading regulatory and policy best practice for reef adaptation and restoration.

Success in the regulatory sub-program would require focus on the following thematic areas:

- **Regulatory capacity:** Identification of short-, medium- and long-term priorities to improve regulatory capacity to address RRAP interventions.
- **Guidelines and training:** Preparation of guidelines and delivery of training to RRAP researchers to ensure they are fully aware of the regulatory environment pertaining to the Great Barrier Reef.
- **Cooperation between regulators:** Facilitation of further cooperation between Great Barrier Reef Marine Park Authority and other relevant regulators, with expert input from RRAP scientists on RRAP interventions involving emerging technologies.
- **Permitting system:** Development of options for improving the permitting system for reef restoration and adaptation interventions.
- **Policy and regulatory innovation:** Development of options for regulatory and policy innovation.
- **Whole-of-government reef restoration policy:** Preparation of options for a ‘whole-of-government’ reef restoration policy development.

A2.2 INTERVENTIONS ASSESSMENT

A2.2.1 Approach

As part of the feasibility study, a long-list of possible on-Reef interventions was identified using a mix of methods:

- Literature search
- International and national workshops, meetings and conferences
- Reviewing targeted development of approaches through commercial suppliers
- External approaches and submissions to RRAP.

This initial list was refined as possible costs, drivers of success and other considerations became more apparent.

A2.2.2 List of interventions considered

The interventions investigated during the RRAP Concept Feasibility Study have been categorised based on three attributes: their functional objective, delivery method and deployment scale, as defined in Table A1.

Table A1: The interventions terminology adopted by RRAP. Further definitions and a glossary are shown in T3: Intervention Technical Summary and T5: Future Deployment Scenarios and Costings.

Term	Description
Intervention	An end-to-end description of the physical action/process undertaken to achieve the stated functional benefit. A **functional objective** achieved by a specific **delivery method**, at a specific **scale**.
Functional objective	The core functional benefit being targeted by an intervention, such as reducing conditions that induce bleaching, or enhancing the ability of Reef populations to recover from, or withstand, bleaching.
Functional objective type	Groupings of like functional objectives used to cluster interventions that share intended functional benefits, such as reducing conditions that induce bleaching or enhancing the ability of Reef populations to recover from, or withstand, bleaching. They have been used for communication and outreach purposes as they commonly have similar social and regulatory considerations.
Delivery methods	The method used to deploy the intervention. Delivery methods consist of three parts: the specific approach, production and deployment on the Reef. The same production and deployment methods may be combined with different approaches to deliver different interventions. For example, aquaculture production can enhance recovery or adaptation depending on the stock and treatments used.
Micro-scale interventions	Small areas in limited sites; represents current levels for restoration methods.
Small-scale interventions	A scale that could retain/protect tourism and other key sites if required; approximately 50 tourism-scale sites.
Medium-scale interventions	A scale that could support ecosystem functioning of several clusters of priority reefs in key areas; approximately 50 reefs.
Large-scale interventions	A scale that would help retaining ecosystem function and core economic and social values for the broader Great Barrier Reef; more than 200 reefs.

Table A2 provides a summary of the interventions examined during the concept feasibility study. The interventions are grouped under functional objective types. Each of these interventions was considered for applicability at four scales: micro, small, medium and large.

Table A2: Overview of interventions, grouped by functional objective (Types 1–7) and delivery methods. Code: C = cooling and shading; S = structure and stabilisation, ER = enhanced reproduction and recruitment, B = (bio)–control, F = field treatments, EE = enhanced performance from existing species or populations and EN = enhanced performance from novel coral stock resulting from genetic engineering and/or synthetic biology. Interventions are applied at a specific scale (micro, small, medium or large).

Code	Intervention (applied at micro, small, medium or large scales)	Description	Delivery Method
Functional Objective Type 1: Cooling and shading to reduce coral stress during acute events			
C1	Cooling by mixing	Mixing shallow reef waters to reduce seawater temperatures in target reef areas, using slow-moving impellers on moored or attached structures. Intended for intermittent operation during summer doldrums conditions to minimise coral bleaching.	Mixing
C2	Cooling by pumping	Pumping deeper, colder water either directly onto the reef, or passed through heat exchangers to reduce seawater temperatures using permanent and attached structures. Intended for intermittent operation during summer conditions to minimise coral bleaching.	Pumping
C3	Shading by cloud brightening	Adding nano-sized salt (or other particles) to the lower atmosphere (< 1000m) to change the water droplet size distribution in clouds to enhance the reflectivity of clouds and restrict the amount of light that reaches reefs over distances large enough to also reduce heat. Particles added via devices mounted on moored platforms, vessels or via aerial dispersal of dry material. Intended for intermittent operation during summer conditions.	Cloud brightening
C4	Shading by fogging	Creating artificial 'sea-fog' by spraying seawater into the air from dispensing devices on moored or attached platforms or vessels. Intended for intermittent deployment during summer conditions to reduce solar radiation reaching reefs and to provide evaporative cooling to minimise coral bleaching.	Fogging
C5	Shading by misting	Adding vaporised biogenic oil to the lower atmosphere from dispensing devices mounted on moored platforms or vessels. Intended for intermittent operation during summer conditions to form a mist of reflective particles to reduce incoming solar radiation conditions and minimise coral bleaching.	Misting
C6	Shading by surface films	Adding ultra-thin surface films manufactured from natural products to surface waters from moored dispensers and/or aerial dispersal. Intended for intermittent deployment during summer conditions to reduce solar radiation reaching reefs and minimise coral bleaching.	Ultra-thin surface films
C7	Shading by microbubbles	Creating nano-sized bubbles in Reef surface waters to reflect light via temporary or permanently-moored platforms. Intended for intermittent operation during summer conditions to reduce incoming solar radiation and minimise coral bleaching.	Ocean microbubbles
C8	Shading by structure	Suspending physical shade structures (e.g. cloth) at or near the surface of local reef areas via structure floats and/or anchors. Intended for intermittent operation	Shade-cloth deployments

		during summer conditions to reduce incoming solar radiation and minimise coral bleaching.	
C9	Shading by algae	Farming suspended macroalgae above reefs to provide localised shade and/or remove nutrients. Requires fixed or moored structures.	Macroalgal shading
C10	Ocean fertilisation	Deploying iron sulphate (or other nutrients) onto the ocean surface to stimulate phytoplankton grown. Described primarily as a method to capture and sequester CO_2, it can also provide shade. As this approach carries significant ecological risk, it was not considered for the Reef and not described in T3: Technical summary of Interventions. *Eliminated based on risk, not assessed further*	Ocean fertilisation
C11	Cooling by high altitude aerosols	Adding sulphate aerosols to higher atmospheric altitudes to globally cool Reef waters. *Eliminated based on risk, not assessed further*	Sulphate aerosols
Functional Objective Type 2: Adding reef and 3D structures to increase substrate stability, and therefore the rate of reef recovery, following major disturbances			
S1	Stabilisation by natural bonding	Enhancing substrate consolidation by promoting natural bonding agents (including crustose coralline algae or other taxa or biological adhesives) from organisms such as bivalves to help increase the rate of reef recovery following a disturbance. Bonding agents/organisms would be produced/cultured in land-based facilities and deployed from barges and small deployment vessels.	Assisted natural bonding
S2	Stabilisation by chemical bonding	Adding manufactured chemical bonding/grouting agents to enhance substrate consolidation to aid reef recovery. The bonding/grouting agents would be produced in land-based facilities and deployed in a semi-automated manner from barges and small deployment vessels.	Chemical bonding and grouting
S3	Stabilisation by mesh	Stabilising substrate by fixing mesh over unconsolidated material to aid reef recovery. The mesh would be produced on land and fixed to the reef using a large barge or floating platform.	Mesh fixing
S4	Stabilisation by removal	Removing unconsolidated substrate via a surface-operated suction device to aid reef recovery. This approach has been successfully applied to reefs affected by ship and boat strikes. It requires a large barge/floating platform and is most effective where rubble beds are relatively thin veneers on top of consolidated coral reef substrate.	Suction removal
S5	Structure by consolidation	Consolidating rubble with gabion baskets to stabilise substrate and provide a 3D structure to aid reef recovery. The mesh baskets would be filled with rubble, providing limited structure and habitat. They would be fabricated and filled onshore and deployed using large barges.	Gabion baskets
S6	Structure by 3D frames	Deploying small manufactured structures, such as the Mars^{TM} Spiders, onto the seafloor in areas of damaged reef to aid reef recovery. The spiders are modular and can be individually tied together by divers, or pre-attached into a chain or strip prior to deployment. They are constructed onshore and could be deployed from small and large barges and deployment vessels.	Mars^{TM} Spiders and other smaller 3D structures

S7	Structure by concrete shapes	Deploying large, manufactured structures such as Bioballs™ or Subcon Mushrooms, to facilitate ecological processes such as coral recruitment, survivorship, herbivory, fish diversity and growth of immobile organisms. They would be deployed from large barges.	Bioballs™ or Subcon Mushrooms
S8	Structure by massive corals	Deploying, or *in situ* re-skinning, natural coral shapes. Artificial massive corals are concrete structures with a coral skin attached. The corals are grown separately, attached to the structures, which are deployed from large and small barges and deployment vessels.	Massive corals (coral-skinned shapes)
S9	Structure by 3D printed shapes	Deploying 3D printed structures that recreate structural complexity and facilitate ecological processes such as coral recruitment, survivorship, herbivory, fish diversity and growth of immobile organisms. The structures would be printed and deployed from large barges.	3D printed complex structures
Functional Objective Type 3: Eenhance coral reproduction and recruitment on recovering reefs, following disturbance			
ER1	Coral seeding by *in situ* coral movement	*In situ* movement of whole coral colonies, or large fragments within reefs, to cluster them and increase fertilisation during natural spawning events (i.e. avoid Allee effects). Existing methods are well-developed and require divers, small vessels and large vessels.	*In situ* movement of corals within reefs to increase fertilisation during natural spawning
ER2	Coral seeding by larval slick movement	Coral seeding by collecting natural, seasonally-produced coral spawn/larval slicks in floating enclosures and towing them short distances to adjacent, high-priority areas for release. This aims to increase the number of corals from the spawning slick that ultimately recruit into reef populations.	Assisted larval movement
ER3	Coral seeding by larval slick translocation	Coral seeding by capturing natural, seasonally-produced, coral spawn/larval slicks into tanks and transporting them via large vessels for release onto local or regional high-priority reefs. This aims to increase the number of corals from the spawning slick that ultimately recruit into reef populations.	Translocation of larval slicks
ER4	Coral seeding by larval slicks settled on devices	Settling coral slick-captured larvae onto devices and deploying onto local or regional reefs. This merges the larval slick and aquaculture methods and is designed to increase the number of corals created within the short annual spawning period.	Translocation of larval slicks and device-based settlement
ER5	Coral seeding by *in situ* harvested fragments	Field-based harvesting of coral (micro) fragments (from areas of high coral cover, or using fragments broken off in weather events) and delivery and planting in high-need areas. It would require automation of established manual methods. Additional treatments with microbes and hardening may be applied.	direct harvest of coral (micro) fragmentation
ER6	Coral seeding by hatchery or nursery aquaculture	Optimising existing manual hatchery and nursery methods using local, unselected coral stock to seed reefs. Facilities could be land or sea-based, using diver-based deployment, supported by barges and small vessels.	Optimised existing hatchery and nursery methods
ER7	Coral seeding by semi-automated aquaculture	Semi-automated, shore-based aquaculture propagation, using either sexual or asexual methods and local brood stock, to seed corals onto reefs. This approach would amalgamate current aquaculture and automation technology with a combination of diver and semi-	Semi-automated shore-based aquaculture

		automated deployment methods from barges and small vessels.	
ER8	Coral seeding by automated aquaculture	Automated, either sexual or asexual, mass-production of corals in shore-based aquaculture using local brood stock and field deployment from the surface using automated systems (no divers) to seed reefs. This method is based on deploying young corals (or small coral fragments) attached to a small device, using barges and small vessels.	Automated, mass production shore-based aquaculture, field delivery systems
ER9	Coral seeding by larval/polyp aquaculture	Significant breakthrough larval/polyp-based sexual or asexual aquaculture that provides a step change in production rates and cost reductions, using local brood stock to seed reefs. These methods seek to vastly reduce production durations (from months/years to hours/days) and increase deployment success (via advanced active deployment devices) to facilitate much larger deployment quantities at an affordable cost.	Breakthrough larval/polyp-based aquaculture
Functional Objective Type 4: (Bio)-control to restore coral reef health and resilience			
B1	(Bio)-control of macroalgae	Manual, automated or biological removal of macroalgae from reefs to promote coral recruitment, growth and survival. The removal methods may require *in situ* or land-based propagation of biocontrol agents. Existing manual methods require divers, robots and small and large vessels.	(Bio)-control of macroalgae
B2	Biocontrol of species with negative impact	For example, managing the predatory sea snail *Drupella* using push-pull technology, biocontrols or genetic engineering. Push technologies (e.g. harnessing chemicals released by *Drupella* predators) deter the snails, while pull-technologies (e.g. pheromones) attract the snails to specific locations where they can be removed. Biocontrol agents or genetic engineering control methods do not currently exist.	Biocontrol
Functional Objective Type 5: Increase coral survival and reef health following disturbance with probiotics, feeding, medicine or other treatment			
F1	Application of field treatments to enhance coral survival	*In situ* application of medicines, food or probiotics (treatments) to corals or reefs to enhance survival during natural stress events. Treatments are grown, cultured or manufactured on land and applied to colonies or reefs during or following stress. A viable deployment method is yet to be identified but could involve small and large vessels, airplanes or drones.	Field treatments
Functional Objective Type 6: Increase the health and tolerance of reef populations by seeding corals with enhanced performance derived from existing stock			
EE1	Seeding enhanced corals from existing stock by larval slick translocation	As in ER3, but using coral stock selected to promote adaptation or fitness in receiving populations, under changing conditions. May include additional treatments such as microbial treatments or hardening.	Translocation of larval slicks
EE2	Seeding enhanced corals from existing stock by settlement of	As in ER4, but using coral stock selected to promote adaptation or fitness in receiving populations, under changing conditions. May include additional probiotic or hardening treatments.	Translocation of larval slicks and device-based settlement

	larval slicks on devices		
EE3	Seeding enhanced corals bred from existing stock with semi-automated aquaculture	As in ER7, but using coral stock selected to promote adaptation or fitness in receiving populations, under changing conditions. May include additional probiotic or hardening treatments.	Semi-automated shore-based aquaculture
EE4	Seeding enhanced corals bred from existing stock with automated aquaculture	As in ER8, but using coral stock selected to promote adaptation or fitness in receiving populations, under changing conditions. May include additional probiotic or hardening treatments.	Automated, mass production shore-based aquaculture
EE5	Seeding enhanced corals bred from existing stock with larval/polyp aquaculture	As in ER9, but using coral stock selected to promote adaptation or fitness in receiving populations, under changing conditions. May include additional probiotic or hardening treatments.	Breakthrough larval/polyp-based aquaculture
Functional Objective Type 7: Increase the health and tolerance of reef populations by seeding corals with enhanced performance, derived from synthetic biology and genetic engineering approaches			
EN1	Seeding enhanced corals bred from engineered stock with semi-automated aquaculture	As in ER7 but using genetically-engineered or synthetic coral stock and treatments. May include additional probiotic or hardening treatments.	Semi-automated shore-based aquaculture
EN2	Seeding enhanced corals bred from engineered stock with automated aquaculture	As in ER8 but using genetically-engineered or synthetic coral stock and treatments. May include additional probiotic or hardening treatments.	Automated, mass manufacturing shore-based aquaculture
EN3	Seeding enhanced corals bred from engineered stock with larval/polyp aquaculture	As in ER9 but using enhanced coral stock derived from genetically-engineering or synthetic biology. It may include additional probiotic or hardening treatments.	Breakthrough larval/polyp-based aquaculture

A2.3 INTERVENTION ANALYSIS

A2.3.1 Introduction and scope

The purpose of the intervention analysis was to examine, quantitatively, the scope for new interventions to sustain or improve coral condition on the Great Barrier Reef and the multiple values inherent in the Reef. To provide such understanding, we approached the problem with a set of linked and tiered questions:

1. What is the likely trajectory of Great Barrier Reef coral condition this century under different climate change scenarios and under the assumption of continued, best-practice conventional management?

2. What is the potential for new restoration and adaptation interventions, separately or in combination, to improve the outlook for the Great Barrier Reef under climate change and best-practice conventional management?

3. If the potential of these interventions could be realised, what would be the likely economic benefits for Australia?

4. Are there circumstances where investment in RRAP is favourable, thus allowing decision-makers to determine whether the program should progress to the next stage?

To address question one, we modelled coral trajectories under two contrasting climate change scenarios: the ideal, best-case scenario of the world achieving the Paris Agreement target of RCP 2.6 and the unmitigated scenario of RCP 8.5. This allowed us to understand the range of possible climate futures within which RRAP would produce solutions and to construct RRAP counterfactuals. Importantly, whether one climate future or another will unfold is associated with uncertainty[34,89]. In turn, uncertainty regarding the climate trajectory will affect the likelihood that RRAP can produce solutions given different constraints on efficacy, logistical challenges associated with different climate scenarios and direct climate impacts on society and human capacity for climate adaptation[90,91]. In our modelling of coral trajectories and associated economic consequences, we assumed best-practice conventional management for all scenarios to demarcate the boundary for where the scope of increasing conventional management strategies stops and where the scope of added RRAP strategies begins.

To address question two, we examined to what extent RRAP interventions could help sustain coral condition (specifically coral cover) under such futures. We limited the scope here to corals (i.e. not fish or other reef-associated groups) based on the premise that corals are to coral reefs what trees are to tropical rainforests[41]. By providing critical habitat, corals underpin the majority of biodiversity on reefs (~0.55 to 1.33 million species)[40] and offer a range of reef ecosystem services. Thus, by focusing on coral cover, we address part of the ecological underpinnings of reef resilience and dependent values. While the specific risks associated with new interventions are a critical element of decision-making associated with intervention deployment, we **focused on intervention scope (potential) only** in this feasibility study. By making this choice, we provide clarity around **the extent to which RRAP could deliver outcomes**, under the assumption that risks can be more fully understood, accounted for and managed in the RRAP R&D Program.

We used a benefit transfer approach to address question three: Estimate the economic benefits of interventions (or no interventions). While primary economic data would have been the preferred approach to understand the economic benefits of the program[92,93], this was beyond the scope of the feasibility study. To understand the benefits arising from multiple coral reef ecosystem services, we used the Common International Classification of Ecosystem Services developed from the work on environmental accounting undertaken by the European Environment Agency. Here, we limit benefit streams from sustained or improved Reef coral condition to Australians from 2020 (using present-day values anchored in 2016) to 2075. We complement the benefit-transfer approach with additional analyses based on per hectare estimates of ecosystem service values for coral reefs globally[37,38].

We undertook a cost-benefit analysis for RRAP to demonstrate, within the high degree of uncertainty inherent in the program, whether there was a strong set of options and assumptions within which investment in RRAP was favourable. This analysis can help decision-makers determine whether the program should progress to the next stage of funding (question four). In other words, the cost-benefit analysis tests whether RRAP showed enough potential net benefits to continue. To this end, a structured decision-making method was used to frame the decision space, to ensure: the options assessed were reasonable, the information relevant and reliable for the level of the decision, trade-offs were understood and sufficient to conduct a logical analysis, and facilitate optimised decisions and commitment to action.

A2.3.2 Selection of analysed interventions

To assess quantitatively the scope for new interventions to build reef resilience and support coral condition on the Great Barrier Reef, we selected a subset of example interventions from the wider set of interventions listed in the previous section, based on the following criteria:

1. Availability of sufficient data or theory to inform the parameters in environmental and ecological models.
2. The example set of interventions should impact on different environmental or ecological processes such that their consequences for coral condition could be assessed quantitatively, and with enough precision to inform assessments of intervention scope.
3. Supporting ecosystem resilience is a central premise of RRAP. The example set of interventions should ideally cooperate and synergise to promote and sustain coral survival, growth and recruitment.
4. The example set of interventions should operate at multiple spatial scales ranging from gene to seascape.
5. Reasonable assumptions around efficacy, feasibility and costs must be possible to inform assessments of scope. The quantitative assessment of risks (e.g. likelihood of unintended consequences or any process that prevents a strategy from meeting its objective) will be a critical component of decision analyses in the RRAP R&D Program. However, we limited model analyses in the feasibility study to assessments of intervention scope (i.e. potential) only.

Applying this set of selection criteria to the interventions outlined in the previous section, along with discussions with colleagues from the RRAP working groups, the modelling team narrowed in on, through iterations, the set of example interventions outlined in Table A3.

Table A3: Interventions used in modelling RRAP strategy scope, based on a set of four criteria (columns). Additional crown-of-thorns starfish control is included given the historical impact of crown-of-thorns starfish outbreaks on Great Barrier Reef coral cover[13], and the assumption that additional control measures could become available[12,94]. Code: S = structure and stabilisation, C = cooling and shading; EE = enhanced performance from existing species or populations and EN = enhanced performance from novel coral stock resulting from genetic engineering and/or synthetic biology.

	Criteria			
Intervention (code)	**Data or theory for parameterisation**	**Processes impacted (underpinning the objective)**	**Spatial scale of operation**	**Cost & feasibility informed, including considerations of method**
Shading by cloud brightening (C3)	Yes (see T6)	Reduced surface irradiance and cooling. Alleviation of bleaching risk via two processes	Regional to Great Barrier Reef-wide (large-scale)	Yes, but developing (see S7)
Warm-adapted corals (EE and EN type Interventions)	Depends on method (symbiont, host, adult, juvenile, larva, spawning slick, see T3).	Gene, cell, coral colony growth and survival, coral populations	Reef site with implications for regions via connectivity (small and medium)	Both are method-dependent, so highly variable. See also NASEM 2019 [30]
Rubble stabilisation (S type interventions)	Yes (see T6)	Increases survival of coral recruits and juveniles that settle on loose rubble	Reef site only (10s to 100s of metres). (small)	Yes, and with good understanding of logistics
Shading by surface films (C6)	Yes (see T12)	Reflects surface light, which reduces bleaching risk	Reef site only (10s to 100s of metres). (small)	Yes, and with good understanding of logistics (see T12)
Mixing/pumping (C1, C2)	Yes, see T12	Mixing or pumping of deeper, cooler water onto shallow coral reef areas	Reef site only (100s of metres to 1km). (Small)	Yes, and with good understanding of logistics (T12)
Prevention of crown-of-thorns starfish outbreaks	(1) decades of research [95] (2) emerging technology (T6)	Coral mortality, preferentially of fast-growing, branching corals	Reef site with implications for regions via connectivity	Costs of conventional methods established, costs for emerging ones developing

The rationale for including crown-of-thorns starfish outbreak prevention in the modelling study and associated economic analyses was that crown-of-thorns starfish are one of the most important causes of coral mortality on the Great Barrier Reef[13,96,97]. Large investments in protecting the Reef under climate change could be at risk unless this mortality factor is managed further. Results of simulations that assume no crown-of-thorns starfish outbreaks must therefore be considered hypothetical until a suitable candidate method can be identified and developed, and associated risks managed. Consequently, we did not produce budget estimates or assessments of logistics for this intervention.

A2.3.3 General modelling approach

We used a suite of models and integrated analyses to predict and characterise likely environmental futures of the Great Barrier Reef, the consequences for coral condition in time and space and their uncertainty, and the likely impacts on economic benefit streams and ecosystem services values. Uncertainty modelled in this study was only a subset of the real uncertainty as we used a limited set of climate projections to force environmental pressures, and did not account for complex drivers and feedbacks in the linked social-ecological system[98]. We modelled uncertainties associated with intervention efficacy by exploring parameter ranges from theory, published data or transparent assumptions. A similar approach was applied to the economic analyses. Table A4 provides a summary of the models used.

Table A4: Summary of models used in this study's supply chain of information from climate projections to cost-benefit analyses. Refer to Appendix C for details on the RRAP report codes listed under references.

Task	Model	Primary variables	Resolution and scale	References
Climate projections	Outputs from Earth system models (HadGEM2-ES) and expected warming trends for the Great Barrier Reef	Sea surface temperature (SST) converted to degree heating weeks	4km x 4km grid cells, Great Barrier Reef-wide	[27,52]
Environmental forcing	eReefs and coupled atmospheric-ocean models	SST, turbidity, chlorophyll, salinity, surface and benthic irradiance, current speed and direction	1km grid for ecological models, down-scaled to 100s of metres for site-scale interventions Great Barrier Reef-wide	https://ereefs.org.au/ereefs T6, T12
Projections of coral condition – large-scale	CoCoNet: Corals and COTS Network model (CSIRO)	Coral and crown-of-thorns starfish growth, recruitment and mortality/survival in response to environment and conventional and new interventions	Individual reefs in a network (via larval connectivity) of 2096 reefs Great Barrier Reef-wide. Models two coral groups: fast and slow-growing	[96] T6
Projections of coral condition – fine-scale	ReefMod: Reef ecosystem model (UQ)	Coral and crown-of-thorns starfish growth, recruitment and mortality/survival in response to environment, species interactions and conventional and new interventions	Gene to coral colony. Used in a network of 156 reefs in the Cairns (Tully–Cooktown) sector of the Great Barrier Reef. Models six coral groups and key fish groups	T6
Economic benefit streams	Millennium Environmental Assessment and CICES framework	Coral condition (based on coral cover and composition) as input into value translations for eight benefits streams	Reef clusters in a spatial grid of 0.5deg x 0.5deg Great Barrier Reef-wide	T10
Cost-benefit analyses	Classic cost-benefit analyses	Outputs (as $ values) from benefit streams and cost projections	Reef-site to Great Barrier Reef-scale	T9

A2.3.4 Key findings – modelling

Key findings of the Great Barrier Reef-wide modelling results and analyses are presented in Figure A3, while findings of the more detailed modelling using ReefMod are summarised in Table A5. The findings can be summarised as follows:

1. Cooling and shading (CS) combined with intensified starfish control (no crown-of-thorns starfish outbreaks, NCO) showed large scope for improved coral condition under RCP 2.6 (Figure A3.F) or reduced loss of coral condition under RCP 8.5 (Figure A3.M).

2. Medium-scale cooling and shading showed the greatest scope to enhance coral condition as a single intervention, especially under RCP 2.6 (Figure A3.B & I).

3. The simulated out-planting of 100 million warm-adapted (+0.4°C added tolerance) corals per year (starting 2031) as a single intervention did not improve relative coral cover under any climate change scenario (Figure A3.A & H).

4. As a single intervention, simulated suppression of crown-of-thorns starfish outbreaks provided intermediate scope and greater impact under RCP 2.6 (Figure A3.C & J).

5. Combining all three interventions (cooling and shading, out-planting of warm-adapted corals and intensified starfish control) produced the strongest impact. Importantly, the combined effect was greater than the summed effect of the individual interventions (T6: Modelling Methods and Findings, Figure 17).

6. All interventions led to an absolute gain in coral cover, but this was strongest when all three interventions were combined (R3: Intervention Analysis and Recommendations, Table 6A). Enhanced corals (EnC) produced only marginal impact as a single intervention for relative coral cover. However, the impact became significant when combined with CS and intensified starfish control, and expressed as change in absolute coral cover (R3: Intervention Analysis and Recommendations Table 6B).

7. Under RCP 2.6, interventions involving cooling and shading combined with either enhanced corals or intensified starfish control (Table A5) would have only 50 percent chance of sustaining coral cover greater than historical levels in the Cairns and Central regions. Specifically, a historical benchmark (target) of 20 percent coral cover was used, as it represents the lower boundary for Reef-wide coral condition before the mass bleaching event in 1998[20] and the average coral condition on the Reef over the past decade[14,91].

8. Under the unmitigated emissions scenario RCP 8.5, these intervention combinations are only likely to sustain high coral cover to the middle of the century, when likelihoods drop to around 15 percent.

9. Lowering the objective to 10 percent coral cover (i.e. aspiring to a lower target for coral cover than historically) increases performance likelihoods by around 20 percent, but mostly under RCP 2.6. Under RCP 8.5, the chance of sustaining more than 10 percent coral cover was only better than 50 percent for cooling and shading interventions and only until 2050 (Table A5).

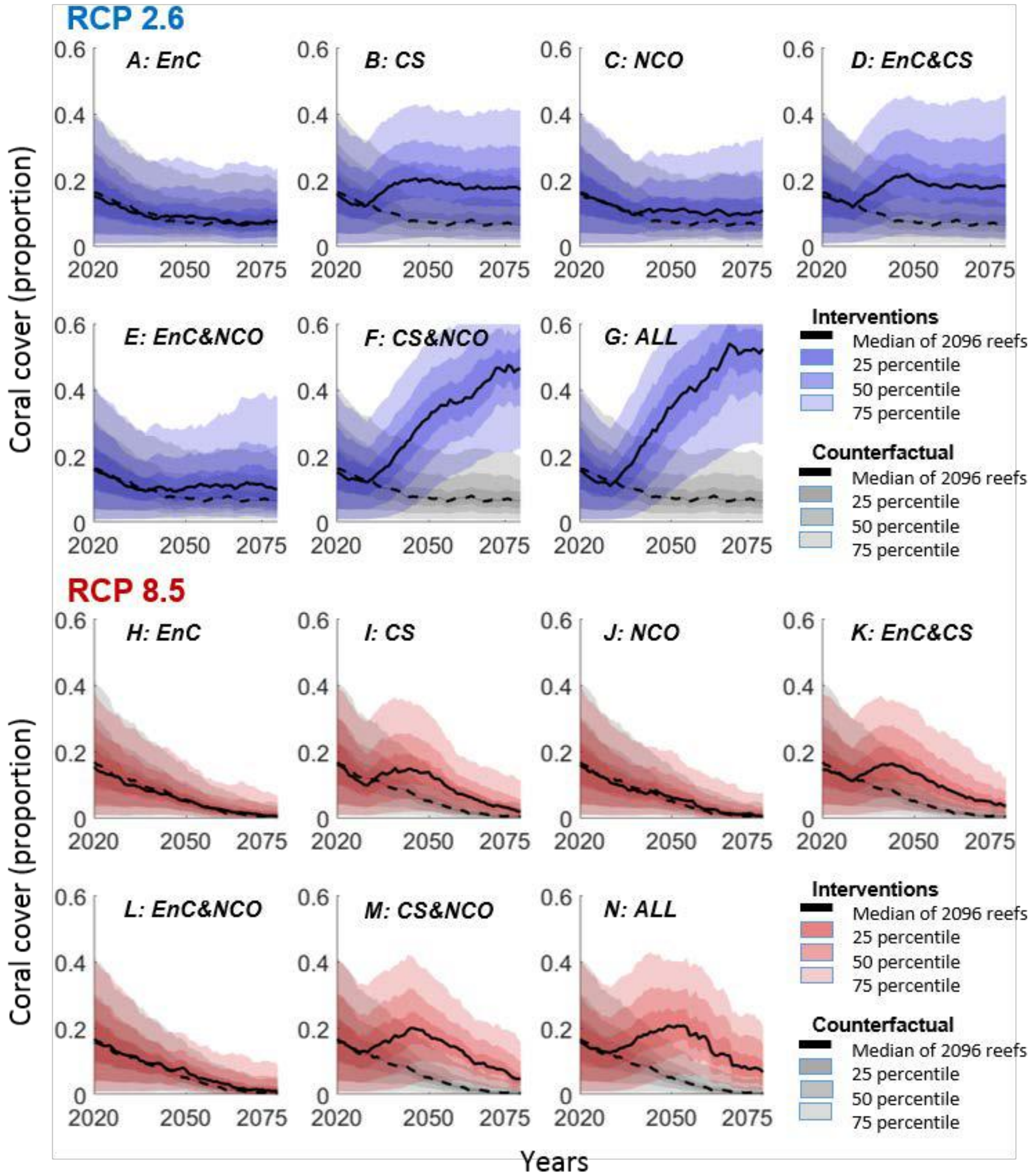


Figure A3: Projections of coral cover for interventions (solid line, blue or red envelopes) and the counterfactual (dashed line, grey envelopes) under RCP 2.6 (A–G) and RCP 8.5 (H–N) based on CoCoNet simulations. Code: EnC: enhanced corals; CS: cooling and shading; NCO: no crown-of-thorns starfish outbreaks. Data are medians and percentile fractions of reefs surrounding the median. See T6: Modelling Methods and Findings for details.

Table A5: Summary of likelihoods (probability) that the objective of sustaining coral cover above 20 percent or above 10 percent could be achieved under the two climate change scenarios and different intervention strategies. Data are conditional likelihoods (as percentages) based on simulated projections of coral cover for the Cairns and Central regions using ReefMod. Code: CS: cooling and shading (0.7°C) region-wide, EnC: enhanced corals, 0.4°C added heat tolerance for 20ha of juvenile corals deployed annually, NCO: no crown-of-thorns starfish outbreaks

				Probability of coral cover exceeding 20 percent		Probability of coral cover exceeding 10 percent	
RCP		**Interventions**		**2050**	**2075**	**2050**	**2075**
2.6		Counterfactual		25	19	37	27
2.6	EnC			34	30	45	43
2.6		NCO		37	44	46	54
2.6			CS	41	47	62	55
2.6	EnC	NCO		41	44	54	56
2.6	EnC		CS	53	46	62	55
2.6		NCO	CS	74	90	80	91
2.6	EnC	NCO	CS	79	91	84	92
8.5		Counterfactual		13	1	21	1
8.5	EnC			13	1	22	1
8.5		NCO		14	1	24	1
8.5			CS	39	2	49	3
8.5	EnC	NCO		16	1	26	2
8.5	EnC		CS	42	3	53	9
8.5		NCO	CS	56	4	67	11
8.5	EnC	NCO	CS	66	15	74	29

Local-scale simulations of rubble stabilisation, surface films and cold-water pumping yielded the following findings:

1. The production of loose coral rubble following wave damage can lead to unconsolidated substrate where juvenile corals are unable to settle or grow for up to five years. Where rubble areas are prominent, efforts to consolidate (stabilise) the rubble may represent an opportunity to enhance coral recruitment.

2. Simulations of rubble stabilisation using a high-resolution model (ReefMod, UQ) indicated this intervention would only have efficacy under RCP 2.6 and generally only where there will be sufficient cover of branching corals to generate rubble in the first place.

3. Under RCP 8.5, rubble stabilisation had no discernible effect on coral cover under any assumption of adaptation or deployment strategy. Reefs in the Cairns sector maintained such low levels of coral cover that disturbances did not create enough rubble to affect juvenile coral survival.

4. Simulations of surface films dispersed on individual coral reefs during warm summer weeks showed only marginal efficacy. Detailed studies of hydrodynamics and reef bathymetries (measurement of ocean depth) reveal the method may have efficacy on a small subset of reefs in the Great Barrier Reef (**T12: Cool Water Injection**).

5. Cold-water pumping and mixing studies showed these interventions would only have efficacy and potentially show cost-efficiency on reefs that met a narrow set of criteria: high-value reef (values can be ecological, economic, social or cultural), proximity to cold (deep) water, shallow receiving reef area, predictable current flow direction and relatively long water residence times (see **T12: Cool Water Injection** for further insight).

A2.3.5 Key findings – cost-benefit analyses

Key findings regarding the cost-benefit analysis are presented in Section 7 of this document and are a synthesis of **RRAP reports, T9: Cost Benefit Analysis, T10: Benefit Streams and R3: Intervention Analysis and Recommendations**.

A2.3.6 Key findings – screening of interventions

The concept feasibility study assessed a suite of 40 interventions (covering seven types of functional objective) applied at four different scales from a total of 160 initial options. Initial screening of the potential for success, and limitations of each option, was carried out to identify a subset of interventions for consideration in the R&D program.

To guide the screening of interventions, the following principle of combined likelihoods (conditional probabilities) was used:

Likelihood of intervention success =

Likelihood of passing the R&D program, combined with:

Likelihood deployment is approved given risks (including costs), and

Likelihood intervention can deliver net benefit at scale, given climate future, and

Likelihood intervention is ready for deployment before reef decline.

Based on the modelling results discussed above (which demonstrated the synergies achieved by multiple interventions acting together at different scales), the R&D program would analyse the performance of intervention combinations rather than individual interventions.

Applying the combined likelihood principle to a selection of interventions taken from Table A6, the following conclusions can be drawn:

C1–2. Cooling by mixing and pumping feasible only at small-scale, able to protect only some reef sites and would require disproportionally large investment (see **T12: Cool Water Injection**). While risks and duration are manageable, these interventions are not recommended for the R&D program based on their cost-benefit ratio and small scale of impact.

C3. Shading by cloud brightening has the potential to show efficacy at the largest scale assessed here, as demonstrated by the modelling study. However, the risk related to delivery is high, in part because of (a) the technical challenge of producing a fully operational system, (b) precaution surrounding solar radiation management interventions and (c) high operational costs. Further, the time from the start of the R&D until full system operation could be eight to 10 years. However, given cloud brightening is one of a few interventions with the potential to operate at the whole-of-Great-Barrier-Reef-scale, and its potential to produce around $4.5B in net benefits (when combined with enhanced corals), cloud brightening should be retained as an option in the R&D program.

C5. Shading by misting (using seawater) may provide an alternative to cloud brightening, operating at small- to medium-scales, with lower risk (real and perceived). Note that costs are absorbed into the risk assessment in Table A4. Thus, medium risk levels for misting also indicate lower cost considerations than for cloud brightening. Given the risk that cloud brightening could fail the combined likelihood test (above) by not achieving approval for deployment based on precaution or costs, we recommend misting be retained in the R&D program.

C11. Cooling by high-altitude aerosols is a global geoengineering intervention with significant risks[99,100] and beyond the scope of RRAP. The option was eliminated based on high risk.

S1–4. Stabilisation interventions include a range of methods to provide stable substrate for coral recruitment. All operate at the small- to medium-scales and the scale of impact is likely limited to the scale of operation. Stabilisation of loose rubble by mesh or removal has a low- to medium-risk (including cost) and could be fully operational within eight years. Implementation and approvals risks are likely to be low and early implementation may support the efficacy of other interventions. Stabilisation interventions may be an early opportunity to support resilience at priority reefs.

ER1–9. Coral seeding nine interventions for the seeding of coral larvae were considered. Their scales range from individual reef site to the entire Great Barrier Reef; their risks range from low to high and their time until full deployment is typically long (Table A4). The highly variable range of scale and risks (including costs) and potential scope of these interventions (via synergies with other interventions, see modelling results above) suggest they should be subject to systematic and detailed analyses before further prioritisation.

EE3–5. Corals bred from natural stock in aquaculture are potentially high-risk/high-reward interventions that, if delivery mechanisms and logistics could be solved cost-effectively, could produce good outcomes for the Great Barrier Reef in the long term. Opportunities lie in solving how enhanced climate tolerance can be spread effectively in space and time, leading to scales of impact larger than scales of operation. Although the modelling study accounted for connectivity, improved spatial optimisation strategies for deployment could enhance outcomes, especially if combined with accompanying interventions including spatially-strategic crown-of-thorns starfish control, cooling and shading, and stabilisation.

EN1–3. Corals bred from engineered stock in aquaculture have the highest risk, but potentially also the highest reward if the world continues on the RCP 8.5 climate trajectory and the capacity for adaptation of enhanced natural coral stock is eventually exceeded. An immediate barrier for these interventions is the level of precaution surrounding synthetic biology or gene editing[86,101,102]. Another is the risk that effective genetic solutions for enhanced thermal tolerance and biological/ecological performance under climate change cannot be found within the closing window of opportunity. While the time needed for safe development and deployment of these interventions is long (more than 10 years), investing in this reserve bank of options could become an insurance policy for the Great Barrier Reef in the long term.

On this basis, as shown in Table A6, eight of the interventions were eliminated at all scales (C1, C2, C8, C10, C11, ER1, ER5 and ER6). A total of 43 interventions (representing all seven functional objectives) were considered worthy of progressing to the R&D program for further assessment, across a variety of scales. All micro-scale interventions (applied to a few square metres of reef) were deemed ineffective at achieving the RRAP mission, and thus were eliminated from further consideration. As a result, of the 160 options considered (40 interventions at four scales), only 43 are recommended for consideration in the R&D program.

It should also be noted that the success of an intervention at the indicated scale could open the possibility of it being applied at a smaller scale. The R&D program would need to be conducted flexibly and adaptively to reflect findings as they emerge.

Table A6: Summary of interventions assessed for potential to be applied at four scales, as well as annual cost, R&D duration, development risk and total duration against an assumed deployment scale.

KEY	Scales	Micro	Represents current restoration method levels (small areas in limited sites)
		Small	A scale that could retain/protect tourism and other key sites if required (50 tourism-scale sites)
		Medium	A scale that could support several clusters of key reefs to support ecosystem function in key areas (~50 reefs)
		Large	A scale that would target retaining broader Great Barrier Reef ecosystem function and its core economic and social values (200+ reefs)
	Annual cost	Estimated deployment costs for the assumed deployment scale. These costs represent the mid-point of each estimated cost range.	
	R&D duration	Estimated R&D duration to achieve a deployment investment-ready status for the intervention at the target deployment scale.	
	Development risk	Low, medium or high, based on an assessment of technical delivery and regulatory approvals risk.	
	Total development duration	Number of years from R&D commencement to field deployment at the target scale. This factors the time from R&D completion to contract services, and establishing the required infrastructure and operational systems. Generally, a sequential approach is assumed. In some instances, timeframes could be reduced by commencing the deployment procurement process in parallel with completing R&D. The risk would be increased; however, the benefits potentially realised earlier. It is presented as two numbers: the first represents the time when deployment could commence, the second when the estimated annual deployment rates would be at the target scale.	

Estimated feasible scale	Possible feasible scale	Infeasible scale	Eliminated based on risk

Code	Intervention Title	Potential Deployment Scales				Assumed Deployment Scale	These criteria are all assessed against the assumed deployment scale				Recom-mended
		Micro	Small	Med	Large		Annual Cost ($M)	R&D Duration	Development Risk	Total Development Duration	
C1	Cooling by mixing					Eliminated					no
C2	Cooling by pumping					Eliminated					no
C3	Shading by cloud brightening					Large	158	5-10	H	8-10	yes
C4	Shading by fogging					Medium	50	5-10	M	8-10	yes
C5	Shading by misting					Medium	25	5	M	6-8	yes
C6	Shading by surface films					Small	30	5	M	7-9	yes
C7	Shading by microbubbles					Small	30	5	M	7-9	yes
C8	Shading by structure					Eliminated					
C9	Shading by algae					Micro (small?)	Not yet assessed				yes
C10	Ocean fertilisation					Eliminated					no
C11	Cooling by high altitude aerosols					Eliminated					no
S1	Stabilisation by natural bonding					Medium	Not yet assessed	5-10	L	10-12	yes
S2	Stabilisation by chemical bonding					Small	26	5	L	8-10	yes
S3	Stabilisation by mesh					Small	26	5	L	7-8	yes
S4	Stabilisation by removal					Small (Medium?)	Not yet assessed	5	L	7-8	yes
S5	Structure by consolidation					Small	60	5	L	7-8	yes
S6	Structure by 3D frames					Small	120	5	M	7-8	yes
S7	Structure by concrete shapes					Small	120	5-10	M	7-8	yes
S8	Structure by massive corals					Small	240	5-10	M	9-11	yes
S9	Structure by 3D printed shapes					Micro	Not yet assessed	5-10	M	13-15	yes
ER1	Coral seeding by *in situ* movement					Eliminated					no
ER2	Coral seeding by assisted larval movement					Small (Medium?)	60	5	M	7-10	yes
ER3	Coral seeding by larval slick translocation					Small (Medium?)	90	5-10	M	8-11	yes

ER4	Coral seeding by larval slicks settled on devices					Medium (Large?)	150	5-10	H	9-15	yes
ER5	Coral seeding by *in situ* harvested fragments					Eliminated					no
ER6	Coral seeding by nursery aquaculture					Eliminated					no
ER7	Coral seeding by semi-automated aquaculture					Small	30	5	L	4-6	yes
ER8	Coral seeding by automated aquaculture					Medium	150	5-10	M	9-15	yes
ER9	Coral seeding by larval/polyp aquaculture					Large	300	5-10	H	9-19	yes
B1	(Bio)-control of macroalgae					Small	Not yet assessed	Unknown	M		yes
B2	Biocontrol of species with negative impacts					Small	Not yet assessed	Unknown	H		yes
F1	Application of field treatments to enhance coral survival					Medium	Not yet assessed	Unknown	H		yes
EE1	Seeding enhanced corals from existing stock by larval slick translocation					Small (Medium?)	90	5-10	H	8-11	yes
EE2	Seeding enhanced corals from existing stock by settlement of larval slicks on devices					Medium (Large?)	150	5-10	H	10-15	yes
EE3	Seeding enhanced corals bred from existing stock with semi-automated aquaculture					Small	30	5-10	M	8-10	yes
EE4	Seeding enhanced corals bred from existing stock with automated aquaculture					Medium	150	5-10	M	9-15	yes
EE5	Seeding enhanced corals bred from existing stock with larval/polyp aquaculture					Large	300	10	H	9-19	yes
EN1	Seeding enhanced corals bred from engineered stock with semi-automated aquaculture					Small	30	10+	H+	11-11	yes
EN2	Seeding enhanced corals bred from engineered stock with automated aquaculture					Medium	150	10+	H+	11-15	yes
EN3	Seeding enhanced corals bred from engineered stock with larval/polyp aquaculture					Large	300	10+	H+	11-19	yes

A2.4 RESEARCH AND DEVELOPMENT PROGRAM

A detailed description of the rationale, objectives and strategies underpinning each of the sub-programs is provided in **R4: Research and Development Program**. The purpose of this section is to provide a synthesis of that report in support of Section 8, following the structure of the R&D program presented in Figure 10.

A.2.4.1 Cross-cutting sub-programs supporting R&D

Engagement and Regulatory Frameworks

The viability of interventions to help preserve the Great Barrier Reef will depend, to a large extent, on the social acceptability of these interventions. This, in turn, hinges on public trust in the implementing organisations and meaningful participation of stakeholders and rights holders. At the same time, most RRAP interventions challenge the existing regulatory system in an unprecedented fashion.

Accordingly, the engagement component of this sub-program would conduct a range of activities involving Traditional Owners and stakeholders that would lead to interventions and decision-making that were socially and culturally-responsible and legitimate to stakeholders, rights-holders, managers and the public. At the same time, the regulatory component of this sub-program would work with regulatory authorities, reef scientists and relevant stakeholders to achieve a fit-for-purpose regulatory environment, and policy best practice for assessing reef restoration and adaptation activities, including the range of risks and impacts associated with novel reef restoration and adaptation interventions.

Decision Support

The Decision Support Sub-Program represents a dedicated and service-focused team that would develop and use a decision-support system to guide effective decision-making at strategic, tactical and technical levels. This system would integrate with the Reef 2050 Plan and the RIMReP. Key elements of the Decision Support R&D Sub-Program include:

- Inform complex investment choices to ensure RRAP will be well-positioned to deliver an effective R&D program and facilitate processes that prioritise the development of the interventions with the highest likelihood of delivering positive outcomes for the Reef.
- Be fully integrated into the RRAP governance framework, bio-physical modelling, ecological responses, regulatory frameworks, and social and economic value assessments and the intervention R&D programs. All decision analyses will include consideration of the uncertainties arising from all information sources (e.g. via modelling, ecological intelligence, economics, Traditional Owner, regulatory or stakeholder engagement).
- Inform RRAP trade-off analyses at all program levels, including among objectives, values, and scales. This open and transparent decision-support process will be used during intervention pilot trials and in the operational deployment phase.

Modelling

Coral reefs are complex ecosystems influenced by a diversity of processes that act at unique spatial and temporal scales. Models are required to handle this complexity, identify the expected benefits of restoration and support implementation strategies (what, where, when). The RRAP Concept Feasibility Study fostered an intense period of modelling and a new era of cooperation among model providers, as well as collaboration with empiricists. Nonetheless, models would need to evolve to cope with the emerging development of new restoration technologies, fill critical gaps that have a direct effect on decision-making and underpin emerging decision support.

The recommended modelling program is highly integrative and would work closely with each component of RRAP and end-users. Key strategic principles include:

- Consult closely with the diversity of users (from RRAP technical personnel to Reef managers) to identify needs and ensure that the model frameworks will be chosen accordingly.
- Use multiple models to respond to different needs and obtain an ensemble of projections that increase the robustness of results.
- Create a strong link between ecosystem state and its functioning for ecosystem services (values), with a specific focus on clarifying how management (including restoration and adaptation) could deliver greater biodiversity, fisheries and coastal protection benefits.

Links between the modelling and how it supports the interventions R&D is outlined in Table A7.

Ecological Intelligence and Risk

RRAP aims to identify the circumstances under which restoration and prevention are warranted and helpful (i.e. where and when). There are critical knowledge gaps that curtail our ability to do this, and uncertainties limit our ability to provide compelling counterfactuals for Reef projections. Where there will always be knowledge gaps, the focus will be on those with a direct and important bearing on future decision-making. This is what is meant by the provision of 'ecological intelligence'.

The second goal of RRAP is to create 'deployment-ready' interventions that have appropriate social and regulatory license. Several real and perceived unintended consequences of restoration have already been identified through the stakeholder engagement activities of the RRAP Concept Feasibility Study. Such issues need to be explored in parallel to intervention development to ensure RRAP recommendations have considered the safety of techniques, and resolved regulatory and stakeholder concerns. Table A7 provides a summary of the objectives and approaches being taken under the Ecological Intelligence and Risk Sub-Program and how this sub-program underpins the intervention R&D sub-programs.

Table A7: The R&D outcomes targeted by the Modelling and Ecological Intelligence and Risk sub-programs, in combination with relevant intervention-specific programs, to enable improved intervention benefits, risks and costs assessments. These outcomes, combined with the intervention-specific R&D outcomes, would inform ongoing R&D investment decisions and the availability of interventions for deployment.

Functional Objective Type		R&D Objectives
#	**Description**	
1.	Cooling and shading	• Refine and quantify the extent of cooling and/or shading required to reduce forecast bleaching probability • Quantify impacts on heat tolerance adaptation rates (noting it could be neutral, improve or reduce rates) • Quantify other impacts on ecological and physiological processes
2.	Reef structures and stabilisation	• Ability to forecast future rubble formation and stabilisation rates and assess the future needs and benefits of stabilising rubble and creating a 3D structure • Quantify functional performance requirements (for example bond strength for methods that stabilise by bonding the rubble together) to stabilise rubble, and the areas/patterns required
3.	Reproduction and recruitment	• Improve forecasting of future larval supply and recruitment rates • Quantify larval connectivity to understand where interventions would have the greatest benefits • Determine quantities required to have an impact under different scenarios
4.	(Bio)-control	• Assess likely future needs and benefits of invasive species removal and macroalgal management (in addition to crown-of-thorns starfish management)
5.	Field treatments	• Quantify the number of corals likely to respond to treatments applied before, during and after a bleaching event • Assess the potential benefits of treatments and determine if treatment-based interventions had sufficient potential to justify an R&D program to develop deployment systems

6.	Enhanced corals from existing stock	• Improve quantification of natural rates of adaptation and the distribution and abundance of heat-tolerant corals • Assess the extent of performance trade-offs of enhanced corals in receiving populations • Assess the level of enhancement required, numbers, receiving conditions and deployment distributions needed for methods to have an impact
7.	Enhanced corals from engineering stock	• Assess the extent of performance trade-offs of enhanced corals in receiving populations • Assess the level of enhancement required, numbers, receiving conditions and deployment distributions needed for methods to have an impact

A.2.4.2 Intervention R&D sub-programs

As shown in Figure 9, the RRAP R&D Program comprises six intervention R&D sub-programs: Cooling and Shading; Rubble Stabilisation; Moving Corals; Enhanced Corals, Treatments and Aquaculture; Early Phase Intervention Assessments and Cryopreserving Biodiversity. An outline of the sequence of activities to assess and develop each intervention, including key decision points to continue or halt investment, is provided in Table A8.

Table A8: Mapping interventions to R&D sub-programs and outlining the sequence of activities to assess and develop each intervention, including key decision points to continue or halt investment.

R&D sub-program	Interventions included		Outline of R&D approach

Cooling and Shading	C3	Shading by cloud brightening	• Simultaneous program to
			  ○ develop performance criteria
			  ○ undertake engineering development and testing of suitable hardware and deployment options
			  ○ field-test to gather data on efficacy/impact (progressive small-scale prototype to larger-scale field evaluations)
			  ○ model development and atmospheric characterisation of the Great Barrier Reef to assess the risk of unintended impacts and improve predictions of efficacy
			• Refine system design and assessments of benefits, risk and cost
			• Ongoing investment and focus subject to the above outcomes

	C4	Shading by fogging	
	C5	Shading by misting	• Rapid assessment of benefits, risks, social acceptability and regulatory approval requirements • Then either eliminate or field-test and, subject to outcomes, available for use
	C6	Shading by surface films	• Trials to assess performance under field conditions • R&D to determine if product volumes per km^2 can be reduced • Test deployment methods (vessels and planes) • Based on outcomes, either eliminate or available for deployment
	C7	Shading by microbubbles	• Desktop study to assess suitability and feasibility for use on the Reef • Field trials to assess performance

			• Ongoing R&D, subject to desktop and field-trial outcomes
Rubble Stabilisation	S1	Stabilisation by natural bonding	• Initial focus on improving rubble formation/stabilisation forecasts and assessing the value of these interventions • If value confirmed, R&D continues • Using the information derived in the value assessment, compare available deployment methods and deployment designs against functional requirements and select the most aligned for development • Test and develop the selected delivery methods (four assumed in the budget).
	S2	Stabilisation by chemical bonding	
	S3	Stabilisation by mesh	
	S4	Stabilisation by removal	
	S5	Structure by consolidation	
	S6	Structure by 3D frames	
	S7	Structure by concrete shapes	
	S8	Structure by massive corals	
	S9	Structure by 3D printed shapes	
Moving Corals	ER2	Coral seeding by larval slick movement	• Test larval release methods and quantify the number of new corals created as a function of receiving conditions • If rates sufficiently high, R&D continues and complete remaining areas of method development (larval slick capture, transport and release)
	ER3	Coral seeding by larval slick translocation	
	ER4	Coral seeding by larval slicks settled on devices	• On hold pending findings from aquaculture and larval transport/translocation R&D. A decision to progress (or not) to occur around year three
	EE1	Seeding enhanced corals from existing stock by larval slick translocation	• Test larval release methods and quantify the number of new corals created as a function of receiving conditions • If rates sufficiently high, R&D continues and complete remaining areas of method development (larval slick capture, transport and release)
	EE2	Seeding enhanced corals from existing stock by the settlement of larval slicks on devices	• On hold pending findings from aquaculture and larval transport/translocation R&D. A decision to progress (or not) to occur around year three
Enhanced Corals, Treatments and Aquaculture	ER7	Coral seeding by semi-automated aquaculture	• Initial focus on four areas: o developing enhanced corals and treatments to confirm the viability of approaches with existing stock, and the extent of performance trade-offs o sexual and asexual production methods o methods to breed target coral species and enhance post-deployment survival o testing viability of innovations in the larval/polyp-based aquaculture method • Depending on the above outcomes, adjust the program to deliver residual R&D for those interventions still viable (noting that of the remaining viable aquaculture delivery methods, only the largest-scale method would be developed) • Enhanced corals from engineered stock (using synthetic biology and genetic modification techniques) may not take longer to develop than methods from existing stock, but they have more complex regulatory requirements and will thus run on a separate timeline
	ER8	Coral seeding by automated aquaculture	
	ER9	Coral seeding by larval/polyp aquaculture	
	EE3	Seeding enhanced corals bred from existing stock with semi-automated aquaculture	
	EE4	Seeding enhanced corals bred from existing stock with automated aquaculture	
	EE5	Seeding enhanced corals bred from existing stock with larval/polyp aquaculture	
	EN1	Seeding enhanced corals bred from engineered stock with semi-automated aquaculture	
	EN2	Seeding enhanced corals bred from engineered stock with automated aquaculture	
	EN3	Seeding enhanced corals bred from engineered stock with larval/polyp aquaculture	
Early Phase investigations	B1	(Bio)-control of macroalgae	• Desktop studies to better quantify potential benefits • Progress to R&D if studies indicate value • Possibly run a competition/prize to generate field treatment delivery method ideas, as
	B2	Biocontrol of species with negative impacts	
	F1	Application of field treatments to enhance coral survival	

	C9	Shading by algae	this is the primary constraint for this intervention

A2.4.3 Cross-cutting engineering R&D sub-programs

Systems Engineering and Integrated Logistics Sub-Program

The Systems Engineering and Integrated Logistics Sub-Program will provide several core functions:

- **Systems engineering:** Assessing the broader aspects of an intervention delivery method and progressively add detail (via engineering and other studies). This would reduce risk and optimise the production and development concept designs. It would operate as a specialist service to the specific intervention R&D programs, allowing knowledge to be shared and factored into other designs.
- **Integrated logistics:** Exploring infrastructure sharing options that reduce costs and risks and increase productivity.
- **Infrastructure distribution:** Exploring centralised vs decentralised infrastructure options and how best to mix factors such as local community engagement and employment with the commercial imperative for mass manufacturing cost efficiencies.
- **Use optimisation:** Optimising the sharing and spatial and temporal use of deployment infrastructure would be a significant driver of cost minimisation. This needs to be considered early in the development process, as it would influence investment business cases, and would need to be operational with the roll-out of interventions, if and when this occurs.

Automation

Even small-scale interventions on the Great Barrier Reef are major undertakings due to the massive scale of the system. Automation and mass production would be essential to deliver interventions at the scale required for a noticeable impact. For example, in assessing aquaculture delivery methods (refer **T5: Future Deployment Scenarios and Costing**), using mass production and automation delivered at least an order of magnitude cost reduction over manual systems. The Automation Sub-Program aims to develop technology that could substantially increase the efficacy and productivity of the RRAP interventions developed.

Most terrestrial automation requirements could be procured from existing automation providers and R&D would not be required. Underwater and offshore marine automation is a niche area and development and testing would be required. Two critical path projects have been identified for immediate progression:

- Deployment automation when seeding corals
- Pre- and post-deployment intervention monitoring (aligned with RIMReP).

Other areas have been broadly identified; however, R&D would only commence once engineering concept designs had been refined and functional requirements documented.

APPENDIX B: GOVERNANCE AND INVESTMENT REQUIREMENTS

B1 GOVERNANCE STRUCTURE

Figure B1 provides a summary of the proposed governance structure for the RRAP R&D Program unincorporated joint venture. Details of each element of the structure are provided below.

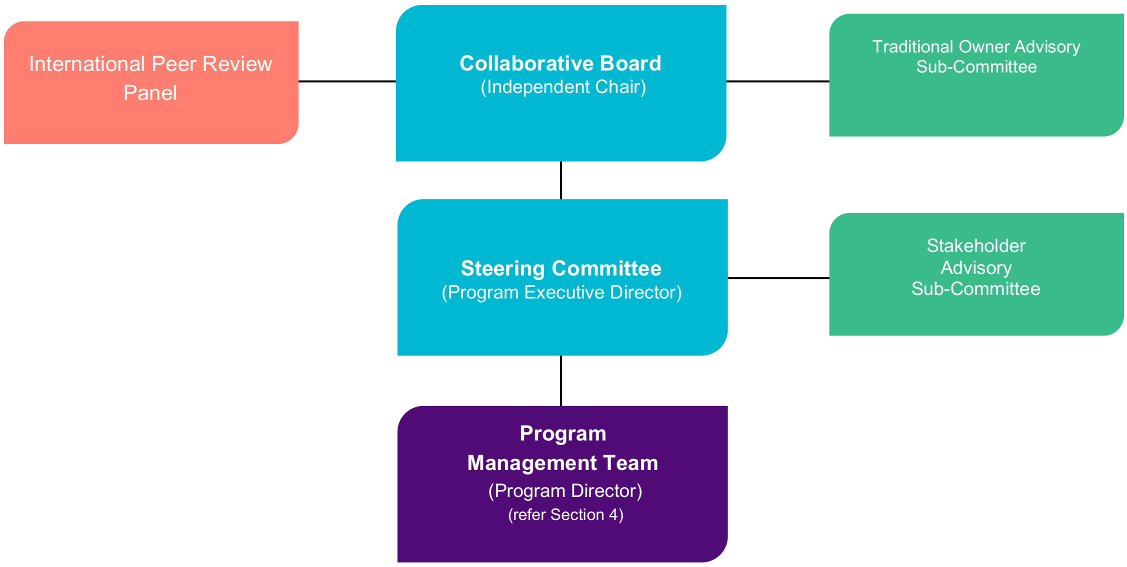


Figure B1: Proposed RRAP governance arrangements.

B1.1 UNINCORPORATED JOINT VENTURE BOARD

The independently-chaired joint venture board would be the ultimate decision-making body for the RRAP R&D Program, noting that for activities funded via the Reef Trust Partnership, the Great Barrier Reef Foundation Board makes decisions about the appropriation of these funds, but will do so informed by the advice of the collaborative board. In addition to ensuring focused program delivery, the collaborative board would manage issues including the societal mandate for the program, maintenance and growth of the consortium, changing stakeholder expectations and the required resourcing for the scale-up of demonstration sites for interventions.

The board would comprise of an independent chair, senior executives from the six partner organisations, at least two independent members (selected on a skills basis), a Traditional Owner representative and three observers from the Great Barrier Reef Marine Park Authority, the Department of Industry Innovation and Science and the Department of Environment and Energy respectively. AIMS and GBRF would be permanent members of the collaborative board.

Because of the Great Barrier Reef Marine Park Authority's regulatory obligations under the *Great Barrier Reef Marine Park Act*, its representative would have a position of non-voting advisor on the board.

B1.2 INTERNATIONAL PEER REVIEW PANEL

The collaborative board would ensure all aspects of the R&D program—including plans, results, deliverables and key strategic decisions—were scrutinised and peer reviewed by a panel of independent international scientific experts at an appropriate level of detail. The panel would consist of core members chosen exclusively from international ranks. Their advice would be received at board level and referred to the steering committee for consideration. Given the Great Barrier Reef focus, the relatively limited pool of key senior specialists in Australia and the involvement of most Australian institutions with capacity in reef-related science and engineering in RRAP, this approach would help limit conflict-of-interest and heighten credibility. The panel could call upon other experts, as required, to ensure the highest level of peer review.

B1.3 TRADITIONAL OWNER ADVISORY SUB-COMMITTEE

The board would be directly advised by a Traditional Owner advisory sub-committee composed of representatives from communities along the length of the Reef. The importance placed on this reflects the unique role of Traditional Owners in helping to develop feasible and socially acceptable Reef intervention strategies.

B1.4 STEERING COMMITTEE

The steering committee, led and chaired by the program executive director, would be the senior technical decision-making body of the venture, responsible for executing the board's strategic direction and charting the critical path to accomplish the mission.

The steering committee would be responsible for overall program formulation, prioritising the intervention options actively pursued, ensuring an adaptive approach was applied through the appropriate use of stage gates (critical decision points), resource allocation among partner organisations and managing the ongoing working relationships between R&D partners. If required it could form sub-structures and/or engage independent specialists to provide technical advice.

The steering committee would consist of key personnel from core partner organisations and associate organisations involved in program delivery. It would receive advice and plans from the program management team and play the primary role in managing trade-offs and conflicts between different options of technical approaches and different levels of impact, and in prioritising resources to the portfolio of approaches. The program executive director role will be vital to the success of the program as an interface between the collaborative board, the partners and the governance and program delivery structures.

The program executive director would chair the steering committee. A comprehensive international search for a candidate who could bring the required skills and culture is recommended.

Reporting to the chair and collaborative board, the executive director would lead this complex research and development consortium and provide strategic oversight of the program in accordance with the RRAP guiding principles. The role would work closely with the managing entity and other partners in the development and implementation of the R&D program.

The executive director would ensure alignment between the UJV partners and funders, and with Traditional Owners and key stakeholders. The executive director would have a responsibility to maintain strong productive relationships internally (board, steering committee, program management team, partner representatives) and externally (government representatives, funders, Reef 2050 and international committees, strategic collaborators and partners).

A comprehensive international search for a candidate who could bring the required skills and culture is recommended.

B1.5 MANAGEMENT TEAM

The program management team, led by the program director, would be responsible for day-to-day management and delivery of the R&D effort (Figure B2). The program director would report directly to the executive director and steering committee and support the executive director in fulfilling their responsibilities and reporting to the collaborative board. While the executive director would be ultimately responsible for the overarching program budget, milestones, risk management and key strategies, the program director would be responsible for all day-to-day development and operational program management activities, including: development of R&D program recommendations, budget management, scheduling, program delivery oversight, program integration and sequencing, quality control, planning and execution of on-Reef pilot trials and use of decision-making protocol to sequence and plan R&D activities.

This is a large R&D program and a team would be established to lead and manage it. The specific nature and design of the program place additional emphasis on several areas:

- **Project management** including contracting, project scheduling, health safety and field work logistics, communications and reporting.
- **Technical leadership:** Each of the R&D sub-program areas outlined in **R4: Research and Development Program** would have a nominated leader and the cross-cutting sub-programs small steering committees. To support these teams, and ensure integrated planning across the teams, a small R&D leadership and coordination team would be established within the program management team.
- **Systems engineering:** A key facet of the R&D program is to develop and progressively refine engineering concept designs for each intervention. These would be used to focus the R&D activities and other innovation processes, to progressively develop and test all aspects required for an operational intervention. The designs would also be central to planning for future deployment, and the integration of production and deployment infrastructure between interventions (critical if costs are to be managed). To facilitate these processes, a small specialist team with these skills has been incorporated into the structure.
- **Commercial transfer:** The R&D program would need to maintain focus on how the interventions would ultimately be implemented. Aspects such as deployment business models, methods of commercial transfer to prospective industry providers and community engagement all impact on the specific outputs required from the R&D program. Capability to participate in planning future implementation, and providing guidance in the R&D program, has been factored into the program management structure.

B2 DETAILS OF INVESTMENT REQUIREMENTS

Outlines of investment requirements to deliver the proposed R&D program as summarised in Section 8.2 were developed for each sub-program and are described in **R4: Research and Development Program**. More detailed R&D plans for each sub-program are being prepared which include their rationale, the R&D gaps and priorities being targeted, their sequencing and intended outcomes.

The purpose of this section is to provide an overview of the costing principles and assumptions underpinning the budget presented in Section 8.2. These can be grouped into a set of overarching, generic principles and assumptions, and additional sub-program-specific principles and assumptions, presented in Table B1 below.

B2.1 GENERAL PRINCIPLES AND ASSUMPTIONS

The intervention sub-program budgets allow all targeted interventions to be assessed initially but assumes only a subset would be progressed to completion. The R&D program would use strategies to rapidly reduce the number of delivery methods, and hence interventions, being progressed. Investment decisions would be informed by the decision-support system, to be developed as one of the cross-cutting support R&D sub-programs (refer to Figure 10).

To develop estimates of investment requirements, multi-institutional teams of experts undertook a process of defining goals, strategies and required sub-program investment areas. In total, approximately 150 investment areas were identified across the sub-programs. R&D tasks to progress each investment area were defined and budget requirements determined. These included labour, infrastructure and services (e.g. Sea Simulator; vessel time), and research and management operating costs.

Standard unit costing rates were used for labour to ensure consistent costing across the sub-programs, and to allow the R&D sub-programs to be ‘organisationally agnostic’. Costings for labour are based on the full cost, including organisational overheads. No attempts were made to allocate the R&D to organisations or individuals this would be the task of the proposed governance and program management framework. **R4: Research and Development Program** provides details of the standard costing rates used, along with assumptions on indexation and overheads.

The R&D program includes extensive field testing and monitoring. These costs were budgeted in the relevant R&D sub-programs, noting it would be a centrally-coordinated, integrated design and delivery. To minimise cost and maximise value, the budget assumed a set of standard testing and monitoring sites would be identified and used: inshore, offshore, north, mid and south.

B2.2 SUB-PROGRAM SPECIFIC ASSUMPTIONS

To help bound the budgets of the intervention sub-programs, additional assumptions were made as to which (or how many) of the underpinning delivery methods (and by default interventions) would be progressed. These are briefly outlined in Table B1. This has directly impacted the investment requirement estimates outlined in Table 2. In addition, Table B2 provides a summary of costing assumptions made for the other RRAP sub-programs.

Table B1: Key sub-program budget assumptions.

R&D Sub-Program	Budget Assumptions
Engagement and Regulatory	The budget assumes several small facilitation teams, funds to support the participation of third parties in engagement and participatory activities and experts to undertake ongoing assessment and development activities.
Decision Support	A small team initially focused on supporting R&D prioritisation, progressively moving to supporting decisions to undertake large-scale pilot trials and ultimately decisions to invest in deployment.
Modelling	The budget assumes several teams of modellers developing an integrated suite of models, along with the governance arrangements to ensure the models deliver the required outputs to the decision support and intervention R&D sub-program areas.
Ecological Intelligence and Risk	The budget is based on a combined field and experimental program designed to address key knowledge gaps. It includes an ongoing field monitoring program that would be leveraged to support monitoring intervention field trials.
Cooling and Shading	The program has a cluster of small-scale interventions assumed to be tested and either proven and available for deployment investment or eliminated. The interventions with longer R&D durations were assumed to pass through stage gates and continue being developed.
Rubble Stabilisation	This sub-program initially focuses on assessing the need for and potential functional benefit of rubble stabilisation, with a stage gate at the end of year two. The budget assumes benefits were confirmed and the program would continue. The budget further assumes that, based on the improved knowledge generated during the review, the current nine interventions were reduced to the four most beneficial, and only these would be developed and tested.
Moving Corals	The budget initially funds two interventions and assumes a third would be progressed from year four, based on the integration of larval slick and aquaculture delivery methods.
Enhanced Corals, Treatments and Aquaculture	R&D to test and develop enhanced corals and treatments is assumed to pass through stage gates and progress to completion. Of the three nominated aquaculture delivery methods, only one was budgeted to completion. The sub-program initially focuses on testing specific technologies and methods to assess feasibility and, based on findings, one of the three methods (or a variant) would be selected and progressed.
Early Phase Intervention Assessments	This sub-program funds desktop studies for two specific intervention areas: field treatments and biocontrol. If these studies recommend moving one or both into an R&D program, then funding would need to be prioritised from other program areas, or additional funding sourced.
Cryopreserving Biodiversity	The budget assumes a coral cryopreservation program would be established in collaboration with the Smithsonian Institution and the Taronga Conservation Society. It allows for the development of techniques, assessment of how cryopreservation could improve interventions, and biobanking high-value coral reef biodiversity.
Systems Engineering, Integrated Logistics	The budget assumes a small dedicated team, plus allowances for industry contractors to undertake systems engineering, integrated logistics, infrastructure distribution and use-optimisation activities.
Automation	The budget allows for two fast-track areas of automation R&D in years one to three, then factors three broader programs of automation R&D commencing in year four. The three broad areas of need have been identified, but commencement delayed for other R&D areas to deliver more precise functional requirements.
International	A small allowance to establish an Australian partnership with the Coral Reef Consortium to foster increased knowledge sharing, and to fund International Coral Reef Initiative (ICRI) activities designed to increase international government awareness as to the needs and benefits of investment in restoration and adaptation R&D.
Program Management	Program management costs were based on labour and operating costs commensurate with the management structure outlined in the previous section. An adaptive planning allowance of $18.8M was been included to buffer against high levels of uncertainty and allow for additional delivery methods to be incorporated.

In addition to the factors discussed above, a wide range of other aspects were considered in the design of the recommended R&D program. Details of these assessment are provided in **R4: Research and Development Program**. Table B2 summarises these additional aspects.

Table B2: Additional considerations in developing the RRAP R&D Program.

Consideration	Commentary
Intervention synergies	The RRAP Concept Feasibility Study identified intervention types would be synergistic in combination, further enhancing specific ecosystem functions and increasing impact for the same investment as the sum of the individual types. Similarly, common deployment infrastructure requirements could be leveraged for cost savings and/or to increase feasible deployment scales. The R&D program would continue to explore and leverage these synergies in the Modelling, Ecological Intelligence and Risk and Systems Engineering and Integrated Logistics sub-programs.
Deployment scale, implementation risk, ramp-up durations	The intervention delivery methods to be developed would have specific scale ranges over which they would be feasible and/or cost-effective, compared with alternatives. They have differing development risk profiles and timelines for development. The Systems Engineering and Integrated Logistics Sub-Program would track and refine these dimensions, to ensure they were considered in decision processes and R&D sub-programs, leading to further efficiencies.
Technical uncertainty and risk	In assessing the intervention types and possible delivery methods, functional performance parameters were identified. These are performance criteria which must be met if an intervention is to have efficacy, and/or an acceptable cost-benefit ratio. In addition to researching and developing methods, the R&D program would have an early focus on reducing risk and uncertainty as to if these performance criteria could be met. The Ecological Intelligence and Risk Sub-Program working in combination with each intervention R&D sub-program would seek to identify and reduce these risks as quickly as feasible.
Modelling systems (physical, ecology, value, decision)	Forecasting long-term future Reef system state and values is an inherently complex modelling challenge, compounded by uncertainty over climate trajectories and their likely impact. In RRAP, potential impact and benefits from the deployment of intervention types under different climate change scenarios are also considered, addressing another layer of complexity. This improvement to current models, and the increased understanding of the underpinning ecology and adaptation processes that drive intervention deployment decisions, would help ensure large investments would achieve the desired outcomes. The R&D program incorporates a combined field program (within the Ecological Intelligence and Risk Sub-Program) to better quantify the ecology and adaptation processes driving uncertainty, to allow model development to be aligned to the specific needs of the program.
Ecological risk	A critical element of the program would be improving the understanding of risk. Current knowledge and capabilities have limited quantitative assessments of risk. Understanding and quantifying risk would be central to future decision-making and regulatory approval, with R&D sub-programs designed to create the required knowledge and supporting models to enable this to occur.

B2.3 INVESTMENT REQUIREMENTS UNCERTAINTY

The forecasts were based on current information and the expertise of teams involved. However, R&D is inherently uncertain, particularly in the current context where interventions are very early in their R&D lifecycle and the needs of (and benefits to) the Great Barrier Reef are uncertain.

The R&D sub-programs have, by necessity, been presented as specific investment scenarios. Actual investments would need to be more dynamic as the program adapts to the emerging state of the Reef, and with improved understanding of needs and benefits.

The sub-program investments make predictions as to the outcomes of stage gate assessments and processes designed to refine and reduce the number of delivery methods being developed.

In each area, assumptions were made about required resourcing and duration, to achieve stated goals. These estimates were based on the combined experience of the teams; however, at this early stage, they are subject to medium to high levels of uncertainty.

The net outcome is that uncertainty increases rapidly beyond the first three years; years four to ten have progressively increasing levels of uncertainty.

APPENDIX C: RRAP DOCUMENT MAP

Reef Restoration and Adaptation Program

Reports		Report synopsis	Author/s	Affiliation	Internal review history – all or sections of this report have been reviewed by:	External review history
RRAP Investment Case						
A1	Investment Case	This document describes the overarching case for investing in a comprehensive R&D program (RRAP) to provide options to help protect and restore the Great Barrier Reef from the impacts of climate change. It includes a summary of the findings of the RRAP Concept Feasibility Study, a fully-costed R&D program designed to provide policy-makers with investment-ready interventions, and an optimal governance and program management structure to deliver it.	Paul Hardisty Patrick Silvey Christian Roth David Mead Ken Anthony	AIMS VenturePro CSIRO AIMS	Peter Mayfield (CSIRO) Anna Marsden (GBRF) Bruce Taylor (CSIRO) Karen Hussey (UQ) Petra Lundgren (GBRF) Danielle Koopman (AIMS) Chris Cocklin (JCU) David Wachenfeld (GBRMPA) Mark Gibbs (QUT) Meg Harlow (DoEE) Key findings were reviewed by the RRAP Executive Committee[5] and the RRAP Steering Committee[6]	Aristides Patrinos (NYU) Howard Wheater (Imperial College) Peter Doherty (AIMS) Carlos Duarte (KAUST)

[5] RRAP Executive Committee members: Paul Hardisty (Chair, AIMS), Peter Mayfield (CSIRO), Ian O'Hara (QUT), Iain Gordon (JCU), Bronwyn Harch (UQ), Anna Marsden (GBRF), Margaret Johnson (GBRMPA), Deb Callister (DOEE) and Jane Urquhart (DIIS)

[6] RRAP Steering Committee members: David Mead (Chair, AIMS), Britta Schaffelke (AIMS), Christian Roth (CSIRO), Mark Gibbs (QUT), Damien Burrows (JCU), Peter Mumby (UQ), Theresa Fyffe (GBRF) and David Wachenfeld (GBRMPA)

Level 1 (Blue) Recommendations These reports contain content (analysis, findings and recommendations) derived from the underpinning technical (T) and planning documents (S). In addition to the reviews listed below, technical and planning content was also reviewed as detailed under the technical and planning documents reviews.						
R1	Engagement and Regulatory Dimensions	A summary of the engagement and regulatory environment findings of the RRAP Concept Feasibility Study and recommendations for the required R&D for these areas.	Bruce Taylor Karen Hussey Pedro Fidelman Karen Vella Kirstin Maclean Maxine Newlands Brent Ritchie Stewart Lockie Justine Lacey Chris McGrath Umberto Baresi Marcus Barber Danielle Koopman	CSIRO UQ UQ QUT CSIRO JCU UQ JCU CSIRO Barrister-at-Law QUT CSIRO AIMS	Britta Schaffelke (AIMS) Damien Burrows (JCU) David Wachenfeld (GBRMPA) Lisa Boström-Einarsson (JCU) Peter Mayfield (CSIRO) Key findings were reviewed by the RRAP Executive Committee[7] and the RRAP Steering Committee[8]	Kirstin Dobbs (GBRMPA) Karen Markwort (GBRMPA) Belinda Jago (GBRMPA) Andrew Simpson (GBRMPA) Rachel Pears (GBRMPA) Aditi Mankad (CSIRO) Lucy Carter (CSIRO) Rosemary Hill (CSIRO) Liz Wren (RRRC/GBRF) Matt Curnock (CSIRO) Michaela Cosijn (CSIRO) Peter Doherty (AIMS)
R2	Intervention Summary	A key reference document summarising the potential on-Reef interventions, how they were identified and organising them according to the ecological objective they were designed to achieve, the method used to deliver them to the Reef and the scale at which they could be applied.	Line Bay David Mead Lisa Boström-Einarsson	AIMS AIMS JCU	Daniel Harrison (USYD/SCU) Mark Gibbs (QUT) Danielle Koopman (AIMS) Christian Roth (CSIRO) Key findings were reviewed by the RRAP Executive Committee[7] and the RRAP Steering Committee[8]	Peter Doherty (AIMS) Carlos Duarte (KAUST)
R3	Intervention Analysis and Recommendations	A summary of the findings of the environmental and economic modelling analyses undertaken in the RRAP Concept Feasibility Study of the proposed interventions and recommendations for how the R&D program would identify and deliver robust intervention strategies for the Great Barrier Reef.	Ken Anthony Jerome Bowen David Mead Paul Hardisty	AIMS Aurecon AIMS AIMS	Christian Roth (CSIRO) Paul Hardisty (AIMS) Lisa Boström-Einarsson (JCU) Danielle Koopman (AIMS) Key findings were reviewed by the RRAP Executive Committee[7] and the RRAP Steering Committee[8]	Peter Doherty (AIMS) Carlos Duarte (KAUST)

[7] RRAP Executive Committee members: Paul Hardisty (Chair, AIMS), Peter Mayfield (CSIRO), Ian O'Hara (QUT), Iain Gordon (JCU), Bronwyn Harch (UQ), Anna Marsden (GBRF), Margaret Johnson (GBRMPA), Deb Callister (DOEE) and Jane Urquhart (DIIS)

[8] RRAP Steering Committee members: David Mead (Chair, AIMS), Dr Britta Schaffelke (AIMS), Dr Christian Roth (CSIRO), Dr Mark Gibbs (QUT), Prof Damien Burrows (JCU), Prof Peter Mumby (UQ), Theresa Fyffe (GBRF) and Dr David Wachenfeld (GBRMPA)

R4	Research and Development Program	A summary of the recommended RRAP R&D Program required to deliver the recommendations of R3—Intervention analysis and recommendations.	David Mead Line Bay Ken Anthony Karen Hussey Bruce Taylor Pedro Fidelman Pete Mumby Daniel Harrison Mark Gibbs Scott Bryan Jonathan Daly	AIMS AIMS AIMS UQ CSIRO UQ UQ USYD/SCU QUT QUT Smithsonian Conservation Biology Institute	Paul Hardisty (AIMS) Danielle Koopman (AIMS) Britta Schaffelke (AIMS) Patrick Silvey (VenturePro) The content in this report has come from the strategy reports below and thus has sections have been reviewed by the authors and reviewers of those reports. Key findings were reviewed by the RRAP Executive Committee[9] and the RRAP Steering Committee[10]	Peter Doherty (AIMS) Carlos Duarte (KAUST) John Schepis (WorleyParsons) – sections only
R5	International Engagement and Partnering	Recommendations for fostering better international coordination and collaboration in reef restoration science, training and implementation. This document provides a road map to harness global knowledge and direct and expand funding and resources for globally-beneficial outcomes.	Petra Lundgren David Mead	GBRF AIMS	Britta Schaffelke (AIMS) Lisa Boström-Einarsson (JCU) Danielle Koopman (AIMS) Peter Mayfield (CSIRO) Key findings were reviewed by the RRAP Executive Committee[9] and the RRAP Steering Committee[10]	Tali Vardi (Coral Restoration Consortium, NOAA) Petra McGowan (Reef Resilience Network, TNC) Tom Moore (NOAA) Peter Doherty (AIMS)
R6	Governance and Program Delivery	This document outlines the recommended optimal governance structure and management systems for the RRAP R&D Program.	Paul Hardisty David Mead Jack Steele Peter Mayfield Theresa Fyffe	AIMS AIMS CSIRO CSIRO GBRF	Christian Roth (CSIRO) Danielle Koopman (AIMS) Key findings were reviewed by the RRAP Executive Committee[9] and the RRAP Steering Committee[10]	Peter Doherty (AIMS) Karen Markwort (GBRMPA)

[9] RRAP Executive Committee members: Paul Hardisty (Chair, AIMS), Peter Mayfield (CSIRO), Ian O'Hara (QUT), Iain Gordon (JCU), Bronwyn Harch (UQ), Anna Marsden (GBRF), Margaret Johnson (GBRMPA), Deb Callister (DOEE) and Jane Urquhart (DIIS)
[10] RRAP Steering Committee members: David Mead (Chair, AIMS), Dr Britta Schaffelke (AIMS), Dr Christian Roth (CSIRO), Dr Mark Gibbs (QUT), Prof Damien Burrows (JCU), Prof Peter Mumby (UQ), Theresa Fyffe (GBRF) and Dr David Wachenfeld (GBRMPA)

Level 2 (Coral) Technical process and detailed findings						
T1	Stakeholder, Traditional Owner and Community Engagement Assessment	This technical document outlines the findings of a representative survey of Australians, industry and stakeholder interviews, a desktop review scoping the issues and needs of Traditional Owners and a social media sentiment analysis. It highlights the critical information needs and challenges in engaging Traditional Owners, industry, stakeholders and the wider community in reef restoration and adaptation	Bruce Taylor Karen Vella Kirsten Maclean Maxine Newlands Brent Ritchie Stewart Lockie Justine Lacey Umberto Baresi Marcus Barber Lintje Siehoyono Sie Melusine Martin Nadine Marshall Danielle Koopman	CSIRO QUT CSIRO JCU UQ JCU CSIRO QUT CSIRO UQ JCU CSIRO AIMS	Britta Schaffelke (AIMS) David Wachenfled (GBRMPA) Damien Burrows (JCU) Lisa Boström-Einarsson (JCU) Key findings were reviewed by the RRAP Steering Committee[11]	Belinda Jago (GBRMPA) Rachel Pears (GBRMPA) Aditi Mankad (CSIRO) Lucy Carter (CSIRO) Rosemary Hill (CSIRO) Liz Wren (RRRC/GBRF) Matt Curnock(CSIRO) Michaela Cosijn (CSIRO)
T2	Regulatory Assessment Findings	This technical document outlines the findings of a comprehensive scan and analysis of the regulatory environment for restoration and adaptation activities in the Great Barrier Reef. It identifies complexity and gaps that would need addressing for effective intervention deployment.	Karen Hussey Pedro Fidelman Maxine Newlands Chris McGrath	UQ UQ JCU Barrister-at-Law	David Wachenfeld (GBRMPA) Lisa Boström-Einarsson (JCU) Key findings were reviewed by the RRAP Steering Committee[11]	Belinda Jago (GBRMPA) Kirstin Dobbs (GBRMPA) (early version) Andrew Simpson (GBRMPA) Rean Gilbert (GBRMPA) Mark Read (GBRMPA)
T3	Intervention Technical Summary	This technical document provides an overview of all potential intervention methods to protect and repair coral reefs considered during the RRAP Concept Feasibility Study. It outlines the current knowledge gaps in understanding the benefits, risks and feasibility of each intervention.	Line Bay Lisa Boström-Einarsson Melissa Rocker Russ Babcock Patrick Buerger Phil Cleves Daniel Harrison Andrew Negri Kate Quigley Carly Randall Madeleine van Oppen Nicole Webster	AIMS JCU AIMS CSIRO CSIRO Stanford Uni USYD/SCU AIMS AIMS AIMS AIMS AIMS	David Mead (AIMS) Britta Schaffelke (AIMS) Danielle Koopman (AIMS) Key findings were reviewed by the RRAP Steering Committee[11]	

[11] RRAP Steering Committee members: David Mead (Chair, AIMS), Dr Britta Schaffelke (AIMS), Dr Christian Roth (CSIRO), Dr Mark Gibbs (QUT), Prof Damien Burrows (JCU), Prof Peter Mumby (UQ), Theresa Fyffe (GBRF) and Dr David Wachenfeld (GBRMPA)

T4	Current Practices	This technical document provides a summary of the current global knowledge of coral restoration methods and practises to date, and highlights common issues encountered as the field has evolved.	Ian McLeod Lisa Boström-Einarsson Dani Ceccarelli Russ Babcock Elisa Bayraktarov Nathan Cook Peter Harrison Margaux Hein Elizabeth Shaver Adam Smith Phoebe Stewart-Sinclair Tali Vardi	JCU JCU JCU CSIRO UQ Reef Ecologic SCU JCU The Nature Conservancy Reef Ecologic UQ NOAA	Key findings were reviewed by the RRAP Steering Committee[12]	
T5	Future Deployment Scenarios and Costing	This technical document investigates possible delivery methods for the proposed Reef interventions, analysing cost and scale implications for each, and identifying potential synergies and efficiencies. It includes concept-level deployment calculations to guide research planning and investment, and cost-benefit assessment, providing insight into method development improvement opportunities.	Mark Gibbs David Mead Russ Babcock Daniel Harrison Zoran Ristovski Peter Harrison Peter Mellor	QUT AIMS CSIRO USYD/SCU QUT SCU WorleyParsons	David Mead (AIMS) Britta Schaffelke (AIMS) Lisa Boström-Einarsson (JCU) Danielle Koopman (AIMS) Key findings were reviewed by the RRAP Steering Committee[12]	John Schepis (WorleyParsons)
T6	Modelling Methods and Findings	This technical document presents the preliminary results of environmental and ecological modelling and analyses to understand the likely trajectories of coral condition on the Great Barrier Reef over time under climate change, with and without proposed RRAP interventions.	Ken Anthony Scott Condie Yves-Marie Bozec Daniel Harrison Mark Gibbs Mark Baird Peter Mumby David Mead	AIMS CSIRO UQ USYD/SCU QUT CSIRO UQ AIMS	Britta Schaffelke (AIMS) Christian Roth (CSIRO) Pete Mumby (UQ) Lisa Boström-Einarsson (JCU) Danielle Koopman (AIMS) Key findings were reviewed by the RRAP Steering Committee[12]	Beth Fulton (CSIRO)

[12] RRAP Steering Committee members: David Mead (Chair, AIMS), Dr Britta Schaffelke (AIMS), Dr Christian Roth (CSIRO), Dr Mark Gibbs (QUT), Prof Damien Burrows (JCU), Prof Peter Mumby (UQ), Theresa Fyffe (GBRF) and Dr David Wachenfeld (GBRMPA)

T7	Decision Support Findings	Discusses approaches for developing a decision-support system for RRAP, with a strong focus on adaptive pathways. RRAP is one of several projects contributing to the goal of a Reef decision-support system. Discussions on how the broader decision-support system needs will be met are continuing and involve multiple stakeholders and research providers. Given this, the recommendations made in this report are now obsolete. While they will inform decisions taken by the RRAP steering committee, they do not constitute program policy.	Hawthorne Beyer Micheli Duarte de Paula Costa Jeff Dambacher Russell Gorddard Kate Helmstedt M Wilson Pedro Fidelman Kerrie Wilson	UQ UQ CSIRO CSIRO QUT UQ UQ UQ	David Mead (AIMS) Pete Mumby (UQ) Ken Anthony (AIMS) Key findings were reviewed by the RRAP Steering Committee[13]	
	Please note that RRAP reports were consolidated and 'T8' was no longer used.					
T9	Cost-Benefit Analysis	This cost-benefit analysis applies structured decision-making to assess proposed interventions under different climate scenarios and in different combinations. It seeks to understand trade-offs, and facilitate optimised decisions and commitment to action, in the context of the current high degree of uncertainty inherent in RRAP	Mayuran Sivapalan Jerome Bowen	Aurecon Aurecon	David Mead (AIMS) Ken Anthony (AIMS) Lisa Boström-Einarsson (JCU) Danielle Koopman (AIMS) Key findings were reviewed by the RRAP Steering Committee[13]	
T10	Benefit Streams	This report describes how economic data were compiled and combined with estimates of coral condition from the modelling study (T6—Modelling Methods and Findings) to estimate current and future benefits of example interventions, under contrasting climate change scenarios, for use in T9—Cost-Benefit Analysis.	Natalie Stoeckl Ken Anthony	Stoeckl Consultants AIMS	Lisa Boström-Einarsson (JCU) Key findings were reviewed by the RRAP Steering Committee[13]	Professor Bob Costanza (ANU) Professor Julia Martin-Ortega (University of Leeds)

[13] RRAP Steering Committee members: David Mead (Chair, AIMS), Dr Britta Schaffelke (AIMS), Dr Christian Roth (CSIRO), Dr Mark Gibbs (QUT), Prof Damien Burrows (JCU), Prof Peter Mumby (UQ), Theresa Fyffe (GBRF) and Dr David Wachenfeld (GBRMPA)

T11	Automated Aquaculture Production and Deployment	This technical document provides engineering concepts for the systems necessary to grow and deploy new corals on the Reef, at scale. It builds on the knowledge and facilities of the AIMS' SeaSim research facility.	Peter Mellor	WorleyParsons	David Mead (AIMS) Mark Gibbs (QUT) Line Bay (AIMS) Andrea Severati (AIMS) Key findings were reviewed by the RRAP Steering Committee[14]	
T12	Cool Water Injection	This technical document uses modelling to investigate cold-water injection (C1, C2) as a potential RRAP intervention, to cool reef waters and help prevent thermal stress, which can lead to coral bleaching. It focuses on Lizard Island as the most physically-favourable of 20 reefs initially investigated.	Mark Baird R Green R Lowe	CSIRO UWA UWA	David Mead (AIMS) Lisa Boström-Einarsson (JCU) Key findings were reviewed by the RRAP Steering Committee[14]	
T13	Ultra-Thin Surface Films	This technical document uses eReefs modelling to investigate the potential benefits of proposed RRAP intervention ultra-thin surface films (C6) in the cooling and shading intervention group.	Mark Baird M Mongin E Bougeot	CSIRO CSIRO CSIRO	David Mead (AIMS) Lisa Boström-Einarsson (JCU) Danielle Koopman (AIMS) Key findings were reviewed by the RRAP Steering Committee[14]	
T14	Environmental Modelling of Large-Scale Solar Radiation Management	This technical document presents the methods, analysis and results of using modelling (weather, atmospheric, hydrodynamic, biogeochemical, bleaching, and atmospheric particle tracking) to investigate the potential benefits of large-scale solar radiation management interventions in the cooling and shading intervention group.	Daniel Harrison Luke Harrison Mark Baird Steve Utembe Robyn Schofield Rogger Escobar Correa Mathieu Mongin Farhan Rizwi	USYD/SCU SIMS CSIRO UMelb UMelb SCU CSIRO CSIRO	Mark Gibbs (QUT) Zoran Ristovski (QUT) Key findings were reviewed by the RRAP Steering Committee[14]	Martine Lawrence (SIMS) Ian Jones (USYD)

[14] RRAP Steering Committee members: David Mead (Chair, AIMS), Dr Britta Schaffelke (AIMS), Dr Christian Roth (CSIRO), Dr Mark Gibbs (QUT), Prof Damien Burrows (JCU), Prof Peter Mumby (UQ), Theresa Fyffe (GBRF) and Dr David Wachenfeld (GBRMPA)

Reef Restoration and Adaptation Program

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