Reef Restoration and **Adaptation Program**

R3: INTERVENTION ANALYSIS AND RECOMMENDATIONS

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

Anthony K¹, Bowen J², Mead D¹, Hardisty P¹ ¹Australian Institute of Marine Science ²Aurecon

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Inquiries should be addressed to:

Ken Anthony or David Mead: <u>k.anthony@aims.gov.au</u> <u>d.mead@aims.gov.au</u>

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1. **PREAMBLE**

The Great Barrier Reef

Visible from outer space, the Great Barrier Reef is the world's largest living structure and one of the seven natural wonders of the world, with more than 600 coral species and 1600 types of fish. The Reef is of deep cultural value and an important part of Australia's national identity. It underpins industries such as tourism and fishing, contributing more than \$6B a year to the economy and supporting an estimated 64,000 jobs.

Why does the Reef need help?

Despite being one of the best-managed coral reef ecosystems in the world, there is broad scientific consensus that the long-term survival of the Great Barrier Reef is under threat from climate change. This includes increasing sea temperatures leading to coral bleaching, ocean acidification and increasingly frequent and severe weather events. In addition to strong global action to reduce carbon emissions and continued management of local pressures, bold action is needed. Important decisions need to be made about priorities and acceptable risk. Resulting actions must be understood and co-designed by Traditional Owners, Reef stakeholders and the broader community.

What is the Reef Restoration and Adaptation Program?

The Reef Restoration and Adaptation Program (RRAP) is a collaboration of Australia's leading experts aiming to create a suite of innovative and targeted measures to help preserve and restore the Great Barrier Reef. These interventions must have strong potential for positive impact, be socially and culturally acceptable, ecologically sound, ethically and financially responsible. They would be implemented if, when and where it is decided action is needed and only after rigorous assessment and testing.

RRAP is the largest, most comprehensive program of its type in the world; a collaboration of leading experts in reef ecology, water and land management, engineering, innovation and social sciences, drawing on the full breadth of Australian expertise and that from around the world. It aims to strike a balance between minimising risk and maximising opportunity to save Reef species and values.

RRAP is working with Traditional Owners and groups with a stake in the Reef as well as the general public to discuss why these actions are needed and to better understand how these groups see the risks and benefits of proposed interventions. This will help inform planning and prioritisation to ensure the proposed actions meet community expectations. Coral bleaching is a global issue. The resulting reef restoration technology could be shared for use in other coral reefs worldwide, helping to build Australia's international reputation for innovation.

The \$6M RRAP Concept Feasibility Study identified and prioritised research and development to begin from 2019. The Australian Government allocated a further \$100M for reef restoration and adaptation science as part of the \$443.3M Reef Trust Partnership, through the Great Barrier Reef Foundation, announced in the 2018 Budget. This funding, over five years, will build on the work of the concept feasibility study. RRAP is being progressed by a partnership that includes the Australian Institute of Marine Science, CSIRO, the Great Barrier Reef Foundation, James Cook University, The University of Queensland, Queensland University of Technology, the Great Barrier Reef Marine Park Authority as well as researchers and experts from other organisations.

2. EXECUTIVE SUMMARY

Purpose and scope

Environmental, ecological and economic models and analyses were integrated to address three central questions for the Reef Restoration and Adaptation Program (RRAP) to inform the recommended research and development (R&D) program:

- 1. What is the potential for restoration and adaptation interventions to sustain coral condition on the Great Barrier Reef?
- 2. How will this impact on the economic value of the Reef for Australians?
- 3. Will benefits exceed costs?

An initial set of 160 interventions were screened based on three criteria: feasibility at scale, risk and cost. A subset of 43 options among seven intervention categories showed initial scope to become feasible at varying scales, ranging from reef-site to the entire Great Barrier Reef, given assumptions around risk tolerance and resource constraints.

Within these, three broad categories of new interventions were assessed quantitatively for their potential to sustain coral condition on the Reef and the economic value that would underpin from 2016 to 2075 under contrasting climate change scenarios:

- 1. Local and regional cooling and shading.
- 2. Assisted coral adaptation via seeding and propagation of coral larvae, recruits and adults.
- 3. Stabilisation of reef substrate.

In addition, the impact of existing versus additional crown-of-thorns starfish control was simulated quantitatively in combination with new interventions as starfish predation is a key driver of coral mortality on the Reef. New restoration and adaptation interventions would have a greater chance of success if starfish were controlled effectively. Further, all simulations assumed best-practice water quality management to help demarcate the boundary where the scope for conventional reef management stops and the scope for new interventions under RRAP begins.

Approach

Simulations were produced by the best available bio-physical models, advanced further for this study. Models simulated the trajectories of coral cover in space (reefs) and time (years) and explored the scope of some example RRAP interventions, individually and in combination, to prevent coral decline or improve coral condition. The examples used for new interventions were deploying warm-adapted corals and large-scale cooling and shading (cloud brightening).

Economic analyses were informed by the ecological modelling results for warm-adapted corals, and cooling and shading as well as additional crown-of-thorns starfish control. 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 examined eight specific, readily-quantifiable, benefit streams representing the current monetary value of benefits flowing from the Great Barrier Reef to Australians. A second method examined aggregated ecosystem service values - the many and varied benefits to humans generated by the natural environment of the Reef.

In combination with analyses of R&D and deployment costs for the two example intervention strategies, estimated benefit streams were used to inform cost-benefit analyses integrated over 60 years (2016 to 2075).

Findings

Ecological modelling showed: an intervention strategy that combines large-scale cooling and shading with the deployment of warm-adapted corals can significantly improve Reef coral cover relative to present levels under moderate climate change (Representative Concentration Pathway [RCP] 2.6, the Paris Agreement target). Importantly, these projections assume the most favourable conditions of intensified crown-of-thorns starfish control, effective water quality management and continued best-practice conventional management.

These interventions may also improve coral cover Reef-wide under the 'business-as-usual' scenario of greenhouse gas emissions RCP 8.5 in the coming decades. However, **once global warming exceeds 2°C, coral cover was projected to decline precipitously** in our simulations to below five percent by 2070, irrespective of interventions. Ocean acidification was not included in model projections and may lead to less optimistic outcomes, particularly under the RCP 8.5 scenario.

The positive response of coral cover to multiple interventions operating in combination was greater than the sum of responses from interventions operating individually, particularly for absolute changes in coral cover. This indicates that interventions synergise as they support multiple processes that together underpin resilience, pointing to the potential for optimal strategy development and maximising benefits with the efficient use of resources.

The stabilisation of reef substrate (rubble) demonstrated lower, albeit varying, benefits depending on the environmental and ecological settings. The scale of benefits flowing from achieving this intervention objective is likely to be limited to individual reefs (small scale) or sites within reefs (micro scale). Importantly, where ecological and economic benefits cannot be achieved at the scale of the Reef, small and medium-scale interventions may sustain critical values within Reef sectors, for example for the tourism industry.

It is acknowledged that the monetary estimates of the value of the Great Barrier Reef provided here 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.

Estimates of benefit streams indicated that gross economic benefits for Australia resulting from large-scale intervention strategies under business-as-usual climate change (RCP 8.5) could reach \$29B.

A shift from RCP 8.5 to RCP 2.6 (i.e. a reduction in carbon emissions from businessas-usual to the best-case scenario) could prevent economic damage in the order of \$28B based solely on differences in coral condition between these counterfactuals.

Under RCP 8.5, economic benefits of interventions were projected to diminish beyond 2060 as pressure from climate change may eventually overwhelm the capacity of any intervention to sustain the Reef and associated ecosystem services as we know them.

Results of the cost-benefit analysis

The cost-benefit analysis involved focused and iterative work with the wider RRAP team to ensure a robust outcome. Over six months, the cost-benefit analysis team collaborated with the steering committee and the modelling, engineering, estimating, economic, engagement and regulatory teams to ensure the analysis was coherent, insightful and communicable.

Taking into account the balance of costs and benefits, the RRAP R&D Program offers significant potential economic benefit at conservative, base-case assumptions of up to \$4.1B net present value (2016, 3.5 percent), which is equivalent to \$28B undiscounted over 60 years. Taking a 90 percent probability interval for 1000 iterations of sensitivity parameters, the potential benefit of RRAP is up to \$14.5B net present value (2016, 3.5 percent). Thus, RRAP is an investable proposition across a broad range of uncertainty, including a wide range of economic benefits valuation conditions (except in the most pessimistic conditions).

The present value estimate of ecosystem services benefits for Australia of the most promising RRAP intervention strategy under RCP 2.6 was \$640B (undiscounted). These are based on low and average per-hectare estimates of ecosystem service values for coral reefs globally. Under RCP 8.5, the estimated gross present value would fall significantly compared with RCP 2.6, highlighting the significant value of achieving the global emissions reductions required to reach the RCP 2.6 path.

From a cost-benefit perspective, active restoration and adaptation interventions are a valid new management strategy for the Reef and should be invested in. The costbenefit analysis for RRAP showed, within the high degree of uncertainty inherent in the program, there was a strong set of circumstances in favour of active restoration and adaptation interventions. It is recommended RRAP progresses to the R&D stage.

Recommendations

Scenario development, intervention analysis and associated ecological and economic modelling of strategy performance must be guided by a structured decision-making framework with clear objectives. This will be critical because prioritisation and trade-offs among reefs, species, benefit streams, and ecosystem services may become necessary under severe climate change.

The RRAP R&D Program must **identify and develop robust solutions** that are effective, cost-efficient and safe across climate scenarios, to minimise risk.

The search for robust solutions must be weighed against the need to provide solutions **in a race against time.** The RRAP R&D Program must seek to reduce critical uncertainty around intervention performance, costs and risks, to best inform time-critical and transparent decision-making.

Formal assessment of risk and critical uncertainty (environmental, ecological, social and economic) must be included in the future modelling of the Reef as a complex, linked social-ecological system. This should include analyses of risk behaviour/tolerance for different objectives in collaboration with the broad stakeholder community.

The R&D program should start with the broad base of interventions identified in the feasibility program, to maximise optionality. Modelling results and decision processes developed during the feasibility program would help fast-track prioritisation of interventions that have the maximum likelihood of achieving RRAP success.

Cost-benefit analysis must be iterated as R&D evolves. This will help support an effective strategy by ensuring **only feasible interventions are advanced** beyond review stage gates.

The 43 interventions that passed the initial screening of the concept feasibility program are recommended for entry into the R&D program because:

- They support different environmental and ecological processes that underpin reef resilience under climate change.
- They represent a minimal but comprehensive set of interventions, providing broad optionality for the R&D program.

3. SCOPE OF THE ANALYSIS

The purpose of this RRAP Concept Feasibility Program intervention analysis was two-fold:

- It narrowed the 160 interventions initially considered into a subset of 43 to form the starting options for the RRAP R&D Program. The rationale was that a high degree of optionality would maximise the scope of the R&D program to deliver solutions, while initial filtration could help fast-track the program by eliminating inviable options.
- It quantitatively estimated the potential capacity of two examples of new interventions (enhanced corals and cloud brightening) to sustain—or improve—coral cover on the Great Barrier Reef and the multiple values it underpins.

The problem was approached with a set of linked and tiered questions. Below are the questions and how they were addressed:

1. What set of interventions would constitute **high optionality for the RRAP R&D Program** while excluding options that have low feasibility at scale and represent prohibitively high risk and cost?

To narrow the 160 candidate interventions to 43, they were considered across four spatial scales (micro = a few square metres; small = tourist sites (a few hectares), a single reef; medium = 20 reefs or more and large = 200 or more reefs up to all of the Great Barrier Reef). Within these, the following elements were assessed:

- Potential to deliver benefits at scale
- Likely risk
- Technology readiness and development requirements
- Likely cost.

2. How might the proposed intervention types **support reef resilience** via their individual and combined impacts on different environmental and ecological processes?

A qualitative/conceptual model was constructed to analyse how different groups of interventions might interact to help alleviate environmental pressures and/or promote biological or ecological processes that underpin resilience.

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

Coral trajectories were modelled under two contrasting climate change scenarios: the ideal RCP 2.6 (if the world achieves the Paris Agreement target and keeps global warming below 2°C) and the business-as-usual RCP 8.5 (potentially exceeding 2°C warming by 2050; IPCC, 2014). This provided insight into the range of possible climate futures within which RRAP could produce solutions. It also served to construct a base case (counterfactual) for each climate change scenario. Because the RCP 2.6 and RCP 8.5 scenarios do not converge significantly until 2040, the modelling of coral trajectories from 2020 to 2050 with and without simulating interventions in part represents a continuum between RCPs in time. Importantly, whether one climate future or another will unfold is associated with uncertainty, driven by uncertainty around the global commitment to emission reductions (Rogelj et al. 2016) and climate sensitivity to emissions (Raftery et al. 2017; Lamontagne et al. 2019). In turn, the uncertainty of the climate trajectory will impact on how the R&D program would produce solutions given different constraints on the efficacy of different interventions, logistics challenges associated with different scenarios, and direct climate impacts on society and human capacity and needs for climate adaptation (Evans et al. 2011; Jones et al. 2012; Stein et al. 2013). In modelling coral trajectories and associated economic consequences, bestpractice conventional management, effective crown-of-thorns starfish control and water guality management were assumed for all scenarios. These assumptions were to demarcate the boundary of where the scope of increasing conventional management strategies stopped and where the scope of added RRAP strategies began. While the management of reef herbivores is a key strategy to build resilience on coral reefs globally (Mumby et al. 2007; McClanahan et al. 2012), it was not modelled here because the fishing of key herbivores (e.g. parrotfishes) on the Reef is limited (McCook et al. 2010; Frisch et al. 2012).

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

The extent to which RRAP interventions could help sustain coral condition (specifically coral cover) under such futures was examined. Here, the scope was limited 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 (Knowlton 2001). By providing critical habitat, corals underpin the majority of biodiversity on reefs (~0.55 to 1.33 million species; Fisher et al. 2015) and a diversity of reef ecosystem services (Moberg and Folke 1999; Sukhdev et al. 2009). Thus, by focusing on coral cover, part of the ecological

underpinnings of reef resilience and dependent values was addressed. While risks of new interventions are a critical element of decision-making associated with intervention deployment, this study **focused on intervention scope (potential) only**. This provides clarity around **the extent to which RRAP could deliver outcomes**, under the assumption that risks could be overcome during the RRAP R&D Program.

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

A benefit-transfer approach was used to estimate the economic benefit of proposed RRAP interventions (compared with no intervention). While primary economic data would have been the preferred approach to understand the economic benefits of the proposed interventions (Wilson and Hoehn 2006; Richardson et al. 2015), this was beyond the scope of the feasibility program. To understand the benefits arising from multiple coral reef ecosystem services, we used the Common International Classification of Ecosystem Services (CICES) developed from the work on environmental accounting undertaken by the European Environment Agency (Haines-Young and Potschin 2012). Here, we limit benefit streams from sustained or improved Reef coral condition to Australians over the 60-year time horizon of 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 (Sukhdev et al. 2009; Costanza et al. 2014).

6. Are there **circumstances where investment in RRAP is favourable**, allowing decisionmakers to determine whether the program should progress to the next R&D stage?

Spanning 344,400 km², the Great Barrier Reef represents approximately 10 percent of the world's coral reefs. The Reef represents a globally outstanding natural and economic capital, in part via its status as a World Heritage Area, and is a multi-use area, managed intensely, under its own Act, by the Great Barrier Reef Marine Park Authority. While monetary estimates of benefits flowing from the Reef are insufficient to measure its total ecological, social, cultural, economic and existence values, a set of conservative economic analyses were undertaken to assess the monetary returns that could be expected from RRAP interventions, under different climate change scenarios. These analyses can inform investment decisions, based on the performance of highly conservative estimates and against economic objectives only.

A cost-benefit analysis of RRAP was undertaken to test within the high degree of uncertainty inherent in the program whether RRAP would show enough potential economic net benefit to continue to the R&D stage. Structured decision-making methods were used to frame the decision space, ensure the options assessed were reasonable, ensure the information was relevant and reliable for the level of the decision, understand the trade-offs, conduct a logical analysis and facilitate optimised decisions and commitment to action.

4. APPROACH

This document synthesises a large body of work conducted by the RRAP Concept Feasibility Program. It includes the wide range of methods used. Throughout the document, references to the reports providing the detail that underpins this synthesis document are provided. An overview of the links between the reports and how they feed into this document is provided in <u>Appendix A</u>.

4.1 Modelled system

The approach of this analysis was to model causal links within a network of drivers forcing environmental change, how the resulting pressures influence biological and ecological processes that lead to changes in ecosystem state and their impact on ecosystem values including ecosystem services (Figure 1). The framework used is that of a linked environmental-ecological-social system, where the focus is on the direct ecological and economic consequences, rather than the social-ecological feedbacks (see R1: Engagement and Regulatory Dimensions). Conventional management and RRAP interventions were integrated into the framework as explicit management levers (responses), influencing multiple pressures and processes and/or alleviating impacts. This approach is informative for RRAP for two reasons: it provides clarity around key drivers of change without RRAP interventions (the counterfactual), as well as how RRAP intervention strategies that target one or more pressures and/or processes might alleviate impacts or convert them from negative to positive outcomes, depending on climate scenarios. The drivers-pressures-stateimpact-response approach is consistent with that used in the Reef 2050 Plan and the Reef 2050 Integrated Monitoring and Reporting Program (Commonwealth of Australia 2018). RRAP represents an additional set of options for interventions that could be integrated into the Reef 2050 Plan/Reef 2050 Integrated Monitoring and Reporting Program decision framework.

The drivers-pressures-state-impact-response framework was used to guide the supply chain of information flowing between models and analyses in the program (Figure 2). Environmental models simulated drivers, which led to pressures in space and time, ecological models simulated resulting biological and ecological responses and economic models analysed impacts on ecosystem services and consequent economic benefits (or loss of benefits) for society. The cost-benefit analysis then assessed the circumstances in which benefits were likely to exceed costs and whether these circumstances were (or could be) significant enough to support the case for investment in the RRAP R&D Program. In <u>T9:</u> <u>Cost-Benefit Analysis</u> these loops (the response path) are closed in an adaptive management context to inform effective, structured decision-making in the RRAP R&D and Deployment Programs.



Figure 1: Driver-pressure-state-impact-response framework used to provide the high-level architecture for the modelling project. Green arrows indicate positive causal relationships and red/orange arrows indicate negative causal ones. While conventional interventions mostly target drivers or pressures, RRAP interventions impact species or other ecosystem components (except cooling/shading that targets a pressure). Ocean acidification is shaded out because it was excluded from consideration in this feasibility program. Similarly, regional socio-economic drivers, fishing and transport were excluded. Codes refer to proposed RRAP interventions and intervention types, see <u>Appendix B</u>. Source: adapted from Anthony (2016).



Figure 2: Supply chain of models used in RRAP and linked programs. The models map against the driverspressures-state-impact-response framework (Figure 1) in a flow from left to right. As several iterations of the modelling were performed during the RRAP Concept Feasibility Program, the supply chain was used as an adaptive management framework to test and improve models sequentially within the program. Codes refer to RRAP reports, see <u>Appendix A</u>.

4.2 Interventions, deployment scenarios, risks and costs

4.2.1 Initial intervention selection, functional objectives and optionality

The scope, risks and feasibility of a large number of new interventions that may support aspects of coral reef resilience were assessed in <u>T3: Intervention Technical Summary</u> and <u>T5: Future Deployment Scenarios and Costing</u>. In addition, the Committee on Interventions to Increase the Resilience of Coral Reefs under the National Academy of Sciences, Engineering and Medicine (NASEM, US) recently reviewed 23 new interventions that may build resilience on coral reefs globally (NASEM 2019). The RRAP Concept Feasibility Program and the NASEM Committee reviewed interventions through a similar lens of efficacy, risks, feasibility, readiness and costs. Both focused on coral condition (cover and composition), based on the premise that corals ultimately underpin most ecosystem values and services on coral reefs (similar to trees in forests), hence providing boundaries on the types of interventions we assess. The RRAP and NASEM projects collaborated via shared team members and reviewers and their reports represent de facto reviews of each's common direction.

A summary analysis is provided here to assess the relative performance of the 43 intervention options that remain following the initial filtration and subsequent elimination of high-risk and prohibitively costly interventions (<u>Appendix B</u>). Key examples of interventions eliminated are global geo-engineering interventions with significant risks involving sulphate aerosols (Matthews and Caldeira 2007; Irvine et al. 2012; Barrett et al. 2014). Interventions involving pumping and mixing were excluded based on cost and because they were only effective at a small scale (<u>T12: Cool Water Injection</u>).

The remaining interventions fell into the following seven functional categories (Appendix B):

- **Cooling and shading:** Reducing exposure of coral reefs to heat and light stress during acute events
- **Stabilisation:** Adding reef structures and stabilisation to increase substrate quality and facilitating coral recovery following disturbances
- **Coral seeding:** Using natural coral larval stock to enhance coral reproduction and reef recovery following disturbance
- Biocontrol: Managing coral predators and competitors to enhance coral survival
- Application of field treatments: Increasing coral survival and health following disturbance with probiotics, feeding, medicines or other treatments
- Seeding enhanced corals from existing stock: Increasing health and tolerance of coral populations by seeding with specimens from existing stock that have enhanced performance
- Seeding enhanced corals bred from engineered stock: Increasing health and tolerance of coral populations by seeding with specimens from genetically engineered or synthetic biology that have enhanced performance.

To provide a preliminary performance assessment, this set of interventions was mapped against:

- Estimated cost at the scale at which each was deemed feasible.
- Estimated risk associated with R&D and deployment (Figure 3).

Quantitative assessment of efficacy at scale was not included in this preliminary analysis but was inherent in the assumption that each intervention was likely to be feasible at the given scale. Although scale and cost were components of objectives (short vs long term, large vs small scale), they were separated here as they were critical to the selection process. Further, risks are typically tied to methods: the real risk arising from potential unintended consequences and the level of precaution (including perceived risk) that arises from new and untested interventions (Kaebnick et al. 2017).



Figure 3: Preliminary performance assessment of 27 (subset of 43 with cost estimates) interventions estimated as feasibility at scale, cost and risk. See <u>Appendix B</u> for details. Note that efficacy was assumed to be inherent in feasibility at scale but will become a separate dimension in the R&D program. The inset shows the objective function (maximise efficacy at scale and minimise cost and risk) to drive optimisation in the R&D program for interventions remaining in, or added to, the program. Note that the scale (x-axis) is logarithmic. See <u>Table B1</u> for details and definitions.

A set of preliminary conclusions can be derived from this performance mapping:

- 1. Delivering benefits at the largest scale generally comes with the highest risk and cost. Coral seeding using both natural (group ER), enhanced (group EE) and engineered (group EN) stock represent a high-risk and high-cost alternative, but potentially with high reward, assuming significant benefits at large scale. Cloud brightening (group C3) is similarly a high-cost/high-risk/high-reward option, in part due to high uncertainties associated with cost-efficient development and deployment methods and uncertainties around social license to operate. Intervention strategies that combine coral seeding with cloud brightening will need to consider how benefits and risks, in particular, might interact. The opportunity versus challenge of such interactions are covered below.
- 2. From an optimisation perspective of maximising the scale of delivery while minimising the cost and risk, C4 and C5 (shading by fogging and misting) are potentially high-performing interventions, especially if they can be made operational relatively rapidly (eight to 10 years, <u>Appendix B</u>).
- 3. If cost constraints were relaxed, then ER8 (coral seeding by automated aquaculture) and S2 (stabilisation by chemical bonding) would perform second best of all interventions, as their risks are medium, assuming efficacy at scale. Importantly, the constellation of

performances of this set of interventions along dimensions of scale, costs and risks will change directionally during the R&D program, driven by a decision-support program structured as an adaptive management strategy. In other words, interventions that are continually deemed feasible and promising within performance criteria will be advanced according to the program's objective function of:

- Maximise efficacy at scale
- Maximise scale of positive impact
- Minimise cost
- Minimise risk (see insert in Figure 3).
- 4. At a smaller scale, interventions S3 and S5 (stabilisation by mesh and consolidation) and ER7 (coral seeding by semi-automated aquaculture) would be optimal from the perspective of low risk (Figure 3).
- 5. It can be argued that interventions C6 (shading by surface films), EN1 (seeding of enhanced corals bred from engineered stock with semi-automated aquaculture) and EE3 (seeding enhanced corals bred from existing stock with semi-automated aquaculture) might be sub-optimal from the perspective of high risk relative to potential gain from a scale perspective, unless targeting only high-value sites or source reefs in a network of highly connected reefs (see below).

From the perspective of retaining versus eliminating options for the R&D program, the current set of interventions distributed across seven functional groups represent a high level of optionality with high scope, but also minimal redundancy. Importantly, the different intervention groups assist different environmental, biological and ecological processes (Figure 4). Cooling and shading alleviate heat stress, which lowers stress on adult corals, recruits and larvae (red arrows). The remaining four intervention types support survival, growth, reproduction and recruitment (population fitness) via different mechanisms (green arrows). Biological and ecological interventions have greater scope to produce impacts under reduced heat stress and may amplify each other's effect.

Optimising spatial design to maximise larval dispersal rates between source and sink reefs should be part of the management strategies involving new and conventional interventions (Hock et al. 2017). The role of amplifying positive effects at the deployment scale to have positive impacts at larger scales via a spatial strategy in a connected network (Figure 5) is explored in more detail below using simulation modelling and would be a priority in the R&D program. While cooling and shading at the regional scale may not be amenable to spatial optimisation, the way the remaining four biological interventions are stacked in space and time may have strong downstream impacts beyond their footprint. Such strategic stacking in space and time may provide scope to support both the resilience of reefs and societal benefits under climate change (Anthony et al. 2015; Anthony 2016; McLeod et al. 2019).

In summary, given the requirement to retain sufficient optionality in the R&D program to avoid missed opportunities and the advantage of having multiple interventions promoting different processes when supporting resilience, it is recommended the remaining 43 interventions be carried forward to the R&D program as they represent a minimal yet comprehensive set of options. A key task of the R&D program would be to apply further

filtration using a comprehensive set of quantitative tools and to further develop strong candidates.



Figure 4: Qualitative model illustrating the causal linkages between intervention types and the environmental, biological and ecological processes impacted. Spatial strategies that enhance connectivity will strengthen flows from adults to larvae and from larvae to recruits. EX refers to intervention codes ER, EE or EN. See <u>Appendix B</u> for details of intervention types.



Figure 5: Spatial deployment strategies that consider patterns of larval connectivity in reef networks may amplify positive impacts at the deployment scale (green bars) by creating cumulative benefits so they achieve impacts at larger scales (grey cones). Crown-of-thorns starfish are shown here because their control must be considered in RRAP intervention designs.

4.2.2 Scale and cost considerations underpinning intervention selection

Understanding scale limitations of interventions is critical for the RRAP mission because scale is linked to program costs, development duration and the upside and downside risks for the Reef and people.

Within RRAP, each intervention comprises a functional objective, a delivery method and a targeted scale. To undertake costing, scale and delivery timing assessments, concept designs for each delivery method were documented (comprising the products, production and deployment systems and required infrastructure). These designs were used to determine unit cost rates as a function of deployment scale. Unit cost rates refer to the cost per item being deployed or action being undertaken e.g. the cost per new coral established on a reef or a cost per km² to shade a section of reef.

Assessing unit cost rates as a function of deployment scale was an essential aspect of the review. While some delivery methods show a trend of reducing unit cost rates as scale increases, others have the opposite trend, and some have large inflection points where unitcosts dramatically increase as scale (numbers) increases. These relationships are critical to the assessments of feasible deployment scale and in comparing between delivery method options.

In some instances, it was feasible to undertake a detailed, bottom-up cost estimate using engineering methods; in others, a high-level 'rates-based' approach was required. Many delivery methods under consideration are in very early development, with limited quantitative concept design details available to engineer and cost.

Assessing uncertainty and costing sensitivity was an important part of the assessment. It identified that, in most instances, the primary uncertainty related to estimating deployment performance parameters. These were significantly greater than uncertainty in engineering cost calculations. For example, many delivery methods seek to seed new corals onto a reef. The assessment sought to determine the cost of each new six-month-old coral (the point at which the ecosystem models started tracking the corals). However, all methods deploy much younger corals (from hours to weeks of age) so the cost calculations needed to factor a conversion rate from the number deployed to the number established. This was a common challenge across delivery methods. In some instances, uncertainty in these conversion rates covered two orders of magnitude. To quantify this uncertainty, the assessment calculated low, expected and high per-unit cost rates.

Details of the assessment process, including industry engagement to support and validate the cost assessments are provided in <u>T5: Future Deployment Scenarios and Costing</u>.

In summary, the delivery method concept assessment revealed the following:

- Deployment costs were substantial. This is not unexpected given the vast area of the Reef and general costs for operating marine infrastructure.
- The extent to which a method could be deployed at scale was driven by unit costs and the available funding for deployment. Within this context, two distinct unit cost versus scale profiles were observed:

- a. Several delivery methods have seasonal or episodic deployment requirements, suggesting it would be more cost-efficient if the existing infrastructure was leased and temporary personnel used. Once these available resources were exhausted, further operational scaling up would require the acquisition of infrastructure, with the cost needing to be amortised over the short use period, and thus creating a major step increase in costs. This places a logistics constraint on these methods unless there is a market to fund the infrastructure when it is not being used for restoration purposes.
- b. Delivery methods that could be deployed year-round had reducing unit costs as scale increases; however, they all had points where the economy of scale flattened, and a commodity price rate was achieved. In this category, delivery methods with low unit costs at large scale often had a higher unit cost at a smaller scale compared with alternatives (needing to amortise the cost of expensive technologies).

As such, intervention delivery methods all have an optimal use scale that needs to be targeted if unit costs are to be minimised. A strategy of developing delivery methods that perform well at a small scale and then seeking to scale these up would likely result in a sub-optimal outcome.

- The range between the low- and high-cost estimates identified in the sensitivity analysis reflects the conceptual and preliminary nature of the delivery methods under assessment. This was a result of the compounding uncertainty in key parameters such as survival rates and efficacy of different methods. For example, with the larval slick capture and movement methods, the cost per coral ranged from less than \$1 to more than \$100, depending on assumptions around the cumulative survival rates. This uncertainty would need to be reduced as a matter of priority and requires validation of the key assumptions making up these cost estimates.
- The study identified significant opportunities to reduce deployment costs through optimising the methods: both within each method and through shared infrastructure. For example, the same vessel could potentially be used for multiple intervention approaches at different times of the year; increasing the use of expensive marine infrastructure. This also requires further investigation to optimise the preferred interventions for deployment.

Generally, there was a positive correlation between the target scale of deployment and the estimated timeframe. Large-scale delivery methods will take longer to develop and deploy.

4.2.3 Quantitative assessment of intervention performance

To quantitatively assess the scope for new interventions to build reef resilience and support coral condition on the Reef, a subset of example interventions was selected based on the following criteria:

- 1. Sufficient data or theory to inform parameterisation in environmental and ecological models.
- 2. 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. Ability to cooperate and synergise with other interventions to promote and sustain coral survival, growth and recruitment (Figure 1 and Figure 4).
- 4. Ability to operate at multiple spatial scales and ideally interact positively across those scales.
- 5. Ability for reasonable assumptions around efficacy, feasibility and costs to inform the assessments of scope. While the quantitative assessment of risks (e.g. unintended consequences or any process that prevents a strategy from meeting its objective) would be a critical component of decision analyses in RRAP, quantitative model analyses in this quantitative feasibility program were limited to assessments of intervention scope (i.e. potential) only.

Applying this set of selection criteria to the 43 proposed interventions, along with discussions with other RRAP working groups, the modelling team narrowed in on, through iterations, the set of example interventions outlined in Table 1.

Prevention of crown-of-thorns starfish outbreaks was not included in Figure 3 (or <u>Appendix</u> <u>B</u>) or the recent review by the National Academy of Sciences, Engineering and Medicine (NASEM 2019). The rationale for including crown-of-thorns starfish outbreak prevention in the modelling study and associated economics analyses is that starfish predation is one of the most important causes of coral mortality on the Reef (De'ath et al. 2012; Pratchett et al. 2014; Condie et al. 2018). Large investments in protecting the Reef under climate change, using new and existing interventions, could be at risk unless this coral mortality agent is managed to the extent that outbreaks can be prevented or suppressed. Further, climate change is projected to exacerbate the risk of crown-of-thorns starfish outbreaks (Uthicke et al. 2015).

While there is an ongoing crown-of-thorns starfish management program on the Reef, there is currently no method to fully prevent or arrest outbreaks, in part because juvenile starfish are difficult to detect or remove effectively using conventional means (Westcott et al. 2016; Pratchett et al. 2017). 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, budget estimates, assessments of logistics or risk analyses were not performed for this additional intervention.

Table 1: Interventions used in the modelling of RRAP strategy scope, based on a set of four criteria (columns). In addition, crown-of-thorns starfish control is included given the historical impact of outbreaks on Reef coral cover (De'ath et al. 2012) and the assumption that additional control measures can become available (Westcott et al. 2016; Hall et al. 2017).

	Criteria			
Intervention (code)	Data or theory for parameterisation	Processes impacted (underpinning the objective)	Spatial scale of operation	Cost and feasibility informed, including considerations of method
Shading by cloud brightening – (C3)	Yes (see <u>T6</u>)	Reduced surface irradiance and cooling. Alleviation of bleaching risk via two processes	Regional to Great Barrier Reef-wide (large-scale)	Yes, but developing
Warm-adapted corals (EE and EN type Interventions)	Depends on method (symbiont, host, adult, juvenile, larva, spawning slick, see <u>T3</u>)	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)
Rubble stabilisation (S type interventions)	Yes (see <u>T6</u>)	Increases survival of coral recruits and juveniles that settle on loose rubble	Reef site only (tens to hundreds of metres) (small)	Yes, and with good understanding of logistics
Shading by surface films (C6)	Yes (see <u>T12</u>)	Reflects surface light, which reduces bleaching risk	Reef site only (tens to hundreds of metres) (small)	Yes, and with good understanding of logistics (see <u>T12</u>)
Mixing/ pumping (C1, C2)	Yes, see <u>T12</u>	Mixing or pumping of deeper, cooler water onto shallow coral reef areas	Reef site only (hundreds of metres to 1km) (Small)	Yes, and with good understanding of logistics (<u>T12</u>)
Prevention of crown-of- thorns starfish outbreaks	 (1) Decades of research (Pratchett et al. 2017) (2) Emerging technology (<u>T6</u>) 	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

Two new interventions underwent quantitative model simulations of intervention strategy performance under climate change: warm-adapted corals (enhanced corals) and regional cooling and shading with cloud brightening as the delivery mechanism. The model also examined the effect of additional crown-of-thorns starfish control leading to the full suppression of outbreaks. The results of these strategies (consisting of individual and combined interventions) were also used to inform economic analyses. The rationale for selecting this combination as an example set is illustrated in Figure 6: regional cooling and shading lower heat exposure, effectively moving the temperature scale to the right, but may be insufficient under severe global warming. Warm-adapted corals shift the coral mortality curve to the right in cooperation with the scale being offset by cooling and shading.

Background coral mortality is reduced by additional crown-of-thorns starfish control, supporting coral recovery following bleaching events. In combination, the three measures reduce exposure as well as promote resilience, which is the recommended dual strategy under climate change (Anthony 2016; Darling and Cote 2018; Gattuso et al. 2018; Hughes et al. 2018; Wolff et al. 2018).



Figure 6: The basis for how two new interventions (enhanced corals and large-scale cooling and shading) combined with intensified crown-of-thorns starfish control potentially cooperate and synergise to support coral survival. Blue and orange curves represent survival curves for natural and enhanced coral populations, respectively. Cooling and shading lower exposure to global warming and, combined with intensified crown-of-thorns starfish control enhancing background coral survival, the need for high rates of natural and assisted adaptation is effectively reduced.

4.3 Models

The Reef is subjected to environmental stressors, including cyclones (Wolff et al. 2016; Cheal et al. 2017), associated flooding and run-off of nutrients and sediment (Brodie et al. 2017), heat waves (King et al. 2017) and ocean acidification (Albright et al. 2016a). These stressors are likely to interact under climate change, with differing expected outcomes for the Reef, people and the environment for different climate change trajectories (Anthony 2016, Roth et al. 2017). Projections of global climate trajectories and associated impacts of other environmental pressures are associated with high uncertainty in space and time (Knutti et al. 2005; Bohensky et al. 2011; Thornton et al. 2014; Wolff et al. 2018).

A suite of models and integrated analyses were used to predict and characterise likely environmental futures of the 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 only a limited set of climate projections was used to force environmental pressures (Figure 1) and did not account for complex drivers and feedbacks in the social-ecological systems (Game et al. 2014). Uncertainties associated with intervention efficacy was

modelled by exploring parameter ranges from theory, published data or transparent assumptions. A similar sensitivity approach was applied to the economic analyses. Table 2 provides a summary of the models used.

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	Wolff et al. 2018b Lough et al. 2018
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 hundreds 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 network (via larval connectivity) of 2096 reefs Great Barrier Reef-wide. Models two coral groups: fast- and slow-growing	Condie et al. 2018 <u>T6</u>
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	<u>T6</u>
Economic benefit streams	Millennium Environmental Assessment (MEA) 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	<u>T10</u>
Cost-benefit analyses	Classic CBA	Outputs (as \$ values) from benefit streams and cost projections	Reef-site to Great Barrier Reef-scale	<u>T9</u>

Table 2: Summary of the models used in this study's supply chain of information from climate projections to costbenefit analyses.

4.4 Strategy design and ecological model assumptions

4.4.1 Design

To help inform discussions around which RRAP strategies might show promise under different climate trajectories, model simulations were run using a design that allowed systematic exploration of the performance of interventions individually and in combination. Large- and fine-scale interventions (Table 1) were separated into two groups:

- 1. Large-scale cooling and shading, and the simulated out-planting of warm-adapted corals (<u>T6: Modelling Methods and Findings</u>).
- Rubble stabilisation (<u>T6: Modelling Methods and Findings</u>), fine-scale shading and mixing and cooling (<u>T12: Cool Water Injection</u>).

Group one was used to assess the scope for improving or sustaining coral condition on the Reef at the largest spatial scale (2096 reefs using CoCoNet, Table 2) – an overarching objective of RRAP. Additional crown-of-thorns starfish control (suppressing population densities to below the outbreak threshold) was simulated also, separately and in combination with new interventions, to assess the relative importance of these interventions and the positive impact a full intervention effort might achieve.

Group two was analysed in parallel, in more detail at a finer spatial scale (156 reefs in the Cairns region of the Reef, ReefMod; see Table 2). While understanding intervention scope at a fine spatial scale is at this point a secondary objective of RRAP, it could become critical if the primary large-scale objective cannot be achieved e.g. under severe climate change. Also, small-scale interventions can combine to produce significant cross-scale impacts if well-coordinated and integrated (Neeson et al. 2015).

All interventions in group one were modelled with two levels, in addition to the counterfactual (no new interventions):

- 1. Large-scale cooling and shading: 0.3 and 0.7°C cooling during summer (12 weeks), equivalent of approximately four and eight degree heating weeks (Gleeson and Strong 1995) of accumulated cooling.
- 2. Warm-adapted (enhanced) corals: 10 million and 100 million corals of five-centimetre diameter, out-planted on 100 of the most connected reefs in the network of 2096 modelled reefs. An additional regional study (northern Reef region of Cairns) examined coral restoration applied to 20 connected reefs in a 156-reef network.

For crown-of-thorns starfish control, two levels were also used: business-as-usual control representing current plans to deploy eight control vessels (see below) versus the currently hypothetical scenario of suppressing crown-of-thorns starfish densities to below the threshold for outbreaks (Babcock et al. 2014).

4.4.2 Testing the strategic space for economic analyses

To assess the potential economic performance of RRAP, a set of options was established that captured enough variety to provide answers to the strategic questions. These options comprised combinations of interventions on the Reef. The strategy table (Table 3) describes the strategic space to be tested.

Among these options, one was selected to provide a reference point for testing the other strategic solutions. The reference option chosen was composed of RCP 8.5 (the current climate change trajectory), a moderate investment in warm-adapted corals, a moderate investment in regional cooling and shading, business-as-usual crown-of-thorns starfish control and base-case assumptions for the benefits modelling. Thus, the performance of RRAP investment scenarios under the key strategic questions could be ascertained by examining the departures from this reference option.

Table 3: Strategic space tested including the strategic questions and potential solutions. Grey highlights indicate the reference option (to compare performances) within this strategic space. The dashes in solution 3 represent varying levels for each scenario or condition.

Strategic question	Climate change	Crown-of- thorns starfish control	Warm-adapted (enhanced) corals	Cooling and shading	Assumptions
Solution 1	RCP 8.5	Business-as- usual	Nil	Nil	Base case
Solution 2	RCP 2.6	No outbreaks	10 million p.a.	0.3°C	Sensitive
Solution 3	_	_	100 million p.a.	0.7°C	

A set of options was then selected to test the boundaries of the potential strategies, without testing every possible combination of solutions. It was deemed that this set of options was sufficient to examine performance patterns under different strategic questions. As such, testing for performance among these strategic questions does not reveal *the optimum* RRAP investment scenario, rather it generally indicates the better-performing characteristics of RRAP investment scenarios. This set of options is shown in Table 4.

Table 4: Options assessed as part of the strategic analysis. Data show the options listed alongside their solutions to the key strategic questions. The *reference case* solutions are highlighted in grey. BAU: business-as-usual, NCO: No crown-of-thorns starfish outbreaks, EnC: enhanced corals with higher thermal tolerance.

Option ID	Climate change scenario	Crown-of- thorns starfish	Enhanced corals (EnC, million juveniles	Cooling and shading (°C)	Sensitivity to benefits
	(RCP)	control	deployed p.a.)		modelling
17	8.5	BAU	10	0.3	Base
04	2.6	BAU	10	0.3	Base
19	8.5	NCO	10	0.3	Base
20	8.5	BAU	10	0.7	Base
07	2.6	BAU	10	0.7	Base
22	8.5	BAU	100	0.3	Base
23	8.5	BAU	100	0.7	Base
10	2.6	BAU	100	0.7	Base
24	8.5	BAU	10	Nil	Base
25	8.5	BAU	100	Nil	Base
26	8.5	BAU	Nil	0.7	Base
23s	8.5	BAU	100	0.7	High
44	8.5	NCO	100	0.7	Base
34	2.6	NCO	100	0.7	Base

4.4.3 Intervention assumptions

While the environmental and ecological systems models for the Reef are the best available, there is limited available information in the literature or theory to comprehensively parameterise the models by the interventions listed in Table 1. The largest area of uncertainty was associated with the simulated performance of warm-adapted corals. Warm-adapted corals (referred to as enhanced corals, EnC) consist of the multiple categories of interventions characterised in Figure 3: ER-coral seeding, EE-seeding enhanced corals, and EN-seeding enhanced corals bred from engineered stock (T3: Intervention Technical Summary). All of these categories and their methods of deployment are associated with different levels of performance uncertainty, unintended consequences, strategy timelines, deployment logistics, feasibility and costs (see also NASEM 2019). A simplifying assumption was made in this study that the deployment of warm-adapted corals would enrich natural populations with corals that have five degree heating weeks higher thermal tolerance and that this trait would be passed on to the metapopulation with intermediate heritability (see T6: Modelling Methods and Findings including Appendix B1).

A key consideration regarding large-scale cooling and shading was: under what meteorological conditions might specific cooling and shading interventions, such as cloud brightening, be feasible? For example, where and when could sufficient amounts of natural sea salt particles (of the right size) be distributed in the lower atmosphere to produce sufficient cooling to avert a heat wave? Importantly, large-scale cooling and shading of the type explored in the feasibility program has erroneously been perceived as a geoengineering approach, whereas in fact **it represents an enhancement of the natural range of salt spray concentrations that reflect light over the ocean.**

In this study, the effect of large-scale cooling and shading was simulated by assuming sea surface temperatures during a thermal anomaly could be lowered by between 0.3 and 0.7°C. Also, it was assumed the probability of failure (or decommissioning) of the cooling and shading system during the simulated deployment horizon was zero, a risk that could elevate bleaching risk into the future as corals and other reef organisms adapt to lower, managed temperatures.

Assumptions around crown-of-thorns starfish control were two-fold: those associated with business-as-usual control and those assuming additional (or replacement) control suppressing crown-of-thorns starfish outbreaks entirely. For business-as-usual control, it was assumed eight control vessels would be operating on the Reef according to the Great Barrier Reef Marine Park Authority's crown-of-thorns starfish management program (Darren Cameron, *pers. comm*) and according to strategies and tactics developed in a current and associated National Environmental Science Program project (<u>T6: Modelling Methods and Findings</u>, Appendix B1). For the simulated strategy to prevent crown-of-thorns starfish outbreaks, starfish population size was suppressed to levels below those assumed to represent thresholds for outbreak densities (Westcott et al. 2016). This means crown-of-thorns starfish were not eradicated in simulations, but populations were simply controlled and kept at a low level.

4.5 Ecological model analyses

Results of a comprehensive design of model simulations were analysed to assess the potential of each intervention (separately and in combination) to sustain or improve coral cover in time and space. Details of these analyses were reported in <u>T6: Modelling Methods</u> and <u>Findings</u>.

Summarised below are the key outcomes:

- 1. Expected trajectories of coral cover on the Great Barrier Reef under different climatechange scenarios and variations among reefs in the absence of new interventions (counterfactuals).
- 2. Capacity for corals to adapt naturally to climate change and how this might vary among Reef sectors.
- 3. Simulated responses of relative and absolute coral cover to a set of example interventions in time and space.
- 4. Assessments of the role of intervention synergies when deployed in combination.
- 5. Assessment of the likelihood that simulated deployment of two new interventions (largescale deployment of enhanced corals and cooling and shading) could sustain relative coral cover (greater than 20 percent or greater than 10 percent) with or without additional crown-of-thorns starfish control and under different climate change scenarios.
- 6. Analyses of the extent to which small-scale interventions could meet small-scale objectives where large-scale interventions are out of scope (e.g. under severe climate change).

4.6 Economic consequences of ecological impacts

Simulated projections of coral condition (specifically the Reef Condition Index (RCI), see <u>T6</u>: <u>Modelling Methods and Findings</u>) under the contrasting climate change scenarios and different intervention strategies were used to inform benefit streams and cost-benefit analyses. Spatial projections of the RCI across the Reef domain were partitioned into 157 boxes (each 0.5 degrees latitude by 0.5 degrees longitude) (Figure 7). This conversion provided a spatial dataset that enabled the consideration of adaptation measures by people and reef industries dealing with environmental and ecological changes on the Reef under climate change, with and without RRAP interventions. This included shifts in tourism operations, fishing grounds and consequences for spatial integrity of the social-ecological system. It also facilitated the calculation of benefit streams within and among regions. Within each geographical box, additional estimates of coral condition were provided to support economic analyses and the scope for human climate adaptation. These included coral condition weighted by reef size, maximum condition in a region and numbers of reefs within a box. This has relevance for the availability of healthy reefs above a threshold size for sustaining, for example, tourism in an area serviced by multiple tour operators.

Analyses included:

- 1. Scope for interventions to sustain or grow economic benefit streams to Australians, partitioned into eight ecosystem services, including non-use values.
- 2. Scope for interventions to sustain or grow the present value of the Reef using conservative per-hectare base values for ecosystem services from global studies.
- 3. Implications for effective intervention strategies to sustain or grow net economic benefits while accounting for cost estimates of an R&D program, and costs of future deployment strategies and associated capital expenses.
- 4. Structured decision analyses to identify strategies that support decisions to invest in the RRAP R&D Program.



Figure 7: Example output in the spatial Reef grid used for the outputs of the RCI, composed of coral cover and composition) estimates informing economic analyses. The RCI scale ranges from 0 (no coral cover, and/or no branching coral species) to 1 (coral cover > 50 percent with a high proportion of branching coral species).

4.7 Framing the investment decision: cost-benefit analysis

4.7.1 Analysis objective

A focused set of workshops in July and August 2018 framed the RRAP investment decision process. The method of choice was a cost-benefit analysis as it enables performance assessments of options against two potentially conflicting objectives: economic benefits and costs. During ongoing discussions with the RRAP team, a coherent objective was determined for the analysis:

Assess how investable RRAP is, given expected costs of deployment and range of risks and uncertainties of intervention strategies and climate change scenarios.

4.7.2 Decision criteria

The decision criteria within the cost-benefit analysis were refined during the analysis (Table 5). These criteria formed the groundwork for the various cost and benefit streams developed by the RRAP team and fed into this analysis. During the analysis, it became clear that some criteria were better examined in other parts of RRAP decision-making, outside the cost-benefit analysis e.g. in Decision Support.

Table 5: Decision criteria for the RRAP structured decision-making process. Includes distinction between criteria valid for the cost-benefit analysis and those potentially applicable to other parts of the RRAP decision-making process.

Decision criteria				
Capital expenditure – research	Operating expenditure – research			
Capital expenditure – implementation	Operating expenditure – implementation			
Crown-of-thorns starfish impact	Climate change impacts			
Ecosystem services of the Reef	Avoided losses to commercial fishing			
Tourism impact	Socio-economic value			
Industry multipliers	Water quality value			
Applicable to other parts of the RRAP decision-making process:				
Schedule risk	Technical delivery risk			
Social risk	Ecological risk			

4.7.3 Setting boundaries for economic analyses

The decision criteria and characteristics of the options were combined into a coherent set of boundaries to ensure the cost-benefit analysis was robust. The boundaries for this assessment are detailed in <u>T9: Cost Benefit Analysis</u>. Capital and operating expenditure was included for Reef implementation (<u>T5: Future Deployment Scenarios and Costing</u>) but not for R&D. Outputs of the ecological modelling (<u>T6: Modelling Methods and</u> <u>Findings</u>) and benefits stream modelling (<u>T10: Benefit Streams</u>) were passed to the cost-benefits team for value translation. Some decision criteria were excluded from the analysis, to be included in other parts of the structured decision-making process including technical delivery risks, schedule risks, social risks, ecological risks, learning and inspiration benefits and expenditure multipliers.

4.7.4 Setting baselines for Great Barrier Reef benefits

To assess the performance range of example interventions, the baseline economic benefits produced by the Great Barrier Reef each year over a 60-year horizon was established. The annual benefit streams were produced by the benefits modelling process for three scenarios. The rationale behind this difference is presented in <u>T10: Benefit Streams</u>:

- RCP 8.5 (Business-as-usual emission scenario)
- RCP 2.6 (mMeeting the Paris Agreement emissions target)
- RCP 8.5 with the benefits having high sensitivity to changes in coral condition.

Note that the counterfactuals (i.e. no-RRAP scenario for each of these climate change scenarios) are referred to as 'baselines' in the cost-benefit analysis. The *high sensitivity to changes in coral condition* scenario represents a set of assumptions within the benefits sub-models showing a higher reduction in benefits as the reef condition deteriorates with climate

change. That is, it tests a scenario where the benefits of the Reef are lost at a higher rate due to climate change than under baseline assumptions.

4.8 Cost-benefit analysis

4.8.1 Gathering information for the analysis

Information fed into the cost-benefit analysis was sourced from various RRAP teams and updated as the feasibility program developed. Several iterations of the analysis ensured the latest estimates from engineering and economic valuations were included in the results, while each iteration helped guide the work of the RRAP teams to provide refined information back into the cost-benefit analysis.

4.8.2 Understanding consequences and trade-offs

The consequences and trade-offs in RRAP were understood by defining the boundaries and baselines for the analysis, accounting for the range of options and the decision criteria. These boundaries and baselines were tested among the RRAP teams to ensure they were robust and communicable. Examining the ways the options affected key costs and values was core to the work of the modelling, engineering, estimating and economic teams, and the cost-benefit analysis team worked with them to ensure these consequences and trade-offs were carried through robustly into the analysis. As iterations of the RRAP modelling, engineering, estimating and economic teams, and the cost-benefit analysis and economic valuations progressed, the level of understanding of these consequences and trade-offs was refined.

4.8.3 Logical analysis

During the evolution of the structured decision-making process, the possibility of using logical analysis methods was kept open until the work of the RRAP teams confirmed the type of cost-benefit analysis to be used. The cost-benefit analysis included:

- Financial and economic costs and benefits
- Sensitivity to uncertainty across financial expenditure and economic benefits
- Sensitivity of economic valuations to changes in ecological condition
- Comparative performance under two contrasting climate change trajectories.

4.8.4 Facilitation of decisions and commitment to action

The cost-benefit analysis team worked iteratively with other RRAP teams to ensure analysis outcomes could effectively facilitate robust decisions about how investable RRAP was, allowing the right level of commitment to be made to future programs. There were three reviews of the results prior to generation of the final results, insights and recommendations. During this process, the combined RRAP team generated, reviewed and finalised a set of findings for decision-makers to consider and potentially commit to action.

5. **KEY FINDINGS**

The following key findings are presented in three sections, consistent with the problem formulation and task of this sub-study: results of bio-physical modelling, gross benefit streams and associated economic analyses, and cost-benefit analyses.

5.1 Bio-physical modelling

5.1.1 Counterfactuals

Model projections of live coral cover and coral condition (a derivative of coral cover that takes account of coral composition) without new interventions (no-RRAP case, counterfactuals) produced three key findings:

- Coral cover (and condition) is expected to decline further under RCP 2.6, but natural adaptation (via a combination of soft and hard natural selection, <u>T3: Intervention</u> <u>Technical Summary</u>) may lead to improved condition after 2050. Global warming is predicted to stabilise mid-century (IPCC 2014) and, under this scenario, surviving coral populations would recover and gain abundance (Figure 8A). Connectivity in the network of reefs may interact with natural adaptation to drive the spatial patterns of coral recovery.
- 2. The projection of coral cover for the RCP 2.6 counterfactual may be optimistic for at least three reasons. First, the levelling-out of coral cover is driven by the survival and recovery of a shrinking gene pool of hardier corals (within and among species). Thus, while coral cover stabilises at a relatively high level, genetic diversity may be reduced. Second, loss of sensitive coral species under climate change was not accounted for in simulations, so there is a hidden biodiversity (community composition) downside not represented in the results. Third, by excluding ocean acidification from model simulations, a key driver of coral decline is ignored—a driver that is potentially already reducing coral reefs' capacity for coral recovery (Albright et al. 2016b; Ortiz et al. 2018) and sustained resilience (Anthony 2016; Hoegh-Guldberg et al. 2017).
- 3. Under expectations of business-as-usual climate change (RCP 8.5), coral cover under the counterfactual was projected to decline throughout the modelled period, with cover in 2075 likely to fall below five percent (Figure 8B). A high capacity for natural adaptation would buy coral cover (albeit at less than 10 percent) for two to three decades after 2050 but would then be followed by decline. Similar to projections for RCP 2.6, the projection of coral cover under RCP 8.5 might also be optimistic, i.e. underrepresenting impacts on genetic diversity and species diversity and the effects of ocean acidification.
- 4. Large variation in predicted reef state (coral cover) under RCP 2.6 indicates some reefs may have naturally high resilience, potentially representing opportunities for high ecological return on RRAP investment.
- 5. Under RCP 8.5, variation in coral cover among reefs is also significant, with some reefs projected to sustain coral cover greater than 10 percent until 2060 under assumptions of high natural adaptation (Figure 8B). Restoration and adaptation strategies that identify

and prioritise intervention on such reefs could be an avenue to enhance program effectiveness under RCP 8.5.



Figure 8: Counterfactuals and natural adaptation. Simulated trajectories of coral cover on the Great Barrier Reef under scenarios of best-case moderate climate change (A, RCP 2.6) and business-as-usual severe climate change (B: RCP 8.5) and low and high rates of natural adaptation. Outputs are for CoCoNet for the Reef domain. See also Figure 11 in detailed modelling report (<u>T6: Modelling Methods and Findings</u>).

Results of projections for the counterfactuals provided the baseline against which the performance of interventions was assessed. Importantly, counterfactuals should only be regarded as likely, but uncertain, future projections in the absence of RRAP, not precise predictions. For this feasibility program, likely projections may be as informative as precise outlooks because results of simulations involving intervention strategies focus on estimated differences between intervention and counterfactuals. Therefore, given multiple sources of uncertainty, and the fact that counterfactuals are largely cancelled out in comparisons of how intervention strategies perform, results reported in economic analyses (margins) are relatively insensitive to variation in the counterfactuals for each of the two climate change scenarios.

Key findings of Reef-wide modelling of interventions results and analyses:

- Regional cooling and shading (RCS) combined with intensified starfish control (No crown-of-thorns starfish Outbreaks, NCO) showed large scope for improving coral condition under RCP 2.6 (Figure 9F) or reducing the loss of coral condition under RCP 8.5 (Figure 9M).
- 2. Regional-scale cooling and shading showed the greatest scope to enhance coral condition as a single intervention, especially under RCP 2.6 (Figure 9B & I).

- 3. The projection for the intervention strategy that simulates all interventions acting in combinations led to more than 50 percent coral cover on the Reef (median for 2096 reefs) under RCP 2.6 (Figure 9G). This finding may be regarded as optimistic for three reasons. First, simulations assume best-practice conventional management including improved water quality and perfect control of crown-of-thorns starfish. Second, exposure to heat waves is reduced by approximately five degree heating weeks each combined with the out-planting of 100 million thermally-enhanced corals per year. Third, the likelihood of RCP 2.6 eventuating given current global commitments is currently less than five percent (Raftery et al. 2017). Based on these assumptions, improvement in coral cover above current levels would be expected, consistent with levels of recovery observed on coral reefs in north-west Australia (Gilmour et al. 2019). It is possible, however, that some continued ocean acidification under RCP 2.6 (IPCC 2018) would compromise the capacity of corals to reach cover beyond 50 percent.
- 4. Given that RCP 8.5 is the more likely climate scenario unfolding and the RRAP mission is to produce interventions that are robust to any climate scenario, the most realistic best-performing projection under RCP 8.5 may be represented by Figure 9N. This option presents an outlook of around 20 percent peak coral cover (median of 2096 reefs) by 2050, subsequently declining to less than 10 percent by 2075. Again, by not accounting for the loss of sensitive species and not including the effects of ocean acidification, this projection may also be optimistic.
- 5. Modelling results illustrate there is a window of opportunity for action at two levels: (1) early global mitigation of emissions and (2) early and effective restoration and adaptation interventions. The potential reward of acting, versus not acting, on both fronts in this window of opportunity is illustrated by comparing Figure 9G with 9N. While RCP 2.6 combined with a strong intervention strategy could potentially safeguard coral condition this century (Figure 9G), restoration and adaptation actions under RCP 8.5 would only serve to postpone eventual decline (Figure 9N).
- 6. Combining all three interventions (regional cooling and shading, out-planting enhanced corals and starfish suppression) produced the strongest impact. This is consistent with the study's premise that the support of multiple processes using different functional categories of interventions is an effective strategy for supporting ecosystem resilience (Figures 4-6). The combined effect was greater than the summed effect of these interventions individually (see Figure 17 in <u>T6: Modelling Methods and Findings</u>).
- 7. The simulated out-planting of 100 million juvenile colonies of 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 9A & 9H). Detailed analyses simulating the out-planting of 40 million juvenile corals with 1°C and 2°C added tolerance on 20 reefs in the Cairns region showed similar results (see Figure 22 in <u>T6:</u> <u>Modelling Methods and Findings</u>).
- 8. As a single intervention, the simulated suppression of crown-of-thorns starfish outbreaks provided intermediate scope, with greater impact under RCP 2.6 (Figure 9C & 9J).
- 9. All interventions led to gain in absolute coral cover (i.e. hectares of coral as opposed to percent area occupied by coral), but, again, the gain was strongest when all three interventions were combined (Table 6). While enhanced corals only produced marginal impact as a single intervention for relative coral cover, impacts became significant when combined with regional cooling and shading and complete suppression of crown-of-thorns starfish outbreaks and expressed as change in absolute coral cover (Table 6).
- Predicted likelihoods of sustaining coral cover above 20 percent in the Cairns and central sections, representing the average Reef coral condition in the past decade (De'ath et al. 2012; Australian Institute of Marine Science 2018), only exceeded 50 percent under RCP 2.6 for strategies involving cooling and shading and either enhanced corals or suppression of crown-of-thorns starfish outbreaks (Table 7).
- 11. Under RCP 8.5, these intervention combinations were only likely to sustain high coral cover to the middle of the century, after which likelihoods drop to two to 15 percent, consistent with the findings of other model studies (Wolff et al. 2018).
- 12. Lowering the RRAP objective to achieving a target of 10 percent coral cover representing a compromise to achieve only half the historical coral cover on the Reef before the mass bleaching event in 1998 (Australian Institute of Marine Science 2018) 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 strategies involving cooling and shading, and only until 2050 (Table 7).
- 13. Projections of coral cover showed high spatial heterogeneity. Thus, some reefs may have higher resilience (e.g. via connectivity in the reef network) or are in locations relatively protected from disturbances (crown-of-thorns starfish, storms and bleaching), and vice versa. Results suggest that the far northern Reef has greater scope for sustaining absolute coral cover with the help of interventions than the southern Reef in particular (Figure 20 in <u>T6: Modelling Methods and Findings</u>).



Figure 9: Projections of coral cover for interventions (solid line, blue envelopes) and counterfactual (dashed line, grey envelopes) under RCP 2.6 (A–G) and RCP 8.5 (H–N) based on CoCoNet simulations. 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 <u>T6: Modelling Methods and Findings</u> for details.

Table 6: Total number of reefs that move to higher categories of coral cover (A: relative, proportional to habitat area and B: absolute area of coral cover) between 2050 and 2075 (Figure 9). EnC: enhanced corals; CS: cooling and shading; NCO: no crown-of-thorns starfish outbreaks.

		Interventions								
Cover	Scenario	EnC	CS	NCO	EnCCS	EnCNCO	CSNCO	EnCCSNCO		
A: Relative (prop)	RCP 2.6	183	734	348	726	359	1247	1152		
	RCP 8.5	68	699	231	791	231	1172	1296		
B: Absolute (km2)	RCP 2.6	12	34	42	45	52	212	265		
	RCP 8.5	7	36	26	30	11	85	142		

Table 7: Summary of likelihoods that the objective of sustaining coral cover at greater than 20 percent or greater than 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. CS: cooling and shading (0.7°C) regionwide, EnC: enhanced corals, 0.4°C added heat tolerance for 100 million juvenile corals deployed annually, NCO: no crown-of-thorns starfish outbreaks.

				Probabili cover ex 20 pe	ty of coral cceeding ercent	Probabilit cover ex 10 pe	ty of coral cceeding ercent
RCP		Intervention	6	2050	2075	2050	2075
2.6		Counterfactua	al	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		Counterfactua	al	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

5.2 Local-scale analyses

5.2.1 Rubble stabilisation

Simulated stabilisation of loose rubble had no detectable effect on coral cover in the Cairns region under the assumption of a low natural rate of adaptation (Figure 10A). Because rubble on the Reef is typically generated by natural physical disturbances (predominantly storms) that break coral, the extent of rubble was projected to remain low within the Cairns sector (max. ~10 percent) due to low coral cover. Consequently, the stabilisation of small rubble beds (i.e. with five to 10 percent cover of rubble) had limited impact on the survival of juvenile corals.

Conversely, rubble stabilisation had higher efficacy under RCP 2.6 when assuming high adaptation potential (Figure 10B). This was because corals achieve greater cover and so may produce more loose rubble following disturbances. While this highlights that loose rubble has a greater impact where corals are abundant, it reveals the magnitude of the negative feedback that impedes coral recovery. One important implication is that healthy reefs today are likely to benefit the most from rubble stabilisation post-disturbance. It is thus more cost-efficient to focus this intervention on reefs where rubble is abundant. It can be anticipated that much greater regional benefits might be achieved with a strategy that optimises the sequence by which reefs are selected for rubble stabilisation. In particular, the threshold value of rubble cover used to trigger intervention is likely to have a disproportionate effect on the benefits measured at the scale of the region. Importantly, the impacts of rubble stabilisation can be overlooked in cost-benefit analyses based on pessimistic reef state projections, i.e. the 'rubble problem' is contingent on the amount of corals available (the source of rubble) prior to disturbance.

Under RCP 8.5, rubble stabilisation had no discernible effect on coral cover under any assumption of adaptation and deployment strategy (Figure 10C and 10D). Similar to the RCP 2.6 scenario of low adaptation potential, reefs in the Cairns region were projected to have such low levels of coral cover that disturbances did not create enough rubble to affect juvenile coral survival.

5.2.2 Key findings

- 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 where there was sufficient cover of branching corals that generated 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 region maintained such low levels of coral cover that disturbances did not create enough rubble to affect juvenile coral survival.

- 4. Simulations of reflective ultra-thin surface films dispersed on individual coral reefs during warm summer weeks showed only marginal efficacy. Detailed studies of hydrodynamics and reef bathymetries, however, reveal the method may have efficacy on a small subset of reefs (see <u>T13: Ultra-Thin Surface Films</u>).
- 5. Cold-water pumping and mixing studies showed these interventions would only have efficacy, and potentially show cost-efficiency, on reefs that meet a narrow set of criteria: high-value reefs (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 (T12: Cool Water Injection).



Figure 10: Simulated impact of rubble stabilisation for 10 and 20 reefs in the Cairns region under projections of (A&B) moderate and (C&D) business-as-usual climate change and low (A&C) and high (B&D) rates of adaptation. The graph shows mean (lines) and standard deviation (envelopes) coral cover for all 156 coral reefs in the region. Means and standard deviations were established for 40 replicate model runs.

5.3 Economic analyses

5.3.1 Directly quantifiable economic benefit streams

The modelling of the economic benefits from the Reef under the baseline climate change scenarios, as well as under interventions, was conducted by the economic benefits team in conjunction with the ecological modelling and cost-benefit analysis teams, to ensure all

information passed among the teams was robust. The details about how the baselines (counterfactuals) and options were modelled are contained in <u>T6: Modelling Methods and</u> <u>Findings</u>, with the benefits streams input to the analysis defined in Appendix G of that report.

The 2015 monetary 'value' of Reef-dependent benefit streams and their low and high cases were used to examine sensitivity to valuations. Ecological modelling results were passed to the cost-benefit analysis team as eight sets of benefit streams per option, as well as eight sets of benefit streams for applicable baselines. These benefits streams were produced using the base-case valuation parameters shown in Table 8. To assess sensitivity, the benefits streams were varied using a range of parameters between the low-case and high-case valuations, also shown in Table 8.

Table 8: Estimates of the monetary 'value' of Reef-dependent benefit streams per annum. Data are used as parameters in the cost-benefit analysis. Figures in \$M p.a. using 2016 values.

Benefit stream	Low (\$M)	Base (\$M)	High (\$M)
Tourism	1200	1543	1800
Non-use (existence, bequest and option)	490	1015	1200
Indigenous	170	629	2000
Option (medicinal)	20	174	1000
Storm surge	10	26	50
Recreational fishing	1.2	11	15
Commercial fishing	2.2	6	8
Coral harvesting	0.02	0.3	0.6

The monetary values of eight benefit streams were estimated using methods derived from the MEA (Millennium Ecosystem Assessment 2005) and CICES (Common International Classification of Ecosystem Services) (Haines-Young and Potschin 2012). This involved integrating ecosystem service values over a 60-year horizon and applying different discount rates, i.e. accounting for the loss of present-day monetary values over time (e.g. Costanza and Daly 2006). Specific ecosystem services analysed were:

- Material benefits (termed provisioning benefits in the MEA/CICES):
 - Commercial fishing
 - Coral harvesting
 - Medicinal option values (reflecting some biodiversity/gene pool values)
- Regulating services
 - Storm surge protection
- Non-material (cultural) benefits
 - Tourism
 - Indigenous cultural values
 - Recreational fishing

• Non-use values.

5.3.2 Present-day values of benefit streams from Great Barrier Reef coral condition

- Present-day estimates of the monetary value of measurable benefits from the Reef to Australians amount to at least \$3.4B per annum. This corresponds to a net present value of approximately \$100B, assuming a 3.5 percent discount rate and a 60-year horizon. Note that the estimated present value of benefits presented here exceeds the \$56B estimate by Deloitte Access Economics (2017), which used a shorter time horizon (33 years) and a higher discount rate (3.7 percent). Adjusting our time frame and discount rate to that of Deloitte's produces a present value estimate of \$64B.
- 2. Cultural services (tourism, non-use values, Indigenous cultural value) account for more than 90 percent of measurable benefits from Great Barrier Reef coral reefs. Option values are presently the next most important benefit.

The benefits of intervention in each option was calculated by subtracting the applicable baseline (counterfactual) from the total Reef benefit streams for that option. The difference between the two is the increase in annual benefits due to the RRAP investment and intervention. The example given in Figure 11 demonstrates this calculation for one option (*RCP 8.5, business-as-usual crown-of-thorns starfish control, 10 million enhanced corals per year* (~2 ha) *and 0.7°C from regional cooling and shading*) compared to the RCP 8.5 baseline. The RCP 2.6 baseline was used for all RCP 2.6 options, and the RCP 8.5 baseline was used for all RCP 8.5 options, except for one option that simulated a high level for the out-planting of enhanced corals (100 million corals per annum) used for the baseline RCP 8.5 High Sensitivity.



Figure 11: Example of the calculation of benefits of intervention. Results are shown as the difference (shaded area) between the baseline benefits under RCP 8.5 (green solid line) and the benefits from one example option (*RCP 8.5, business-as-usual crown-of-thorns starfish, 10 million enhanced corals p.a., 0.7°C cooling*), dashed line. The benefit of intervention is also plotted separately (solid grey line) to show on the same scale as the overall Reef benefits. Note that the relatively low sensitivity of benefits to changes in coral condition under the RCP 8.5 scenario is driven by assumptions of high capacity of adaptation by individuals and industries (e.g. tourism and fisheries, see <u>T10: Benefit Streams</u>).

5.3.3 Projections of benefit streams from healthy Great Barrier Reef corals under climate change and new intervention strategies

- Under RCP 8.5, the projections of annual benefit streams (undiscounted) for the counterfactual scenario amounted to a loss of \$1.2B to \$1.8B between 2016 and 2075 (<u>T10: Benefit Streams</u>).
- Economic damage avoided (for benefit streams only) by alignment with the moderate (RCP 2.6) compared to the severe (RCP 8.5) climate change trajectory is in the order of \$28.5B before considering the benefits of interventions (see also <u>T10: Benefit Streams</u>).
- 3. Under RCP 2.6, the estimates of potential damages avoided (or gains achieved) via new interventions, using the most effective intervention strategy relative to the counterfactual, ranged from \$10.7B to \$17.5B (Table 9).
- 4. Under RCP 8.5, the scope for new interventions to prevent economic damages ranged from \$3B to \$29B (Table 9). The greater scope to prevent damages under RCP 8.5 compared with RCP 2.6 is a function of the steeper predicted decline in coral condition (i.e. more damage to prevent) for the RCP 8.5 counterfactual.
- Economic damage prevention for tourism and non-use values including indigenous values were orders of magnitude more important than those for commercial and recreational fishing and coastal protection (Table 9). Also, we assumed relatively low medium-term economic benefits from coastal protection for the Reef compared to other more nearshore reef systems (Ferrario et al. 2014).
- 6. Results based on the estimates of scope only suggest that the value of damage prevention by RRAP interventions could be larger than the current value of benefit streams for both climate-change scenarios, but in particular for RCP 2.6 (Table 9).

5.3.4 Ecosystem services economic benefit modelling

To complement the estimates of how benefit streams are likely to be affected by RRAP interventions, the magnitude by which area-based ecosystem service values might change under climate change and intervention strategies was estimated. These estimates were built on the mid to lower range of published ecosystem service values for coral reefs globally, specifically \$90k per ha per year (TEEB 2009/UNEP; Sukhdev et al. 2009) and \$352k per ha per year (Costanza et al. 2014). The low base estimate used here is derived from a United Nations Environment Programme study (The Economics of Ecosystems and Biodiversity 2009), which showed Reef ecosystem values may reach US\$1.14M per ha per year (2007 values). In the low estimate, coastal protection from storm damage was excluded. This was based on the rationale that changes in live coral cover per se may have a limited effect on the Reef's capacity to protect the Queensland coast this century. In the longer term, sealevel rise, combined with the loss of coral and erosion of calcium carbonate structures (Woesik et al. 2015; Perry et al. 2018), may affect coastal wave exposure.

The following assumptions were used to produce these estimates. First, only areas of coral real estate were included, i.e. areas categorised as hard consolidated reef suitable for coral growth (Hedley et al. 2018). This may underestimate ecosystem service values by an order

of magnitude. Second, it was assumed that per hectare ecosystem services scale directly with coral condition, i.e. coral cover and composition. Third, only high-effort levels for interventions were presented, consistent with results in Table 7, i.e. only high intervention potentials were explored.

5.3.5 Summary of present value estimates for interventions based on reef area

- A RRAP strategy that combines large-scale cooling and shading and out-planting of warm-adapted corals, under intensified crown-of-thorns starfish control may produce undiscounted gross benefits relative to the counterfactual of up to \$640B over 60 years under RCP 2.6. A discount rate of 3.5 percent takes the estimated benefits under this scenario up to \$143B (Figure 12 and Figure 13).
- 2. Under RCP 8.5, estimated benefits for the above intervention strategy fall to about **half of those under RCP 2.6** (for both undiscounted and discounted values).
- 3. The \$29B estimate of total damage avoidance to benefit streams by this strategy under RCP 8.5 is bracketed within the discounted high-value estimates presented here (\$84B).
- 4. As single interventions, large-scale cooling and shading could deliver twice the ecosystem services benefits compared with intensive crown-of-thorns starfish control (i.e. no crown-of-thorns starfish outbreaks). Varying assumptions with respect to cooling and shading efficacy, risk of system failure and scale of deployment could change this ratio markedly.
- Warm-adapted (enhanced) corals as a stand-alone intervention was only projected to produce significant economic benefits under RCP 2.6 over the 60-year horizon (45 years effectively as deployment is simulated as starting in 2031) and only for undiscounted estimates (Table 10).

Table 9: Estimates of economic benefits resulting from intervention strategies involving large-scale cooling and shading and out-planting of warm-adapted corals under intensified crown-of-thorns starfish control and contrasting climate change scenarios (RCP 2.6 versus 8.5). Benefits are calculated as undiscounted damages over 60 years (2016 to 2075).

			Predicted undisco avoided via RRA		
Benefit Stream	Current value in \$M per year (range)	Mechanisims 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)	



Figure 12: Present value benefits to the Reef of the intervention options in 2016 dollars, discounted at 3.5 percent per annum over 60 years. Base-case and high-case benefits values are presented, using the directly quantifiable method and the high-case for the ecosystem services method, respectively. See Table 4 for intervention codes.



Figure 13: Total benefits of the intervention options to the Reef in 2016 dollars, showing an undiscounted view of benefits over 60 years. Base-case and high-case benefits values presented using the directly quantifiable method and the high-case for the ecosystem services method, respectively. See Table 4 for intervention codes.

5.4 Option costing

Costings for developing and deploying the interventions were produced by the engineering team and are available in <u>T5: Future Deployment Scenarios and Costing</u>. These are detailed along with timelines in Table 10. Capital costs were broken into lifecycle costs, according to the following principles:

- Capital expenditure is based on a three-year build, starting in 2027, with the cost spread equally over three years
- Capital expenditure on maintenance is the annual sustaining capital costs estimated at four percent of initial build costs, starting in 2030 and continuing over the life of the program
- Capital expenditure mid-life refurbishment/replacement is 33 percent of initial build costs, based on a three-year refurbishment, starting in 2054, with costs spread equally over three years.

Table 10: Capital and operating costs used in the construction of options costing.

Intervention	CapEx (\$M)	CapEx Maint. (\$M)	CapEx Refurb (\$M)	OpEx (\$M)
Aquaculture				
10 million enhanced corals p.a.	203	8.2	68	31
100 million enhanced corals p.a.	2030	82	677	306
Timeline	2027–2029	2030–2075	2054–2056	2030–2075
Cooling and shading				
Low cooling (0.3°C)	-	-	-	107
High cooling (0.7°C)	-	-	-	213
Timeline	-	-	-	2025–2075

5.5 Cost-benefit analysis

The cost-benefit analysis intends to determine, within the uncertainty inherent in the program, whether there is a wide range of options and assumptions over which investment in RRAP is favourable. This is to assist decision-makers in determining whether the program should progress to the R&D stage. The high degree of uncertainty within RRAP at many levels of the investigation means the results of this cost-benefit analysis should be considered an early attempt to examine the performance of potential program elements, not as a demonstration of what will or should be implemented, nor a recommendation of where specific investments should be made. Recommendations around investment in specific interventions will be guided by the RRAP Decision Support Sub-Program.

5.5.1 Analysis parameters

Key parameters were determined in framing the cost-benefit analysis, research was undertaken into appropriate economic multipliers and analysed over a range to capture key uncertainties. The analysis parameters are shown in Table 11. To express the time-value of money, a base-case discount rate of 3.5 percent was selected, reflecting common economic discount rates (including that used in the recent Deloitte study (3.7 percent)). Further, a low-case discount rate of 0 percent was selected for the *sensitivity* analysis to test the concept that the future is as valuable as the present (i.e. the future is not discounted). Capital and operating expenditure were tested with a range of +50 percent and -50 percent to give an appreciation of the effect of uncertainty in the costings on the performance of RRAP. Expenditure multipliers, although not directly included in the cost-benefit assessment, were determined as an indicator of the amount of flow-on effects from expenditure associated with RRAP into the local economy (for more details on the economic multipliers, see <u>T9: Cost-Benefit Analysis</u>).

Cost-benefit analysis Units Low Base High parameter 1 Period years 2016-2075 (60 years) Lifecycle years 0 3.5 Annual discount rate % Capital expenditure % 50 100 150 Operational expenditure % 50 100 150 0 Expenditure multiplier \$/\$ _ 0.86, 1.42

Table 11: Parameters used to frame the RRAP cost-benefit analysis.

5.5.2 Benefits to the Reef

Key findings of the cost-benefit analysis:

- All RRAP intervention options explored here through simulations are projected to provide economic benefits to the Reef, with higher levels of intervention generally showing higher levels of net benefits.
- Assuming a high efficacy level for regional cooling and shading (0.7°C) would result in higher benefits to the Reef, beyond present benefits ranging from \$0.9B to \$4.6B.
- Generally, greater control of crown-of-thorns starfish provides more substantial benefits to the Reef, showing difference in present benefits of between \$7.9B and \$6.7B.
- Generally, an increase in investment in warm-adapted (enhanced) corals (when accounting for synergies with other interventions) result in greater net benefits to the Reef, showing differences in present benefits of between \$0.7B and \$1.5B.

Examining the effect of climate change scenarios on the benefits to the Reef of RRAP interventions must be carefully understood in terms of baselines. In particular, limiting climate change (a wider effort that is outside the RRAP scope) would represent economic benefits in the order of \$28.5B (see also results of benefit stream analysis, <u>T10: Benefit</u> <u>Streams</u>).

5.5.3 Costs of options to intervene

These results demonstrate the differences in potential total RRAP costs according to the level of interventions, as well as annual variation in costs including upfront capital costs and mid-life capital replacement. Annual costs for the most expensive options vary up to \$600M ongoing, with upfront costs of \$900M per year for three years. Annual costs for the least expensive options vary down to \$30M ongoing, with upfront costs of \$80M per year for three years.

Key findings on the costs of options to intervene:

- Higher levels of RRAP intervention generally show higher costs.
- Across options, greater investment in warm-adapted (enhanced) corals shows an increase in present costs of approximately \$4B.
- Greater efforts in regional cooling and shading shows increase in present costs of approximately \$1.9B.
- Investment in the prevention of crown-of-thorns outbreaks would represent costs of approximately \$0.4B.

5.5.4 Expenditure in the Australian economy

The RRAP expenditure presented in this analysis could provide a range of flow-on effects to the Australian economy. The cost-benefit analysis does not include expenditure multipliers as they are secondary benefits. However, in this section, we indicate the ranges of potential flow-on effects in the Australian economy, separate to the cost-benefit analysis.

While it is likely that a significant portion of the expenditure will be within the Australian economy on local resources, it is also likely that some portion of the expenditure will be international. At this early stage of RRAP, there is not sufficient resolution on the breakdown of costs to gain a full understanding of expenditure in the Australian economy. However, using broad assumptions, we can start to understand the potential multiplier benefits. For this assessment, we present two options:

- 80 percent expenditure in the Australian economy with a simple multiplier of 0.82 representing the gross value added generated directly by the sector receiving the expenditure (direct effect) and the sectors' supply chains (indirect effect).
- 80 percent expenditure in the Australian economy with a total multiplier of 1.42 representing the gross value added generated through direct and indirect effects and through consumer spending of income from employment in affected sectors (induced effect).

Over the RRAP lifecycle, there is potential for expenditure in the Australian economy including flow-on effects of between \$1.2B and \$28B present value (2016, 3.5 percent), depending on the option chosen (Figure 14).



Figure 14: Present value expenditure and flow-on effects in the Australian economy of interventions on the Reef in 2016 dollars and discounted at 3.5 percent per annum. Results are presented for a simple multiplier of 0.82 (lower edge of box) and a total multiplier of 1.42 (upper edge of box) and include capital expenditure (CapEx) and operational expenditure (OpEx) presented for base-case cost values. Key to intervention codes: Intervention ID in brackets, '2.6' and '8.5' refer to RCP 2.6 and 8.5, respectively; 'BAU' and 'NCO' refer to business-as-usual and no crown-of-thorns starfish, respectively; '10m' and '100m' refer to 10 million and 100 million enhanced corals deployed, respectively; and '0.3degC and 0.7degC refer to cooling levels assumed for regional cooling and shading, respectively. See also Table 4 for intervention codes.

5.5.5 Net benefits of RRAP

The net benefits of RRAP options were calculated over the analysis lifecycle to compare them directly. A net present value calculation was then applied to obtain a clearer picture of the comparison between options given annual variation in costs including upfront capital costs and mid-life capital replacement. The net present value was calculated in 2016 dollars, with an annual discount rate of 3.5 percent, a typical economic discount rate. The results are presented in Figure 15 as the yellow line along with a breakdown of the present value costs and benefits. These results are for the base-case for benefit values and the base-case for capital expenditure (CapEx) and operational expenditure (OpEx) parameters. The balance of \$6.8B and a net present value of \$4.1B (2016, 3.5 percent).



Figure 15: Present value of net benefits of interventions on the Reef in 2016 dollars and discounted at 3.5 percent per annum. Values include breakdown into capital expenditure, operational expenditure and benefits presented for base-case benefit values and cost values, including capital expenditure (CapEx) and operational expenditure (OpEx). See Figure 14 and Table 4 for intervention codes.

Using an annual discount rate of zero percent, the total net benefits from RRAP intervention options in 2016 dollars without discounting were also examined (Figure 16). Over the 60 years, the total net benefits vary between \$28B and \$17.6B.



Figure 16: Total net benefits of interventions on the Reef in 2016 dollars, showing an undiscounted cost-benefit analysis of RRAP. Data are for base-case benefit values and cost values. See Figure 15 for details of intervention codes.

Key findings – net benefits of RRAP:

- Higher levels of regional cooling and shading increase costs, but the increased benefits are roughly equivalent to the increased costs in the low enhanced corals scenario (compare options (24), (17), and (20) in Figure 13).
- Higher levels of cooling and shading show increased costs, but are outweighed by increased benefits in the high enhanced corals scenario (compare options (25), (22) and (23) in Figure 13) about \$4.5B net benefit over 59 years when moving from cooling and shading of 0°C to cooling and shading of 0.7°C.
- Higher enhanced corals show increased costs that are not outweighed by increased benefits in the high cooling and shading scenario (compare options (26), (20) and (23) in Figure 13) – about \$5.5B net cost over 59 years when moving from cooling and shading of 0°C to cooling and shading of 0.7°C.
- Higher enhanced corals show increased costs that are not outweighed by increased benefits in the low or no cooling and shading scenarios (compare options (17), (22), (24) and (25) in Figure 13) – about \$6B net cost over 59 years from enhanced corals of 10 million per annum compared with 100 million per annum with 0.3°C cooling and shading.
- Higher investment in crown-of-thorns starfish control shows strong net benefits, which is evident in the comparisons between (23) and (44) and (10) and (34) in Figure 13, showing differences in the net present value of \$7B and \$5.9B, respectively.
- Increased sensitivity to changes in the RCI shows an increase in the net benefits of high enhanced corals + high cooling and shading (23) versus (23s) – about \$3B over 59 years, moving it from a negative value proposition to a neutral one from an economic perspective.
- Across RRAP, the options have positive net economic outcomes except for high investments in enhanced corals.

Implications of these findings:

- Higher cooling and shading show limited net benefits unless more than 10 million enhanced corals are out planted per annum.
- The out-planting of 100 million enhanced corals per annum, however, is less beneficial, due to the high costs.
- There is potentially an interim option where less is spent on enhanced corals, but a proportionally larger benefit is gained (e.g. ~30 million corals per annum); this is particularly attractive to investigate as it would increase the benefits accruing due to cooling and shading expenditure.
- The complete control of crown-of-thorns starfish outbreaks shows significant positive change in net value relative to the business-as-usual control level.
- Higher values for the sensitivity of benefits streams to changes in coral condition (i.e. economic responsiveness to ecological change) even at just base-case benefits valuations can transform some of the negative performing scenarios into neutral or positive, with positive performing scenarios performing even better.

5.5.6 Sensitivity analysis

When examining the overall RRAP investable space from a probabilistic perspective, the findings become clearer. The present values of net benefits were calculated over 1000 iterations of sensitivity parameters where each of the sensitivity parameters (benefits

valuations, expenditure parameters) was assigned a PERT distribution to weight occurrence towards the expected value (which in this cost-benefit analysis are the base-case parameters). The probability distributions are plotted in Figure 17 and Figure 18. The probabilistic analysis demonstrates that there is likely to be a narrower range of cost-benefit performance of RRAP than is articulated under a full range of assumptions. It is important to emphasise that as RRAP enters successive stages, uncertainty about costs and benefits will be reduced and underperforming options will be removed or adjusted to ensure optimum performance. Thus, it is likely that the lower-performing options and ranges of this costbenefit analysis become less likely, while the better performing options and ranges of this analysis become more likely. In Figure 18, this is demonstrated visually by removing the worst performing options, as they would be unlikely to be implemented, showing a better performing set of cost-benefit performance for RRAP.



Figure 17: Present value of net benefits of interventions on the Reef in 2016 dollars and discounted at 3.5 percent presented as a probability distribution (mean, 90 percent probability interval, and standard deviation boundary) of 1000 iterations across PERT distributions for ranges of sensitivity parameters (benefits valuations and cost parameters). This demonstrates the ranges of potential RRAP performance, noting that as the interventions are researched and developed, uncertainty will decrease, and underperforming options will be eliminated to focus on better performing ranges. See Figure 14 for intervention codes.



Figure 18: Present value of net benefits of interventions on the Reef in 2016 dollars and discounted at 3.5 percent, removing poorly performing options (largely the 100 million enhanced corals options) presented as a probability distribution (mean, 50 percent probability interval, 90 percent probability interval) of 1000 iterations across PERT distributions for ranges of sensitivity parameters (benefits valuations and cost parameters); this visually demonstrates a focus on better performing ranges. See Figure 14 and Table 4 for intervention codes.

Key findings of the sensitivity analysis results:

- Despite the range of uncertainty, there is a significant potential economic upside of RRAP at base-case assumptions of up to \$4.1B net present value (2016, 3.5 percent), which is equivalent to \$28B undiscounted over 60 years.
- Taking a 90 percent probability interval for 1000 iterations of sensitivity parameters, the potential upside of RRAP is up to \$14.5B net present value (2016, 3.5 percent).
- RRAP is an investable proposition across a broad range of uncertainty, which includes across a wide range of economic benefits valuation conditions.
- As the cost-benefit analysis is refined in future stages of RRAP, net benefits can be assured before investment in implementation.
- Initial findings suggest an optimal option may exclude higher investment interventions (such as for enhanced corals approaching 100 million per annum) if benefits are shown to be lower than expected.
- Investment in the complete suppression of crown-of-thorns starfish outbreaks provides net benefit over business-as-usual crown-of-thorns starfish control at high levels of enhanced corals and solar radiation management (cooling and shading) intervention but does not show net benefits at low intervention levels.

5.6 Strategies for maximising benefits and minimising costs and risks via an effective RRAP R&D Program

A key principle of structured decision-making in identifying effective solutions for nature conservation, medicine or business is to begin strategy development with as many options as possible. Eliminating options too early with the rationale of reducing costs at the outset can lead to risks of losing the best options before they are identified (Mankins 2009; Engel et

al. 2012). On the other hand, retaining the full suite of options for too long under limited resources means the program will be weighed down by inviable options (Bottrill et al. 2009). The optimal situation is to apply a fast but rigorous filtration process of interventions against four key criteria:

- Expected capacity to deliver against the objective
- Scale of operation and impact
- Method required to deliver against the objective at scale and associated costs and risks
- Duration of R&D and time until full deployment, relative to the rate of decline in the absence of intervention.

The initial filtration of interventions from 160 to 43 was the first step in this process (<u>T5:</u> <u>Future Deployment Scenarios and Costing</u>).

The purpose of this concluding section is to draw together information from the qualitative and quantitative intervention assessments to generate strategy recommendations for the R&D program. As a first generalisation, the likelihood that an intervention strategy can meet key objectives (environmental, ecological, economic and social) can be defined as:

Likelihood of intervention success =

- 1. Likelihood of scope to deliver benefits against one or more objectives at scale, AND
- 2. Likelihood that risks can be kept low or managed, AND
- 3. Likelihood that costs can be kept low, AND
- 4. Likelihood intervention is ready for deployment before substantial reef decline AND
- 5. Likelihood intervention strategy will be given approval to be deployed.

An additional component is the degree to which an intervention can amplify, or be amplified by, other interventions in a strategy (i.e. set of intervention combinations).

In the context of the likelihood of intervention success, results of quantitative model simulations presented in this report only provide information on likelihood components 1 (benefit) and 3 (costs). Importantly, risk was not formally modelled. While the two interventions analysed (enhanced corals, regional cooling and shading) along with the complete suppression of crown-of-thorns starfish outbreaks led to high performance in combination, with respect to coral condition and economic benefits, they are classified as medium to high risk (Figure 3). Large-scale cloud brightening (C3), especially, is perceived as high risk. While, in reality, risks associated with cloud brightening may be manageable (likelihood component 2), approval risk may be high (likelihood component 5). Similar conclusions could be drawn for most interventions involving coral seeding (except ER2, ER3, ER7 and ER8, Figure 3).

The likelihood of RRAP intervention success must be seen in the context of the likelihood of success under the no-intervention scenario (the counterfactual). Economic analyses suggest values at risk without intervention could, conservatively, be in the order of \$28B undiscounted over 60 years under RCP 8.5, a currently likely climate change scenario.

In line with the likelihood components that define the chance of success, the development of optimal intervention strategies under the RRAP R&D Program will thus require measures to:

- Maximise efficacy in delivering benefit
- Minimise risk via R&D
- Minimise costs, in part via maximised deployment efficiency
- Aim for early but safe deployment given climate risks
- Ensure ongoing engagement with stakeholders to provide transparency and two-way information flows that prepare society while risky but promising interventions become safe and potentially deployment-ready
- Provide targeted and rapid monitoring information to ensure intervention strategies are effective and safe, to guide adjustments and to minimise critical uncertainty.

An example of how these co-dependent likelihoods might be reconciled to inform decision making under contrasting climate scenarios and contrasting system states is presented in Figure 19. A few general directions can be drawn from this:

- Under expectations of moderate climate change for reefs in currently good condition (i.e. high coral cover), delayed action may be warranted for risky interventions if the R&D program can improve the ratio of upside to downside risks relative to the counterfactual (Figure 19A). This would support extended R&D of interventions such as cloud brightening and gene editing, both from the perspective of precaution and the management of real and perceived risks (Anthony et al. 2017; Kaebnick et al. 2017; Piaggio et al. 2017; van Oppen et al. 2017).
- Under expectations of severe climate change for reefs in a good condition, early action may be warranted if downside risk is not exceedingly worse than the counterfactual (Figure 19B). Given that RCP 8.5 is the more likely scenario and that parts of the Great Barrier Reef can still be considered in good condition compared with other reefs globally, this may be a relevant decision context for the RRAP R&D Program. Two decision elements are critical: (1) whether the downside risk of delay (risk margins indicated by the red arrows) is greater than the risk of early intervention and (2) whether the scale of early action can benefit Reef condition to warrant the risk. Most high-risk and large-scale interventions—including cloud brightening and genetic engineering—will require 10–15 years' development time, thereby already building in delayed action. If downside risks of delay are already significant (assuming a severe climate outlook), this would call for fast-tracking large-scale, but inherently risky, interventions. While early action using low-risk/small-scale interventions (Figure 3) would be warranted from a benefit versus risk perspective, such interventions are less likely to change the condition of the Reef at the large scale.
- For reefs in poor condition, under the expectation of moderate climate change, delayed **intervention may be warranted** (Figure 19C). Additional decision factors at play are: (1) decisions are more time-critical for reefs in poor condition, and consequently (2) risk tolerance is increased because there is less capital at risk. A priority for the R&D program would be to guide effective strategies that consider the full spectrum of benefits and risks of different decisions across climate outlooks, system states and intervention uncertainty.
- For reefs in poor condition and where a severe climate change trajectory is expected, early action of large-scale and potentially risky interventions is warranted in that it may be the only chance to sustain the system (Figure 19D). While this may not be the situation on the Great Barrier Reef, delayed action under the expectation of severe climate change may render this a scenario and a decision problem for RRAP in the

future. This would argue for the active development of large-scale interventions in preparation for such a situation.



Figure 19: Risks of early versus delayed action under climate uncertainty. Grey solid lines represent counterfactuals – i.e. expected trajectories under best-practice conventional management. Green and red arrows indicate upper and lower boundaries for upside (benefits) and downside risks, respectively. Dashed arrow represents a median expected path following intervention. A: expected moderate climate change on reefs with high coral cover, B: expected severe climate change on reefs with high coral cover, C: expected moderate climate change on reefs with low coral cover, D: expected severe climate change on reefs with low coral cover.

6. CONCLUSIONS AND RECOMMENDATIONS

- 1. Restoration and adaptation solutions that combine multiple new interventions with best practice conventional management have scope to sustain coral cover until 2050 for a large proportion of Great Barrier Reef coral reefs, even under projections of business-as-usual climate change (RCP 8.5).
- 2. Sustained coral condition Reef-wide will be substantially more likely if global warming is kept below 2°C. Under RCP 2.6, strategic combinations of RRAP interventions have significant scope to increase coral condition on the Reef above the current state.
- 3. Assuming the potential of interventions analysed here could be realised, undiscounted economic gross benefits of damage prevention and potential improvement of Reef condition beyond the current state range between \$3B and \$640B, depending on the method of, and assumptions around, benefit assessments.
- 4. Accounting for the balance of costs and benefits, there is a significant potential economic upside from RRAP at base-case assumptions of up to \$4.1B net present value (2016, 3.5 percent), which is equivalent to \$28B undiscounted over 60 years. Taking a 90 percent probability interval for 1000 iterations of sensitivity parameters, the potential upside from RRAP is up to \$14.5B net present value (2016, 3.5 percent). Thus, RRAP is an investable proposition across a broad range of uncertainty, which includes across a wide range of conditions for economic benefits valuation (except for the most pessimistic conditions).

- 5. While regional-scale cooling and shading combined with additional crown-of-thorns starfish control showed significant scope to produce positive impact Reef-wide, a deeper understanding of intervention efficacy, risks and costs are needed to provide a full assessment of net benefits. A Decision Strategy and Plan will be designed to help identify solutions in the R&D program that maximise benefits and minimise risks.
- 6. Enhanced corals as a single intervention showed limited potential, both as a large- and small-scale intervention. However, detailed analysis of the contribution of enhanced corals to interventions that combined cooling and shading and additional crown-of-thorns starfish control, showed the enhanced corals contribution to reef resilience in a three-pronged intervention strategy shifted between 53 (RCP 2.6) and 57 (RCP 8.5) reefs into higher categories of absolute coral cover (Table 6, see also Figure 19 in <u>T6: Modelling Methods and Findings)</u>. While the efficacy potential of warm-adapted corals is not evident as a single intervention using relative coral cover, its potential grows significantly if combined with cooling and shading and the suppression of crown-of-thorns starfish. This underscores the importance of developing restoration and adaptation strategies that promote multiple ecological and environmental processes with a mission to support reef resilience (Figure 6).
- 7. When developing enhanced corals as an intervention strategy under the RRAP R&D Program, building thermal tolerance must be complemented with efforts to sustain tolerance to other environmental stressors, thereby giving Reef coral the best chance of maintaining resilience.
- 8. While the suppression of crown-of-thorns starfish was based on a hypothetical delivery method in this study, our analyses indicate that preventing starfish outbreaks via intensified conventional or emerging management intervention can improve the outlook for Reef corals, especially when combined with cooling and shading (see Figures 18 and 19 in <u>T6: Modelling Methods and Findings</u>). Although intensified crown-of-thorns starfish control is not part of the RRAP R&D interventions, results illustrate the importance of coordinating and integrating RRAP solutions with those emerging under the Reef 2050 Plan.
- 9. Summaries of ecological and economic results presented here are based on scope only; barriers for intervention efficacy and risks are not formally included and neither are uncertainties around deployment feasibility. Barriers and risks are intervention- and scenario-specific and add uncertainty to the likelihood that strategies can deliver program objectives. Formal assessment of these will be a central challenge of the RRAP R&D Program.
- 10. From a cost-benefit perspective, active restoration and adaptation interventions are a valid new management strategy for the Reef and the results of our analyses support a decision to invest. The cost-benefit analysis has shown that, within the high degree of uncertainty inherent in RRAP, there is a strong set of circumstances where active restoration and adaptation interventions are a valid new management strategy for the Reef. As a result, investment in RRAP is favourable, and thus it is recommended that the program progress to the next stage of investigation.
- 11. The high degree of uncertainty within RRAP, at many levels, means the cost-benefit analysis should be considered an early attempt to examine the performance of potential

program elements, not as a demonstration of what should, or will be, implemented. It does not assume that engineering and scientific action will be taken that results in poor performance; rather, it flags where further research is needed to reduce uncertainty, to realise potential performance and ensure only well-performing interventions are progressed.

- 12. Given the potentially severe climate change outlook and the fact the Great Barrier Reef has recently show climate vulnerability following the back-to-back bleaching events of 2016 and 2017, it is recommended the RRAP R&D Program takes a strategic approach that formally weighs current and future benefits against risks of early versus late intervention and against the substantial risk of the 'do-nothing' scenario.
- 13. Continued systematic and strategic evaluation and fast-tracking of evolving subsets of the 43 intervention candidates will give the RRAP R&D Program a strong chance of delivering options that can help sustain the Reef condition and values for Australia.

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APPENDIX A – RRAP DOCUMENT MAP

Reef Restoration and **Adaptation Program**



APPENDIX B – INTERVENTION ASSESSMENT SUMMARY

Table B1: Full set of interventions that were explored and filtered in the feasibility program. See Table B2 for definitions of scale and <u>T5: Future Deployment Scenarios and Costing</u> for further details of the selection process. Feasible usage scale (green) and high risk (red) were used as key filters. Additional cost criteria relative to feasibility reduced the list of prospective candidates to 43.

Feasi	ole scale Po	ssible te	asible	scale		Inteasible	scale	Elimina	ated based o	n risk	
		Po	ential I Sc) eploy	ment	Assumed Deployment	These crit	teria are all ass deployr	essed against t nent scale	he assumed	Recomm ended
Code	Intervention Title	Micr	o Small	Med	Large	Scale	Annual Cost (\$M)	R&D Duration	Development Risk	Total Development Duration	
C1	Cooling by mixing						•	Eliminated	•	•	no
C2	Cooling by pumping					Lorgo	159	Eliminated	Ц	<u> 9 10</u>	no
C3	cloud brightening					Madium	50	5-10	N4	0-10	yes
C4	Shading by fogging					Medium	50	5-10	IVI	0-10	yes
C5	Shading by misting					Medium	25	5	M	6-8	yes
C7	Shading by surface hims	s				Small	30	5	M	7-9	ves
C8	Shading by structure						•	Eliminated	•		
C9	Shading by algae					Micro (small?)		Not ye	tassessed		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	n				Small	60	5	L	7-8	yes
S6	Structure by 3D frames					Small	120	5	M	7-8	yes
S7	shapes					Small	120	5-10	IVI	7-8	yes
S8	Structure by massive co	rals				Small	240	5-10	M	9-11	yes
S9	shapes					Micro	Not yet assessed	5-10	М	13-15	yes
ER1	Coral seeding by in situ movement						Eliminated				
ER2	Coral seeding by assiste larval movement	d				Small (Medium?)	60	5	М	7-10	yes
ER3	Coral seeding by larval s translocation	lick				Small (Medium?)	90	5-10	М	8-11	yes
ER4	Coral seeding by larval slicks settled on devices					Medium (Large?)	150	5-10	Н	9-15	yes
ER5	Coral seeding by <i>in situ</i> harvested fragments						Eliminated				
ER6	Coral seeding by nurser aquaculture	/						Eliminated			no
ER7	Coral seeding by semi- automated aquaculture					Small	30	5	L	4-6	yes
ER8	Coral seeding by automa aquaculture	ated				Medium	150	5-10	М	9-15	yes
ER9	Coral seeding by larval/polyp aquaculture					Large	300	5-10	Н	9-19	yes
B1	(Bio)-contrN2 and EN3o macro algae	of				Small	Not yet assessed	Unknown	М		yes
B2	Biocontrol of species wit negative impacts	h				Small	Not yet assessed	Unknown	Н		yes
F1	Application of field treatments to enhance c survival	oral				Medium	Not yet assessed	Unknown	Н		yes
EE1	Seeding enhanced coral from existing stock by la slick translocation	s rval				Small (Medium?)	90	5-10	Н	8-11	yes
EE2	Seeding enhanced coral from existing stock by settlement of larval slicks devices	s on				Medium (Large?)	150	5-10	н	10-15	yes
EE3	Seeding enhanced coral bred from existing stock semi-automated aquaculture	s with				Small	30	5-10	М	8-10	yes

APPENDIX B - INTERVENTION ASSESSMENT SUMMARY

EE4	Seeding enhanced corals bred from existing stock with automated aquaculture			Medium	150	5-10	М	9-15	yes
EE5	Seeding enhanced corals bred from existing stock with larval/polyp aquaculture			Large	300	10	Н	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

Table B2: Definitions of deployment scale and examples of deployment efforts for each scale. Deployment scale is considered a component of the objective function via its impact on costs. Note that the out-planting of 10 million corals with 5cm diameter corresponds to approximately 2ha of added coral cover.

Scale	Objective	Characteristics	Assumed annual quantities required for method to have impact at this scale
Micro	Sustain values at a few sites	Sites within reefs	100 000 corals deployed p.a. 1ha rubble stabilised p.a.
Small	Sustain values at more key sites/reefs	More small sites within 50 reefs	50 x 2ha sites shaded 1 million to 10 million corals deployed p.a. 100ha rubble stabilised p.a.
Medium	Sustain values and key ecosystem functions in sector	More larger areas within 50 reefs	Five multi-reef areas shaded 10 to 100 million corals p.a. 1000ha rubble stabilised p.a.
Large	Sustaining broader Reef ecosystem function and core economic and social values	Larger areas within more than 200 reefs distributed across the Reef	Full Reef shaded More than 100 million corals deployed p.a. More than 10 000ha rubble stabilised p.a.

Reef Restoration and **Adaptation Program**

GBRrestoration.org

K.anthony@aims.gov.au D.mead@aims.gov.au

Reef Restoration and Adaptation Program, a partnership:









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