R4: RESEARCH AND DEVELOPMENT PROGRAM

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

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Contents

List of figures

List of tables

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, and 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. INTRODUCTION

This comprehensive Reef Restoration and Adaptation Program (RRAP) Research and Development (R&D) Program was formulated to deliver the recommendations summarised in **R3: Intervention Analysis and Recommendations**. This document presents the key aspects of this proposed program. Additional detail is provided in the suite of supporting documents, particularly the strategies and plans for the specific sub-programs.

This R&D program is based on current knowledge and estimates of future reef state trajectories. As knowledge increases, and as the state of the Reef unfolds into the future, the program will need to adapt. Accordingly, while the program presents a very specific suite of R&D activities to estimate timelines and investment requirements, the details should be considered a starting point, subject to refinement.

An ongoing and deep understanding of the needs and contributions of Traditional Owners, communities and other stakeholders in reef restoration and adaptation is critical, both as the technical R&D work is designed and as the development and deployment of interventions occur. Similarly, the proposed interventions need to achieve regulatory approval before they can be deployed to create the desired benefits for the Great Barrier Reef. These areas are outlined in this document to illustrate their integration with the broader R&D program and, due to their importance to the success of the program, they are also separately presented in more detail in **R1: Engagement and Regulatory Dimensions**.

2.1 Overview

Climate change is accelerating the impact of many stressors to the Reef faster than it can naturally adapt. Time is of the essence to minimise damage, hasten protective measures and minimise both economic and ecological costs. The recommended RRAP R&D Program was designed to quickly and cost-effectively deliver new interventions ready for investment to deploy, should they be required.

The challenge was to develop a program that best managed the inherent uncertainty associated with such an approach and struck an appropriate balance between risk, time and investment requirements. To achieve this balance, the minimum recommended R&D program was based on the following principles:

1. Drive early deployment of smaller-scale interventions as soon as feasible, to help protect high-value reefs.
2. Quickly identify interventions with the highest likelihood of success. Reduce uncertainty around the benefits, risks and costs of those interventions.
3. Deploy the required R&D expertise in a flexible and cost-efficient way, through a mix of capability teams and project teams.

The minimum recommended R&D program is a departure from traditional research modes. It embraces an innovation- and research-based, structured engineering approach, predicated on fit-for-purpose teams. During the first five years, the focus would be on delivering the underlying cross-cutting research and moving smaller-scale interventions towards deployment. As time goes on, and research is gradually phased out, the focus will shift to deploying larger-scale interventions.

The program was designed to facilitate a strategy of beginning with a large number of potential interventions, encompassing a wide range of functional objectives, delivery methods and potential deployment scales. This drove the need for a specific style of program: one that was focused on end-to-end[1] interventions, rapidly identifying the most prospective of the interventions being assessed and focusing investment on developing these. It uses several key approaches to deliver these outcomes, including:

- Each intervention consists of a functional objective and an engineering concept to produce and deploy the required actions or products onto the Reef at the targeted scales. Some are new ideas with limited concept details. Others are more evolved and further progressed in the assessment and development lifecycle. The program would progressively refine, test and develop these concepts. Engineers would refine designs and research investment into specific areas of high uncertainty and risk. Findings would be reviewed at specified 'stage gates' and the sub-programs adapted accordingly. This could include halting investment in interventions found to be less feasible than expected and moving it to higher priority areas.
- The assessment and development of each intervention would require a broad-spectrum R&D sub-program, from stent to infrastructure design. Further, there are overlapping R&D needs across the interventions. To improve knowledge sharing, increase critical mass in specialist areas, improve efficiency and significantly reduce cost, the R&D program would operate as a matrix of intervention-specific and cross-cutting activities that, in aggregate, deliver a subset of deployment-ready interventions.
- The R&D program focuses on and minimises investment requirements using three mechanisms:

  a) Rapid delivery (or elimination) of interventions with higher readiness levels.
  b) In areas where there are many intervention alternatives (e.g. interventions to stabilise rubble), the R&D program would first focus on developing improved functional requirements. Intervention alternatives would then be reassessed against these requirements and only the most aligned alternatives would be progressed.
  c) In interventions where the delivery method is a variant of aquaculture (e.g. level of automation and innovation), the R&D program would first assess critical areas of technology and performance uncertainty in the different variants, then focus on developing the most prospective of the alternatives.

In combination, these mechanisms would enable the R&D program to assess a broad number of interventions and progressively deliver new reef management options for deployment in a cost-effective and efficient manner.

[1] End-to-end refers to the need to assess and develop all aspects of a potential new intervention option. From social acceptance and regulatory approval to the infrastructure and systems to produce and deploy the actions and products to deliver the intervention.

2.2 R&D timing

The intended duration of the initial RRAP R&D Program is five years, with an option for a further five years (Figure 1). The first five-year period would deliver knowledge, decision, social and regulatory outcomes to enable informed intervention deployment decisions. In parallel, it would seek to fast-track a suite of interventions that could be developed quickly (likely to be those designed for small- to medium-scale use), while assessing and confirming the viability of other interventions that would take longer to develop, but would ultimately be suitable for larger-scale deployment and impact. The second five-year period would be dependent upon confirming the viability of larger-scale interventions.

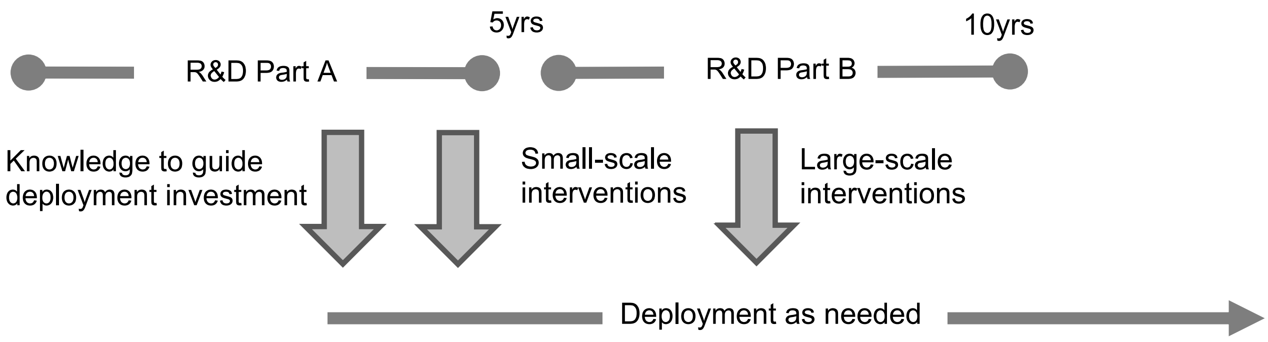

Figure 1: Recommended RRAP R&D function and phasing over 10 years.

2.3 Investment requirements

R&D investment estimates were based on detailed plans prepared by teams of experts. These plans are a best estimate as to what would be required, understanding that in many instances, the ideas are very early in their development lifecycle and considerable uncertainty remains. The minimum recommended Phase A investment requirement is estimated at $325M, with Phase B estimated at $220M. Further details are provided in Section 7.

3. R&D PROGRAM – GOALS

3.1 RRAP objectives

The core objective of RRAP is to develop a new suite of interventions that could be deployed, as required, to protect and retain the core environmental, social and economic values of the Great Barrier Reef. In doing so, they would need to be logistically feasible, at a scale sufficient to have the required impact on ecological function and affordable to deploy across entire reef scapes. To achieve these objectives, the program needs to identify the circumstances under which restoration and prevention are warranted and helpful (i.e. what, where and when).

Several conclusions from the RRAP Concept Feasibility Study impacted the design of the recommended R&D program to deliver these objectives:

1. The Great Barrier Reef is still resilient. This provides the opportunity to not only focus on restoration, but also develop methods that help retain and facilitate this resilience, aiming to avoid the need for large-scale restoration.

2. The Reef is too large and complex for a 'direct' approach to be feasible—in terms of efficacy and cost. The concept feasibility findings suggest that, of the interventions examined, it would not be feasible to 'treat' every reef or every part of each reef on the Great Barrier Reef. The possible exceptions were a selection of cooling and shading-type interventions; however, even these are unlikely to deliver benefits evenly, see **T14: Environmental Modelling of Large Scale Solar Radiation Management**. All other interventions, even if deployed in combinations, would be limited in deployment to a subset of total reefs. If the Reef reaches a state where large-scale impact is required, interventions would need to be designed such that they 'seed' an outcome that is greater than the direct inputs. For example, treated reefs supporting adjacent reefs by providing increased larval supply and aiding their recovery after disturbances. Deployment design would be critical to this being achieved.

3. Benefits would be maximised when interventions could be deployed at large scale; however, significant benefits could be achieved with interventions deployed at small to medium scale, both as 'early intervention' options and operating in combination with larger-scale interventions. Options value would be maximised the earlier these interventions could be bought to a deployment investment-ready status.

4. There are many possible ways to deliver each of the targeted interventions. These 'delivery methods' were characterised by the specific approach, production and deployment technologies and systems they would use. Some would be logistically- and cost-feasible only for smaller scales, others only for larger scales. Further, there were strong correlations between development risk and targeted scale and R&D durations and establishment ramp-up durations. Potential delivery methods that appear logistically- and cost-feasible at a large scale are more complex, requiring a longer/larger R&D investment, higher levels of innovation and breakthroughs, and once confirmed as viable would take longer to establish and reach full production levels.

5. Ideally, the interventions would be designed to guide the system to an acceptable novel and stable state and/or facilitate adaptation to future climate conditions to the point where they could be halted. The modelling has suggested this may be feasible under scenarios with strong global action on emissions reduction, but less feasible under business-as-usual climate trajectories (**T6: Modelling Methods and Findings**). Ongoing large, annual investments are undesirable and potentially financially infeasible.

These findings nuance the intervention objectives and goals of the R&D program. They place value on small- to medium-scale interventions, particularly if they can be delivered quickly. Further, interventions are more likely to have a large and long-lasting impact if they facilitate system resilience and adaptation. This would require intervention deployments to be highly optimised. The RRAP R&D Program needs to focus on interventions that improve adaptation and on deployment designs that deliver impact that is larger than the area directly impacted by the intervention (Figure 2).

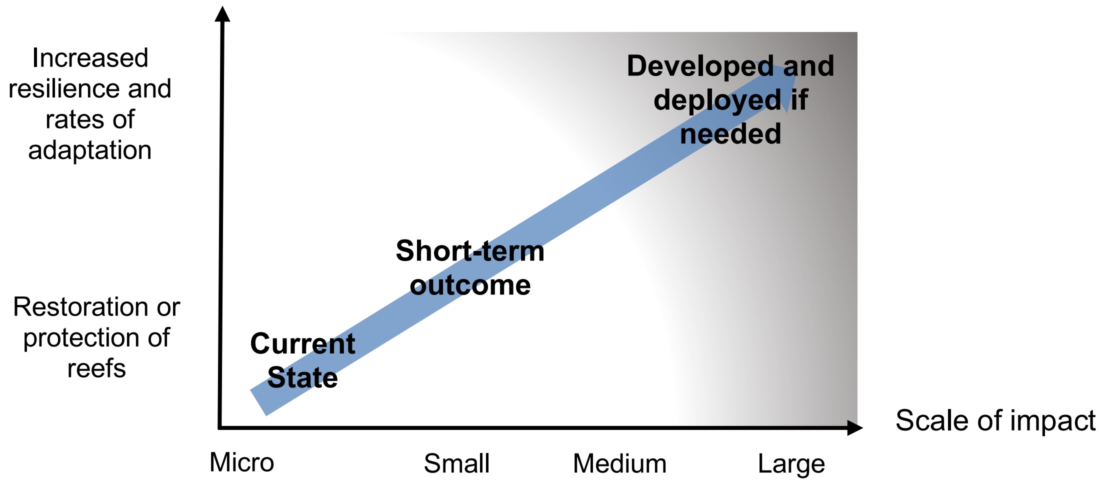

Figure 2: Conceptual diagram illustrating the drivers and scale of the RRAP R&D Program. We plan to start by nudging this huge ecosystem at potential leverage points based on best available knowledge gained from decades of research. While we are doing this, we will evaluate other more aggressive options to be applied in a scaled approach in the event we discover the system has been pushed past a tipping point and/or has too much inertia to recover without further assistance.

This concept is illustrated in Appendix B for the development of interventions, with aquaculture as the delivery method.

3.2 R&D goals

The RRAP R&D Program seeks to expediently advance knowledge to enable practical, affordable and effective at-scale reef restoration and adaptation interventions to occur. It would drive the early deployment of smaller-scale interventions as soon as feasible, to help protect high-value reefs. It would seek to understand and reduce regulatory risk. Through engagement with Traditional Owners, industry, stakeholders and the wider community, it would facilitate input into addressing the critical questions: if, what, when and where interventions should occur.

The goal of the RRAP R&D Program is therefore to progress, and continually assess, a broad list of intervention options to the point where they can be either:

- Determined to be 'investment ready', should decision-makers choose to directly intervene on the Reef.
- Eliminated from further consideration.

Where intervention 'investment ready' is defined as:

- Acceptable uncertainty around the intervention risks and benefits
- Well-described delivery method (with quantification of critical performance parameters)
- Resolved method or technology risk
- Low-risk residual development requirements
- Regulatory approval likely.

The optimal time at which an intervention is 'investment ready' is highly intervention specific. It depends on several interrelated factors including:

- The ability to achieve regulatory approval and social alignment.
- The business model being used for deployment and its ability to carry risk.
- The extent to which the intervention is scalable. Some have delivery methods that can operate efficiently across a range of deployment scales, others are highly scale specific. Those that could be deployed across a range of scales could initially be deployed at a small-scale and ramped-up over time, allowing more risk to be carried into the deployment phase. Those that are large-scale-specific would require a higher level of initial investment for additional R&D to reduce the increased investment risk.

In developing the R&D program, where feasible, these factors were considered for each proposed intervention. Each intervention R&D sub-program was designed to undertake the minimum required for an intervention to be investment ready. These assessments would be updated and refined as uncertainty reduces over the course of the R&D program and sub-programs are adjusted accordingly.

A more complete assessment of the R&D implications of the potential deployment business models is provided in Appendix C.

3.3 Steps beyond the R&D program

Once an intervention is investment ready, additional steps would be required for deployment (Figure 3).

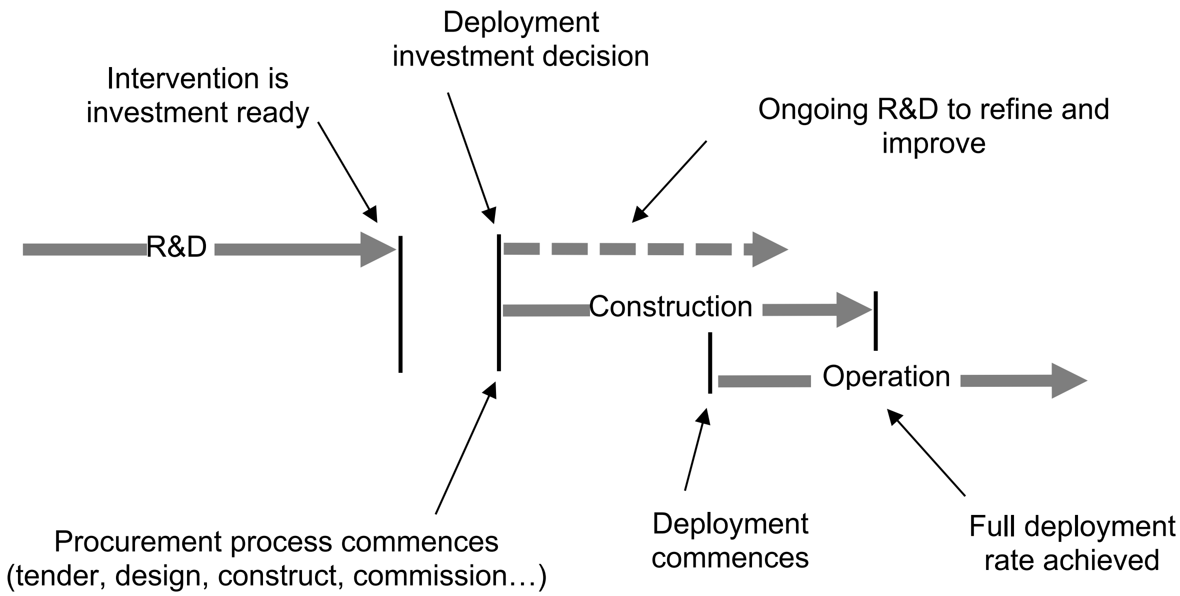

Figure 3: Steps required for an intervention to move from 'investment ready' to reef deployment at scale.

Significant procurement, infrastructure construction and commissioning activities may be required, and in many instances, production would ramp-up over time. This could range from one to more than 10 years. For example, a large-scale aquaculture capability would be developed in stages, with multiple production facilities and would take at least 10 years to establish and reach full annual production levels. In contrast, deploying surface films to protect 10, high-value sites, might be achieved within 12 months.

To illustrate this concept further, an example of developing a large-scale high-automation aquaculture capability is provided in Appendix D.

4. R&D PROGRAM – INTERVENTIONS

4.1 Priority interventions

The recommended R&D program was designed to begin with a suite of interventions that, in aggregate, cover all seven functional objective types identified in the concept feasibility study (Table 1). They also cover a spectrum of estimated deployment scales. The R&D program would test these scale assumptions, increasing feasible scale where possible and improving correlations between deployment scale and impact. Only then, could more refined cost-benefit assessments be completed, with deployment requirements more accurately forecast and the appropriate interventions selected for use.

Table 1: Interventions proposed to be carried forward to the RRAP R&D Program. For simplicity, in this table, where an intervention could be potentially deployed at multiple scales, these were combined into the one listing.

Code	Intervention	Estimated deployment scale
C3	Shading by cloud brightening	large
C4	Shading by fogging	medium/large
C5	Shading by misting	medium
C6	Shading by surface films	small
C7	Shading by microbubbles	small
C9	Shading by algae	small
S1	Stabilisation by natural bonding	small/medium
S2	Stabilisation by chemical bonding	small/medium
S3	Stabilisation by mesh	small
S4	Stabilisation by removal	small/medium
S5	Structure by consolidation	small
S6	Structure by 3D frames	small
S7	Structure by concrete shapes	small
S8	Structure by massive corals	small
S9	Structure by 3D printed shapes	small
ER2	Coral seeding by larval slick movement	small/medium
ER3	Coral seeding by larval slick translocation	small/medium
ER4	Coral seeding by larval slicks settled on devices	medium/large
ER7	Coral seeding by semi-automated aquaculture	small
ER8	Coral seeding by automated aquaculture	medium
ER9	Coral seeding by larval/polyp aquaculture	large
B1	Biocontrol of macroalgae	small
B2	Biocontrol of species with negative impact	small
F1	Application of field treatments to enhance coral survival	small/medium
EE1	Seeding enhanced corals from existing stock by larval slick translocation	small/medium
EE2	Seeding enhanced corals from existing stock by settlement of larval slicks on devices	medium/large
EE3	Seeding enhanced corals bred from existing stock with semi-automated aquaculture	small
EE4	Seeding enhanced corals bred from existing stock with automated aquaculture	medium
EE5	Seeding enhanced corals bred from existing stock with larval/polyp aquaculture	large
EN1	Seeding enhanced corals bred from engineered stock with semi-automated aquaculture	small
EN2	Seeding enhanced corals bred from engineered stock with automated aquaculture	medium
EN3	Seeding enhanced corals bred from engineered stock with larval/polyp aquaculture	large

Details of the process to select the interventions to be carried forward are provided in **R3: Intervention Analysis and Recommendations**. Intervention and scale descriptions are provided in **R2: Intervention Summary**.

Additional interventions

The RRAP R&D Program would facilitate a process of ongoing identification of new interventions while assessing those already under development.

It is expected most new ideas identified would be related to new delivery methods or variants of methods under assessment. The R&D program design would facilitate this by clustering interventions with similar delivery methods into combined programs. Already, during the RRAP Concept Feasibility Study, aspects of delivery methods from three coral seeding interventions (ER2- coral seeding by larval slick, ER3- coral seeding by larval slick translocation and ER7- coral seeding by semi-automated aquaculture) were combined to create a new intervention (ER4- coral seeding by larval slicks settled on devices).

In parallel, an online summary of the interventions under assessment and development, along with their likely performance levels (functional outcomes, risk, scalability and deployment cost) and opportunities for improvement, would be publicly available. This would enable informed third-party reviews and suggestions.

All new ideas would be assessed and progressed in accordance with the program's stage-gate process, designed to create critical stop/go decision points.

Late in the RRAP Concept Feasibility Study, a cluster of potential interventions was identified but not assessed. These relate to engineering changes to reef geomorphology to make corals less susceptible to light-induced bleaching or to increase cooler, deeper water flowing onto reefs. These are considered unlikely to be practical; however, will be assessed in more detail at the commencement of the RRAP R&D Program.

4.2 R&D outcomes targets

Many interventions could be delivered (or eliminated) within the first five years (Table 2). For those that would take longer, their R&D programs have been designed to deliver valuable outcomes within the first five years, in preparation for further development in the subsequent five years (Table 3).

Table 2: Recommended RRAP R&D Program outcomes – first five years.

Interventions	Five-year outcomes
All interventions	Uncertainty in intervention cost, benefits and risk reduced to enable deployment decisions to be made. Underpinning knowledge, models and decision systems developed to facilitate investment/elimination decisions and deployment designs (how, when and where). Stakeholders engaged in decision processes. A joint understanding with regulators regarding deployment approval risks. Appropriate field testing and monitoring of outcomes. Outcomes from the delivery method R&D sub-programs inform decisions as to which interventions/delivery methods are: • Available for deployment • Recommended for ongoing R&D investment • Eliminated
Small/medium scale	Ready for deployment or eliminated
Medium/large scale	Key efficacy, performance and technical delivery risks quantified and reduced to a level that justifies the ongoing investment to complete the remaining R&D (or the method is eliminated).

Table 3: Recommended RRAP R&D outcomes – second five years

Interventions	Second five-year targets
All interventions	These are yet to be planned in detail, but would include: • Ongoing assessment of current and future Reef condition and modelling of deployment scenarios to provide updated cost-benefit risk assessments. • Development of decision-support systems to guide intervention deployment programs (how, when and where). • Ongoing Traditional Owner, stakeholder and community engagement and participation.
Small/medium scale	• Monitoring deployment outcomes, effectiveness, unintended impacts and social response to deployment. • Export of proven technologies and know-how. • R&D to support the interventions selected for deployment.
Medium/large scale	All residual R&D completed and ready for deployment

These outcomes translate to each intervention as shown in Table 4.

Table 4: Target outcomes for recommended intervention R&D.

Code	Intervention	R&D duration[2] (years)	Target five-year outcomes[3]	Target 10-year outcomes
C3	Shading by cloud brightening	5–10	• General efficacy proven, deployment methods tested and field trials in progress to refine the understanding of risk and benefits • Further design and testing required	Available for development
C4	Shading by fogging	5–10		
C5	Shading by misting	5	• Available for deployment	n/a
C6	Shading by surface films	5	• Available for deployment	n/a
C7	Shading by microbubbles	unknown	• Desktop study completed within first 12 months; further R&D contingent on outcomes	n/a
C9	Shading by macroalgae	unknown	• Desktop study completed within first 12 months; further R&D contingent on outcomes	To be determined
S1	Stabilisation by natural bonding	5–10	• Rubble stabilisation and 3D structure needs, benefits and functional requirements quantified • Interventions most aligned to the above selected (budget assumes four) and small-scale field trials completed • Pilot-scale testing commenced (results would take several years to finalise)	Available for deployment
S2	Stabilisation by chemical bonding	5		
S3	Stabilisation by mesh	5		
S4	Stabilisation by removal	5		
S5	Structure by consolidation	5		
S6	Structure by 3D frames	5		
S7	Structure by concrete shapes	5–10		
S8	Structure by massive corals	5–10		
S9	Structure by 3D printed shapes	5–10		
ER2	Coral seeding by larval slick movement	5	• Available for deployment	n/a
ER3	Coral seeding by larval slick translocation	5–10	• Available for deployment	n/a
ER4	Coral seeding by larval slicks settled on devices	5–10	• R&D contingent on outcomes from ER2, ER3, ER8 and ER9 and would not commence until year three or four. Target: initial viability tests undertaken.	Available for deployment
ER7	Coral seeding by semi-automated aquaculture	5	• Available for deployment	n/a
ER8	Coral seeding by automated aquaculture	5–10	• Viability of the larval/polyp aspects of the aquaculture delivery method tested • If unlikely to be viable, the R&D program would switch to a focus on ER8	ER9 is available for deployment, with a fall-back to ER8 if required
ER9	Coral seeding by larval/polyp aquaculture	5–10		
B1	Biocontrol of macroalgae	Unknown	• Desktop study completed within first 12 months; further R&D contingent on outcomes	To be determined
B2	Biocontrol of species with negative impact			
F1	Application of field treatments to enhance coral survival	Unknown	• Desktop study completed within first 12 months; further R&D contingent on outcomes	To be determined

[2] R&D durations have been clustered into three groups: less than five years, 5–10 years and greater than 10 years.
[3] While the target outcome is an intervention is 'available for deployment', a possible outcome is that the intervention is eliminated. Elimination could be the result of many factors including risk, regulatory factors, social licence, technical feasibility or unacceptable cost-benefit.

Code	Intervention	R&D duration[2] (years)	Target five-year outcomes[3]	Target 10-year outcomes
EE1	Seeding enhanced corals from existing stock by larval slick translocation	5–10	• Available for deployment	n/a
EE2	Seeding enhanced corals from existing stock by settlement of larval slicks on devices	5–10	• Refer to ER4	Available for deployment
EE3	Seeding enhanced corals bred from existing stock with semi-automated aquaculture	5–10	• These three interventions use the same aquaculture methods as ER7, ER8 and ER9 and would be delivered by the same R&D program and timing. • The unique aspect is that the brood stock used in the aquaculture process would be specifically bred for enhanced performance. There are several different enhancement methods to be tested and developed (marker-assisted selective breeding, interspecific hybridisation, microbial symbiont manipulation and stress hardening). At the end of five years, the target is that some of these methods would be available for some coral species.	Available for deployment
EE4	Seeding enhanced corals bred from existing stock with automated aquaculture	5–10		EE5 ready for deployment, with a fall-back to EE4 if required
EE5	Seeding enhanced corals bred from existing stock with larval/polyp aquaculture	10		
EN1	Seeding enhanced corals bred from engineered stock with semi-automated aquaculture	10+	• These are the same as EE3, EE4 and EE5, except synthetic biology and genetic modification methods are used to create enhanced brood stock. • Within the first five years, the target is to progress these methods to better quantify viability and risk.	• It is too early to determine whether these interventions can be developed within 10 years. The technical and regulatory challenges are significant. An assessment would be made at the end of the first five years as to if ongoing R&D was warranted
EN2	Seeding enhanced corals bred from engineered stock with automated aquaculture	10+		
EN3	Seeding enhanced corals bred from engineered stock with larval/polyp aquaculture	10+		

5. R&D PROGRAM – SUMMARY

5.1 Basis of design

Each intervention comprises a functional objective, delivered to the Reef by a physical action or product. For this delivery to occur, knowledge encompassing product design, production, deployment systems and decision support needs to come together into an overall, integrated system.

The recommended R&D program, therefore, constructs each intervention as an end-to-end design concept. Under the program, each design is progressively refined as the ideas are tested and the underpinning technologies and systems developed. Deployment scale and all associated considerations (e.g. industry engagement, production and deployment infrastructure, business models etc.) are explicitly considered from the start.

This is a classic engineering design and development solution; however, in isolation, this approach is insufficient to deliver the needed interventions. RRAP is targeting ambitious objectives that cannot be delivered solely with off-the-shelf knowledge and technologies. It requires high levels of new and innovative systems and technologies to be developed that require extensive research and innovation. The adopted approach is to integrate the research and innovation processes into the broader engineering development process. Stage gates are then used to control progression.

Research associated with each delivery method will be broadly focused on three areas:

- **Efficacy/risk-checking research:** Will the intervention produce the functional benefit being targeted and what are the risks?
- **Logistics/cost-checking research:** Can it be delivered at a price and scale that has functional benefit?
- **Method development research:** Developing all aspects that cannot be procured as part of the deployment processes.

Supporting these research efforts, catalysts for innovation such as challenges and prizes would be used to resolve specific challenges, particularly where the research program has not identified viable solutions. For example, the feasibility of F1 application of field treatments to enhance coral survival, is limited by a lack of suitable deployment method ideas. Treatments can be designed, but not applied. A challenge or prize could be established to generate new ideas as to how these treatments could be applied at scale. Challenges and prizes also provide valuable external engagement opportunities to help communicate the breadth and depth of the program, its progress and the challenges in developing the Reef restoration and adaptation toolkit.

Balancing uncertainty, risk, time and investment

The minimum recommended R&D program is structured to manage the significant uncertainty and strike an appropriate balance between risk, time and investment requirements. Table 5 provides a summary of the key factors considered in establishing the program design.

Table 5: Factors considered, and strategy adopted, to balance risk, time and investment requirements for the recommended R&D program.

Factor	Strategy
The extent to which the program adopts a parallel versus sequential process. For each intervention, given uncertainty levels, should the program initially focus on improving quantification of functional benefits and risks, then invest in researching and developing the required delivery methods? Or should a parallel process be adopted?	**Reducing uncertainty** around the benefits, risks and costs of different interventions can only occur in parallel with the development and testing of interventions because they are intrinsically linked. Most recommended intervention R&D sub-programs therefore adopt a parallel development approach. The exceptions are interventions that are very early phase concepts (C7, C9, B1, B2 and F1). Further desktop studies and modelling would occur before a decision to invest further.
The breadth of interventions initially selected to be progressed. Should the program commence with a small number and bank on these being the winners, reverting to the next in line if they cannot be developed or have unacceptable social or regulatory factors? Or should it begin with a broader suite and use a stage-gate process to focus in on the most prospective as knowledge levels improve?	The assessment concluded that the R&D program could progress a broad range of interventions without a significant cost penalty. **Retaining option value** on a broad range of intervention types and delivery methods ensures interventions are ready for application on the Reef as early as possible. This approach is facilitated because the multiple delivery methods for each intervention can be progressed in clusters. Examples of how this would be achieved: • There is a broad range of potential rubble stabilisation and 3D structure interventions, with differences in delivery methods. While each would work best in different contexts, only a subset would ever be required. The R&D program would initially focus on developing improved functional requirements, then assess delivery methods, only progressing method development R&D on a subset of interventions (approximately four). • A broad range of proposed interventions is underpinned by one of several aquaculture delivery methods. Rather than develop each method, the program would focus on testing the viability of the technologies associated with the methods that have the most scale potential. The method with the most scale potential (and viable technologies) would then be developed to a deployment-ready stage.
Approaches to avoid a corresponding increase in cost if a broad suite of interventions was initially progressed	
How to best provide the required expertise and critical mass. Should R&D programs be intervention-based, or should a matrix delivery model be used?	A **matrix model** was selected as the only viable approach for several reasons: • Delivering each intervention would require a broad, multidisciplinary R&D program. It was not feasible or practical to replicate this for each intervention, rather it is recommended that cross-cutting programs be established. • There are high levels of functional and delivery method synergies among interventions. A matrix model facilitates exploring options and benefits. • R&D associated with delivery methods comprises the largest expense area and a matrix model reduces duplication and cost.

The net result of the strategies outlined in Table 5 is an R&D program that progressively delivers interventions ready for deployment, while focusing efforts on the most prospective interventions (Figure 4).

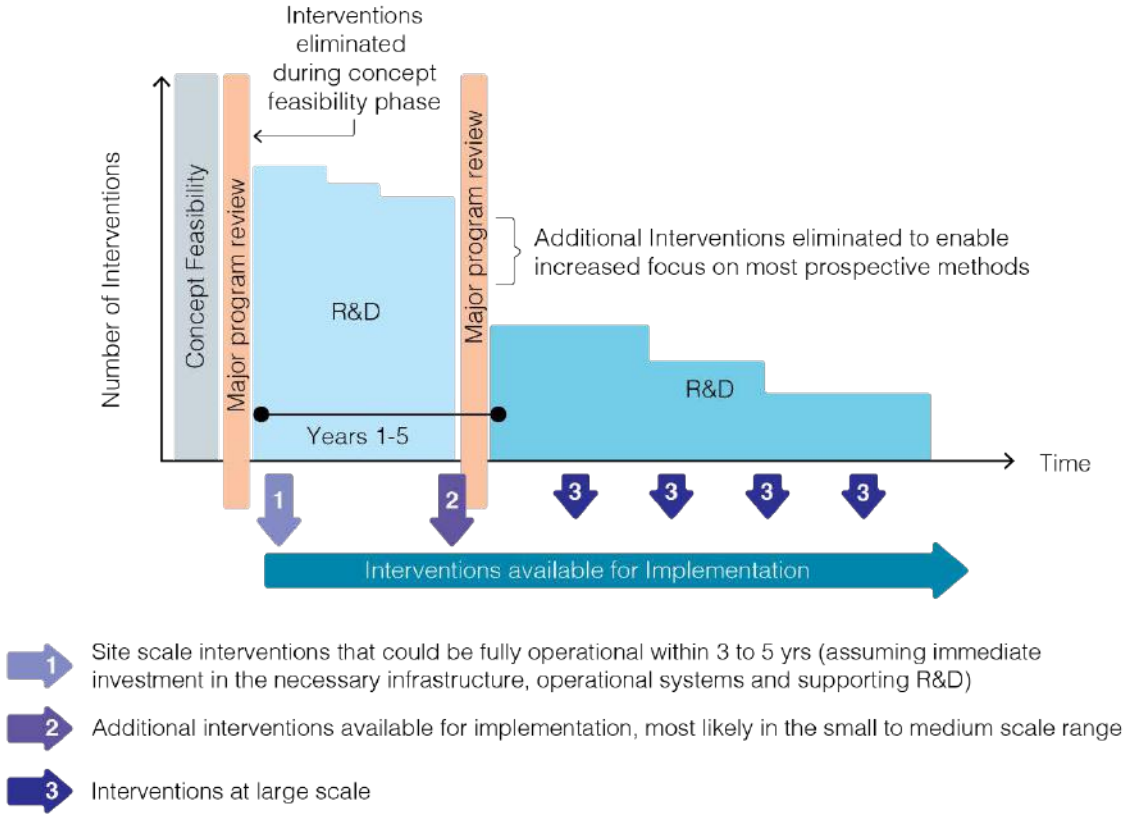

Figure 4: Outcome of strategies to progressively deliver interventions and refine the focus of the program.

In addition to the factors discussed above, a wide range of other aspects was considered in the design of the minimum recommended R&D program. Details of these assessments are provided in Appendix E. In summary, the additional aspects shown in Table 6 were considered.

Table 6: Considerations in developing the RRAP R&D Program.

Consideration	Commentary
Intervention synergies Appendix E1	The RRAP Concept Feasibility Study identified that intervention types would be synergistic in combination to further enhance specific ecosystem functions, creating increased impact for the same investment level. Similarly, there were common deployment infrastructure requirements that could be leveraged to provide cost savings and/or increase feasible deployment scales. The R&D program would continue to explore and leverage these synergies within the Modelling, Ecological Intelligence and Risk and Systems Engineering and Integrated Logistics sub-programs.
Deployment scale, implementation risk, ramp-up durations Appendix E2	The intervention delivery methods, to be developed, would have specific scale ranges over which they would be feasible and/or cost-effective, compared with alternatives. They have differing development risk profiles and timelines for development. The Systems Engineering and Integrated Logistics Sub-Program would track and refine these dimensions to ensure they were considered in decision processes and R&D sub-programs.
Technical uncertainty and risk Appendix E3	In assessing the intervention types and possible delivery methods, functional performance parameters were identified. These are performance criteria that must be met if an intervention is to have efficacy and/or an acceptable cost-benefit ratio. In addition to researching and developing methods, the program would have an early focus on reducing risk and uncertainty as to whether these performance criteria could be met. The Ecological Intelligence and Risk Sub-Program, working in combination with each intervention R&D sub-program, would seek to identify and reduce these risks as quickly as feasible.
Modelling systems (physical, ecology, value, decision) Appendix E4	Forecasting long-term future Reef system states and values is an inherently complex modelling challenge, compounded by uncertainty over climate trajectories and their likely impact. In RRAP, the potential impact and benefits from the deployment of intervention types, under different climate change scenarios, are also considered - addressing another layer of complexity. This improvement to current models, and the increased understanding of the underpinning ecology and adaptation processes that drive intervention deployment decisions, would help ensure large investments would achieve the desired outcomes. The R&D program would incorporate a combined field program (within the Ecological Intelligence and Risk Sub-Program) to better quantify the ecology and adaptation processes driving uncertainty and the development of models aligned to the specific program needs.
Ecological risk Appendix E5	A critical element of the program would be improving the understanding of risk. Current knowledge and capabilities have limited quantitative assessments of risk. Understanding and quantifying risk would be central to future decision-making and regulatory approval, with R&D sub-programs designed to create the required knowledge and supporting models to enable this to occur.

5.2 R&D program structure

The R&D program has been structured as a series of complementary sub-programs that, in combination, are designed to deliver the targeted outcomes (Figure 5).

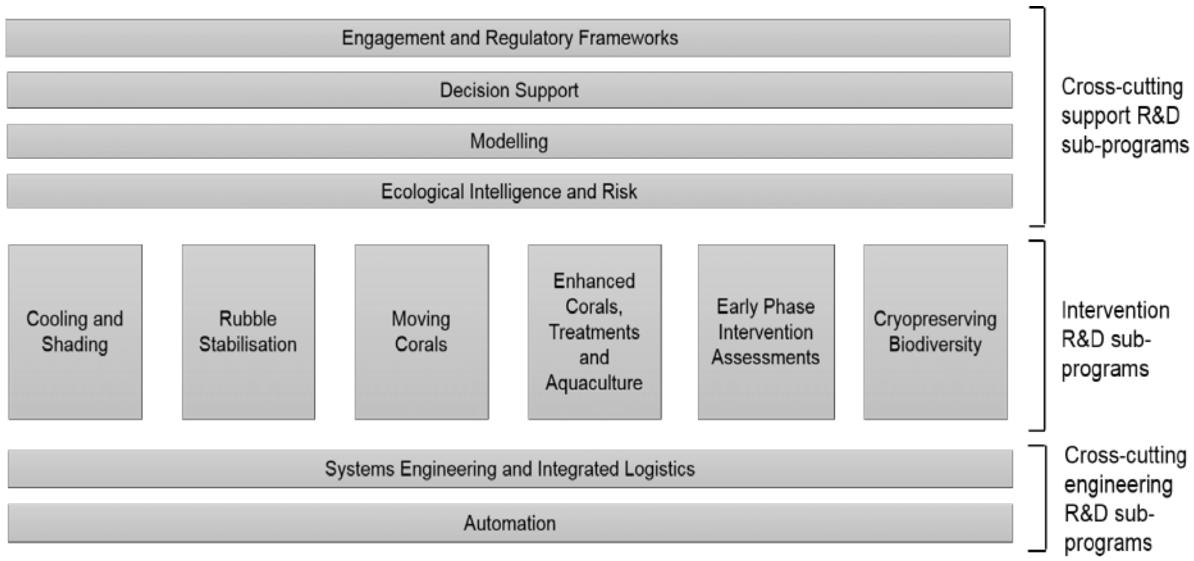

Figure 5: Recommended RRAP program structure, illustrating the relationship between the R&D sub-programs in areas of cross-cutting science and engineering support and intervention methods

The sub-programs work together as follows:

- The Engagement and Regulatory Sub-Program facilitates and guides the required interaction and engagement between the program, Traditional Owners, key stakeholders and regulators.
- The Decision Support Sub-Program provides the overarching framework upon which to assess different intervention options and R&D investment prioritisation and focus.
- The Modelling and Ecological Intelligence and Risk sub-programs assess the functional benefits and risks of interventions and quantify relationships between aspects such as the scale of deployment, performance characteristics and impact, and integration with other interventions. Ecological Intelligence refers to filling the core ecological knowledge gaps, which is required to reduce uncertainty in critical process understanding. Table 7 provides an outline of the key questions being addressed.
- The Cooling and Shading; Rubble Stabilisation; Moving Corals; and Enhanced Corals, Treatments and Aquaculture intervention sub-programs each develop a cluster of interventions. Each sub-program is specifically designed to maximise efficacy and facilitate the progressive focus on the most prospective interventions. Table 8 details a summary of the high-level R&D approach to be taken in these clusters.
- The Early Phase Intervention Assessments Sub-Program would conduct desktop reviews of new and emerging interventions, to determine whether R&D investment was warranted. It would also assess new ideas as they are bought into the program.
- The Cryopreserving Biodiversity Sub-Program would develop specific enabling capability to increase the rate of R&D in the areas linked to annual coral spawning cycles and may potentially enable productivity improvements in coral seeding interventions. It would also provide the capability to biobank endangered Reef coral species for future breeding and re-deployment.
- The Systems Engineering and Integrated Logistics Sub-Program guides the progressive refinement and development of each intervention concept design. It would also look at the design of integrated deployment systems (including shared infrastructure and systems, centralised vs distributed production and deployment models) and how industry and communities would engage in the deployment phase.

- The Automation Sub-Program aims to develop technology that can substantially increase the efficacy and productivity of interventions developed in RRAP. Even small-scale interventions on the Great Barrier Reef are major undertakings due to the massive scale of the system. It is envisaged that most terrestrial automation requirements could be procured from existing automation providers. Underwater and offshore marine automation is a niche area and development would be required. Tables 7 and 8 provide a summary of the objectives and approaches to be taken under the different components of the program. More detailed information about each R&D sub-program is provided in Appendices F1 to F12 and comprehensive outlines for each R&D sub-program are available upon request.

Table 7: Target R&D outcomes to enable improved intervention benefits, risks and costs assessments. These outcomes, combined with the intervention-specific R&D outcomes, would inform ongoing R&D investment decisions and the availability of interventions for deployment.

Functional Objective Type		**R&D Objectives**
#	**Description**	
1.	Cooling and shading	• Refine and quantify the extent of cooling and/or shading required to reduce forecast bleaching probability. • Quantify impacts on heat tolerance adaptation rates (noting it could be neutral, improve or reduce rates). • Quantify other impacts on ecological and physiological processes.
2.	Reef structures and stabilisation	• An ability to forecast future rubble formation and stabilisation rates and assess the future needs and benefits of stabilising rubble and creating a 3D structure. • Quantified functional performance requirements (for example bond strength for methods to stabilise by bonding rubble together) to stabilise rubble and the areas/patterns required.
3.	Reproduction and recruitment	• Improved forecasting of future larval supply and recruitment rates. • Quantify larval connectivity to understand where interventions will have the greatest benefit. • Determine quantities required to have an impact under different scenarios.
4.	(Bio)-control	• Desktop assessment of likely future needs and benefits of predatory or invasive species removal and macroalgal management (in addition to existing crown-of-thorns starfish management programs).
5.	Field treatments	• Quantify the number of corals likely to respond to treatments applied before, during and after a bleaching event. • Assess the potential benefits of treatments to determine whether treatment-based interventions have sufficient potential to justify an R&D sub-program to develop deployment systems.
6.	Enhanced corals from existing stock	• Improve quantification of natural rates of adaptation and the distribution and abundance of heat-tolerant corals. • Understand the extent of performance trade-offs of enhanced corals in receiving populations. • Assess the level of enhancement required, numbers, receiving conditions and deployment distributions needed for methods to have an impact.
7.	Enhanced corals from engineering stock	• Points 2 and 3 above.

Table 8: Mapping interventions to R&D sub-programs and an outline of the sequence of activities to assess and develop each intervention, including key decision points to continue or halt investment

R&D sub-program	Interventions included		Outline of R&D approach
Cooling and shading	C3	Shading by cloud brightening	• Simultaneous program to o Develop performance criteria, undertake engineering development and test suitable hardware and deployment options. o Field test to gather data on efficacy/ impact (progressive small-scale prototype to larger-scale field evaluations). o Model development and atmospheric characterisation of the Great Barrier Reef to assess the risk of unintended impacts and improve predictions of efficacy. • Refine system design and assessments of benefits, risk and cost. • Ongoing investment and focus, subject to the above outcomes.
	C4	Shading by fogging	
	C5	Shading by misting	• Rapid assessment of benefits, risks, social acceptability and regulatory approval requirements. • Intervention and then either eliminated or field-tested and, subject to outcomes, available for use.
	C6	Shading by surface films	• Trials to assess performance under field conditions. • R&D to determine whether product volumes per km^2 can be reduced. • Test deployment methods (vessels and planes). • Based on outcomes, intervention is then either eliminated or available for deployment.
	C7	Shading by microbubbles	• Desktop study to assess suitability and feasibility for use on the Reef. • Field trials to assess performance. • Ongoing R&D subject to desktop and field trial outcomes.
Rubble stabilisation	S1	Stabilisation by natural bonding	• Initial focus on improving rubble formation/stabilisation forecasts and assessing the value of these interventions. • If value confirmed, R&D continues. • Using the information derived in the value assessment to compare available deployment methods and deployment designs against functional requirements and select the most aligned for development. • Test and develop the selected delivery methods (four assumed in the budget).
	S2	Stabilisation by chemical bonding	
	S3	Stabilisation by mesh	
	S4	Stabilisation by removal	
	S5	Structure by consolidation	
	S6	Structure by 3D frames	
	S7	Structure by concrete shapes	
	S8	Structure by massive corals	
	S9	Structure by 3D printed shapes	
Moving corals	ER2	Coral seeding by larval slick movement	• Test larval release methods and quantify the number of new corals created as a function of receiving conditions. • If rates sufficiently high: continue intervention R&D, complete remaining areas of method development (larval slick capture, transport and release).
	ER3	Coral seeding by larval slick translocation	
	ER4	Coral seeding by larval slicks settled on devices	• On hold pending findings from aquaculture and larval transport/translocation R&D. A

			decision to progress (or not) to occur around year three.
	EE1	Seeding enhanced corals from existing stock by larval slick translocation	• Refer ER3
	EE2	Seeding enhanced corals from existing stock by settlement of larval slicks on devices	• Refer ER4
Enhanced corals, treatments and aquaculture	ER7	Coral seeding by semi-automated aquaculture	• Initial focus on four areas: o Developing enhanced corals and treatments to confirm the viability of approaches using existing stock and the extent of performance trade-offs. o Methods to breed target coral species and enhance their survival once deployed. o Methods to increase sexual and asexual production rates. o Testing the viability of innovations in the larval/polyp-based aquaculture method. • Depending on the above outcomes, adjust the program to deliver the residual R&D of viable interventions (noting that, of the remaining viable aquaculture delivery methods, only the largest-scale method would be developed). • Enhanced corals from engineered stock (using synthetic biology and genetic modification techniques) may not take longer to develop than methods from existing stock but have more involved regulatory requirements and will thus run on a separate timeline.
	ER8	Coral seeding by automated aquaculture	
	ER9	Coral seeding by larval/polyp aquaculture	
	EE3	Seeding enhanced corals bred from existing stock with semi-automated aquaculture	
	EE4	Seeding enhanced corals bred from existing stock with automated aquaculture	
	EE5	Seeding enhanced corals bred from existing stock with larval/polyp aquaculture	
	EN1	Seeding enhanced corals bred from engineered stock with semi-automated aquaculture	
	EN2	Seeding enhanced corals bred from engineered stock with automated aquaculture	
	EN3	Seeding enhanced corals bred from engineered stock with larval/polyp aquaculture	
Early phase investigations	B1	Biocontrol of macroalgae	• Desktop studies to better quantify potential benefits. • Progress to R&D if studies indicate value. • Possibly run a competition/prize to generate field treatment delivery method ideas, as this is the primary constraint for this intervention.
	B2	Biocontrol of species with negative impact	
	F1	Application of field treatments to enhance coral survival	
	C9	Shading by algae	

5.3 Field testing and monitoring

Field testing and monitoring of outcomes would be undertaken as part of the individual R&D sub-programs. Additionally, the Ecological Intelligence and Risk Sub-Program (Appendix F3) incorporates an extensive field testing and monitoring program. These sub-programs would be managed and optimised together, and economies of scale would be achieved by working at a coordinated set of field sites that would take into account cross shelf and latitudinal variation.

6. R&D PROGRAM – DELIVERY

6.1 Governance and program management

This is described in R6: Governance and Program Delivery.

6.2 R&D stages

Under the minimum recommended RRAP R&D Program, the interventions would progress through a lifecycle, starting with an idea and little other information upon which to make decisions (Table 9). As information increases, progressively larger amounts of R&D funding would be required to test and refine the idea. At any one time, there would be interventions across a broad spectrum of development stages.

To provide structure to the R&D program, R&D stage descriptions were developed and used:

- As a standard method to articulate the high-level intervention assessment/development status
- As activity clusters to document R&D strategies/plans/investment needs for each intervention
- To aid ongoing R&D investment prioritisation and make it easier to reflect changes into strategies and plans.

Due to time and resource constraints, it is a simple, interim, bespoke system, which currently only extends to a ‘proof-of-concept’ research stage.

Table 9: Recommended RRAP R&D Program stages overview.

Stage		Description
1	Idea	• No assessment completed.
2	First principles assessment	• Unfunded first principles assessment.
3	Desktop study	• Low-cost desktop assessment to develop early phase estimates of the intervention and the associated benefits, costs and risks.
4	Development and small-scale field trials	• Quantitative assessment of costs, benefits and risks to implement the intervention including undertaking all underpinning R&D and field testing required. • Confirmation that key performance criteria (those that materially impact on the viability of an intervention/method) can be met. • All residual R&D required to develop an intervention/method to final proof-of-concept, scale-testing stage.
5	Large-scale field trials	• Large-scale field testing using targeted ‘production phase’ methods to assess and confirm forecast benefits, risks and costs. May require prototype-scale facilities and infrastructure to be developed and commissioned. • Further field validation testing, as needed, based on the above outcomes. May merge into commercial deployment.
If an intervention subsequently progresses to implementation, additional stages would be required. These would be context-specific and likely to involve a progressive program of ramping-up production and deployment. It would be highly dependent on the commercial and service provision model adopted and the targeted scale and timing.		

Details of the specific stage-gate assessment criteria are provided in Appendix G.

During the first 12 months of the RRAP R&D Program, this system would be upgraded to an industry standard system. This upgrade would most likely move the system from simply using technology readiness levels that cannot measure all the dimensions needed to progress an intervention through to deployment to manufacturing readiness levels. Manufacturing readiness levels appear to be a good fit for developing Reef interventions as they can assess a wide range of factors including level of concept design, market/benefits assessments, cost assessments, supply chain factors, development risk and regulatory approvals. Manufacturing readiness levels also include the full lifecycle, up to full-scale production.

6.3 Risk management

For a program of such wide-ranging complexity, with such a diverse stakeholder community and so much at stake, risk and uncertainty will always be present. The R&D program, and any future deployment of interventions, must manage this complexity and uncertainty. This means developing risk management and decision-making approaches to produce robust solutions, across a wide range of possible future conditions, which are stable over time, even as the environment changes.

A risk management plan, including sub-program and project-level risk registers and management plans would be formulated during the first six months of the RRAP R&D Program. The plan would be consistent with Australian/New Zealand Standards (AS/NZS ISO 31000:2018: Risk Management – Guidelines). It would outline the risk management framework, including the mandate and board-approved risk appetite statement; the risk management principles and policy; and the plans, relationships, accountabilities, resources, processes and activities employed to manage risks. The plan would include policies, processes and procedures for risk oversight, identification and control. Workshops would be held with key RRAP R&D personnel to identify and develop effective controls to manage material risks at both the program and sub-program levels.

A key additional aspect of risk management would be to adopt the 'red team vs blue team' approach, successfully used by the US Government when dealing with especially contentious, complex decisions. Developed by the US military, the concept involves establishing expert teams who challenge each other to test how robust a plan or proposition is. One team defends and another attacks the proposition in a simulated exercise. The RRAP R&D Program would deploy red vs blue throughout its governance structure, forming multi-institutional red and blue teams to test critical issues and decisions and develop risk management and mitigation strategies.

At a technical level, the process of risk identification commenced during the concept feasibility assessment and development of recommended R&D sub-programs. Appendices E2, E3, E4 and E5 provide a summary of the specific risks identified and how they would be managed in the R&D program, with further details documented in the intervention R&D sub-programs.

Material strategic risks for RRAP

In addition to these specific technical risks, material strategic risks for RRAP were identified. These are risks that may materially impact upon the ability to achieve the intended strategic outcomes of RRAP and where controls have been incorporated into the structure of the R&D program and governance arrangements.

1. **Funding withdrawn or reduced, or the timing of drawdowns hinders progress** **(Likelihood: medium, consequence: high)** Delivery of the first five years of the proposed R&D program is estimated to require a minimum of $350M (combined cash and in-kind funding) and further funds thereafter. If the initial cash funding from the Australian Government (via the Reef Trust Partnership) and any of the partners or other key stakeholders is lower than budgeted, this may affect progress. The timing of funding and allocation of funds to critical path activities are important considerations.

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

2. **Inability to deliver intended program results in the time required due to regulatory or other constraints** **(Likelihood: medium, consequence: high)** As with any major applied R&D program, there are high levels of uncertainty at the early stage including in relation to future climatic state, future Reef health, adaptation rates of corals to global warming, the efficacy of novel interventions, unintended impacts, the requirements and likelihood of achieving regulatory approval for different intervention types and changing views of society. For example, the existing regulatory and policy environment for the Great Barrier Reef is robust and acknowledged internationally. However, some of the interventions will challenge the existing regulatory framework, given the range of novel interventions proposed. Methods for assessing the proposed activities and observing, monitoring and reporting on the impacts will not necessarily be established or tested.

   Mitigation: Retain broad optionality at the start of the program and refine intervention options and strategies as uncertainty is reduced and accounted for. The strategy is to assess and develop several options in parallel to ensure the highest likelihood of success. Early deployment is a priority. Where an intervention has a greater chance of improving the system than harming it, and it lays the foundation for better outcomes from subsequent actions, it will be favoured. The less degraded the Reef, the more likely it will be that the adaptation interventions will make a lasting difference. To help ensure intervention deployment at the earliest time, the recommended program was designed to allow for a broad range of interventions and assessments including ecological process studies, scoping of the Traditional Owner engagement context and preliminary stakeholder engagement and regulatory requirements, to be occurring in parallel. Additionally, the suite of interventions is targeted across a wide range of deployment scales, including those that can be delivered more quickly (and target retention of the highest value sites/reefs) and others that may take longer to develop but have higher impact (targeting regional scales). **Residual risk = medium**

3. **Governance and engagement do not meet government, stakeholder or community expectations** **(Likelihood: low, consequence: medium)** The R&D program will be conducted in the context of a complex governance system around the management of

the Great Barrier Reef Marine Park area, characterised by many and diverse stakeholders, policies and regulatory frameworks. It is important the program appropriately engages in that system to identify issues and opportunities early and ensure complementarity with other Great Barrier Reef programs. Robust and well-functioning governance and management are critical to success. Under-investment in these aspects may result in significant risk of non-delivery.

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

4. **Community support for RRAP wanes** **(Likelihood: medium, consequence: high)** Maintaining the current high in-principal support for proposed intervention needs to be based on effective Traditional Owner, community and stakeholder engagement. Balancing the short-term risks to the Reef system of intervention actions, against the medium to long-term risks of no action, must be clearly understood by the public.

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

5. **Ecological intervention risk** **(likelihood: medium, consequence: medium)** As climate change is predicted to overwhelm the capacity of conventional management approaches to sustain coral reefs, strategies that actively incorporate novel and validated interventions in the Reef management toolbox could produce an improved outlook for coral reefs. It will, however, be necessary to assess whether the ecological rewards of the intervention (the upside risk) are likely to be greater than the negative consequences (the downside risk, including ecological consequences) of actions or inaction. Formal analyses of both the upside and downside risks of intervening to improve reef condition earlier versus later, or not intervening at all (action and inaction), need to guide decision-making.

Mitigation: All proposed restoration and adaptation technologies will be assessed against current legislation and regulations. Ongoing assessment of ecological risk and potential adverse environmental impacts will be conducted in addressing the requirements for regulatory approval, as the testing of interventions progresses from research scale to proof-of-concept and ultimately deployment. RRAP will explore, assess and develop interventions, but none will be deployed unless, or until, the benefits of intervention, as a function of the state of the ecosystem at the time, are determined to outweigh the likely costs and risks (i.e. until the risk/return profile for intervention is acceptable). The framework to deliver this approach comprises a dedicated decision-support system to guide decision-making at strategic/program, tactical and technical levels, backed by the work of the Modelling and Ecological Intelligence and Risk sub-programs. **Residual risk = medium**

6. **Genetic intervention risk** **(Likelihood: medium, consequence: high)** Several interventions may advertently or inadvertently impact the genetics of coral reef organisms. Genetic diversity is a key component of the health, fitness and resilience of populations and could be beneficially (the upside risk) or negatively (the downside risk) impacted at an individual, population or species level. Indeed, this is the actual intent of many proposed interventions, see **T3: Intervention Technical Summary** for a comprehensive discussion). It will be necessary to assess whether any proposed intervention will have net positive effects on the genetics of population and species. This will involve cutting-edge genomic analyses of natural populations (before and after R&D), experimental samples combined with evolutionary modelling and theory to inform risk analysis and guide decision-making. Gene editing and synthetic biology approaches introduce novel genes or organisms. They have the dual potential to both act to prove the function of genes in processes (such as heat tolerance) and enhance the trait. These approaches carry a different level of risk to the population genomic risks discussed above and are surrounded by a more stringent regulatory environment.

   Mitigation: All proposed restoration and adaptation technologies will be assessed against current legislation and regulations. Ongoing assessment of genetic risk and potential adverse environmental impacts will be conducted as part of the R&D sub-programs and as steps to gain regulatory approval (a staged series of controlled laboratory and field-testing programs). It is unlikely R&D with genetically engineered or synthetic biological material will be conducted outside quarantine conditions in the foreseeable future. The framework to deliver this approach comprises a dedicated decision-support system to guide decision-making at strategic/program, tactical and technical levels, backed by the work of the Modelling; Enhanced Corals; Treatments and Aquaculture; and Ecological Intelligence and Risk sub-programs. **Residual risk = medium**

7. **Environmental intervention risk** **(Likelihood: medium, consequence: high)**

   Some proposed interventions aim to alter the environmental conditions of the atmosphere, water column or benthos (flora and fauna on the ocean floor). Changes to the local or regional environment may include the application of engineering processes and other technologies to cool water or shade corals at a variety of spatial scales. These generally carry a medium-to-high risk of adverse environmental impacts that may be short or long lived. Other approaches may add biological material, chemicals or structures to treat corals or the substratum. These may introduce or promote invasive species or altered environmental states that negatively impact ecological interactions.

Mitigation: All proposed restoration and adaptation technologies will be assessed against current legislation and regulations and acceptance will be broadly tested with stakeholders. 'Red vs blue' testing will be used here in particular. Ongoing assessment of potential adverse environmental impacts will be conducted as part of the R&D sub-programs and as steps to gain regulatory approval. R&D will encompass steps to measure risk and gain regulatory approval via a staged series of controlled laboratory and field-testing programs. This approach will be guided by a dedicated RRAP decision-support system, integrated with the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP), to guide decision-making at strategic/program, tactical and technical levels, backed by the work of the Modelling, Ecological Intelligence and Risk, Cooling and Shading, Rubble Stabilisation and Emerging Interventions sub-programs. **Residual risk = medium**

7. INVESTMENT REQUIREMENTS

7.1 Base case requirements

Background

The R&D program detailed in this report is designed to retain high levels of intervention optionality while seeking to minimise risk and investment requirements. As such, it is recommended as the minimum investment case.

Four key decisions in this program design drive the rate and duration of the required R&D investment:

1. The program is progressing interventions that encompass all seven functional objective types to retain optionality and build on the initial findings that combining interventions with different functional impacts will provide the highest benefits. In some instances, this is limited to a desktop study. Should these indicate viability, an appropriate R&D program would be developed and funding sourced (new funding or via offsets by halting other R&D areas).

2. The program is progressing interventions in parallel. For example, development of interventions to cool and shade is occurring in parallel with the development of interventions to seed enhanced corals. This shortens the program but increases the rate of investment required, particularly over the first five years.

3. Multiple interventions are being progressed within each functional objective cluster to provide options at different deployment scales and costs, and to manage the risk that not all will be feasible. To manage costs and provide an efficient outcome, the R&D program was designed to progressively focus on the most prospective interventions, with only a subset assumed to be funded to completion of R&D.

4. At the intervention level, a sequential R&D approach will be taken. In general, the R&D program's first focus will be on assessing and reducing key risk areas, then, subject to satisfactory outcomes, the program moves to completing the residual R&D activities to deliver a deployment-ready intervention.

Discussion on optionality regarding these decisions is provided in Section 7.2.

Development process and key assumptions

Outlines of the investment required to deliver the proposed R&D strategy were developed for each sub-program. These budgets allow all targeted interventions to be initially assessed and assume only a subset would be progressed to completion. The R&D program would harness strategies to rapidly reduce the number of delivery methods to the most viable, and hence reduce the number of interventions being progressed.

To develop the estimates of investment requirements, multi-institutional teams of experts undertook a process of defining goals, strategies and required investment areas. Approximately 150 investment areas were identified across the sub-programs. R&D tasks to progress each investment area were defined and budget requirements determined. Standard unit costing rates were used to ensure consistent costing across the program areas and to allow the R&D programs to be 'organisationally agnostic'. No attempts were made to allocate the R&D to organisations or individuals, this would be the task of the proposed governance and program management framework. Appendix H provides details of the standard costing rates used, along with assumptions on indexation and overheads.

To help bound the budgets of the intervention sub-programs, additional assumptions were made as to which (or how many) of the underpinning delivery methods (and by default interventions) would be progressed. These are briefly outlined in Table 10 and directly impacted the investment requirement estimates outlined in Tables 11 and 12. In addition, Table 10 provides a summary of costing assumptions made for the other RRAP sub-programs.

Table 10: Key budget assumptions

R&D Sub-Program	Budget Assumptions
Engagement and Regulatory	The budget assumes several small facilitation teams, funds to support the participation of third parties in engagement and participatory activities and experts to undertake ongoing assessment and development activities.
Decision Support	A small team initially focused on supporting R&D prioritisation, progressively moving to supporting decisions to undertake large-scale pilot trials and ultimately decisions to invest in deployment.
Modelling	The budget assumes several teams of modellers developing an integrated suite of models, along with the governance arrangements, to ensure the models deliver the required outputs to the decision support and intervention R&D sub-program areas.
Ecological Intelligence and Risk	The budget is based on a combined field and experimental program designed to address key knowledge gaps. It includes an ongoing field monitoring program that would be leveraged to support monitoring intervention field trials.
Cooling and Shading	The program has a cluster of small-scale interventions assumed to be tested and either proven and available for deployment investment or eliminated. The interventions with longer R&D durations are assumed to pass through stage gates and continue being developed.
Rubble Stabilisation	This sub-program initially focuses on assessing the need for, and potential functional benefit of rubble stabilisation, with a stage gate at the end of year two. The budget assumes benefits are confirmed and the program continues. The budget further assumes that, based on the improved knowledge generated during the review, the current nine interventions are reduced to the four most beneficial and only these four are developed and tested.
Moving Corals	The budget initially funds two interventions and assumes a third is progressed from year four onwards, based on the integration of larval slick and aquaculture delivery methods.
Enhanced Corals, Treatments and Aquaculture	R&D to test and develop enhanced corals and treatments is assumed to pass through stage gates and progress to completion. Of the three nominated aquaculture delivery methods, only one is budgeted to completion. The sub-program initially focuses on testing specific technologies and methods to assess the feasibility and, based on findings, one of the three methods (or a variant) is selected and progressed.
Early Phase Intervention Assessments	This sub-program funds desktop studies for two specific intervention areas: field treatments and biocontrol. If these studies recommend moving one or both into an R&D program, funding would need to be prioritised from other program areas or additional funding sourced.
Cryopreserving Biodiversity	The budget assumes a coral cryopreservation program is established in collaboration with the Smithsonian Institution and the Taronga Conservation Society. It allows for the development of techniques, assessment of how cryopreservation could improve interventions and biobanking of high-value coral reef biodiversity.
Systems Engineering, Integrated Logistics	The budget assumes a small team, with allowances for industry contractors to undertake systems engineering, integrated logistics, infrastructure distribution and optimisation activities.
Automation	The budget allows for two fast-track areas of automation R&D in years one to three, then factors three broader programs of automation R&D commencing in year four. The three broad areas of need have been identified; however, their commencement would be delayed for other R&D areas to deliver more precise functional requirements.
International	A small allowance to establish an Australian node of the Coral Reef Consortium to foster increased knowledge sharing and to fund International Coral Reef Initiative (ICRI) activities to increase international government awareness of the need and benefits of investment in restoration and adaptation R&D.
Program Management	Program management costs are based on labour and operating costs commensurate with the management structure outlined in R6: Governance and Program Delivery. An adaptive planning allowance of $18.8M has been included in the budget to buffer against high levels of uncertainty and to allow for additional delivery methods to be incorporated.

Investment requirements

Table 11: Budget for the first five years of the recommended RRAP R&D Program, 2019–24.

Sub-program	Total cost (2019–24) ($M)	2019/20 ($M)	2020/21 ($M)	2021/22 ($M)	2022/23 ($M)	2023/24 ($M)
Program Management (including contingency)	41.3	3.4	7.3	10	10.2	10.4
Engagement and Regulatory	12.9	2.1	2.8	2.7	2.7	2.6
Decision Support	4.8	0.9	1.3	1.2	0.8	0.6
Modelling	10.7	1.8	2.8	3	1.9	1.2
Ecological Intelligence and Risk	18.1	2.4	4.4	4.6	3.9	2.8
Enhanced Corals, Treatments and Aquaculture	93.4	7.7	17.7	22.6	23.1	22.3
Moving Corals	21.9	2.9	4.8	5.2	4.6	4.4
Rubble Stabilisation	22.4	2.1	5.9	6.3	4.8	3.3
Cooling and Shading	62.3	5.7	12.3	15.4	14.9	1.4
Early Phase Assessments	2.3	0.6	0.5	0.4	0.4	0.4
Cryopreserving Biodiversity	9.6	1.1	1.9	2.1	2.4	2.1
Systems Engineering and Integrated Logistics	14.9	1.6	2.7	3	3.7	3.9
Automation	9.8	1.7	2.5	1.3	0.6	3.7
International Engagement	1.8	0.4	0.35	0.35	0.35	0.35
Total	326.2	33.7	66.5	77.4	73.6	71.3

Table 12: Budget for the second five years of the recommended RRAP R&D Program, 2024–29 and the total costs for the full 10 years, 2019–29.

Sub-program	Total cost (2024–29) ($M)	2024/25 ($M)	2025/26 ($M)	2026/27 ($M)	2027/28 ($M)	2028/29 ($M)	Total cost (2019–29) ($M)
Program Management	44.4	10.6	10.8	9.4	6.7	6.9	85.7
Engagement and Regulatory	7.3	1.7	1.4	1.4	1.4	1.4	20.2
Decision Support	2	0.4	0.4	0.4	0.4	0.4	6.87
Modelling	4.2	0.9	0.8	0.8	0.8	0.9	14.9
Ecological Intelligence and Risk	8.8	1.9	1.7	1.7	1.7	1.8	26.9
Enhanced Corals, Treatments and Aquaculture	36.8	15.4	9.5	5.5	3.6	2.8	130.2
Moving Corals	11.3	4.7	4.1	1.5	0.5	0.5	33.2
Rubble Stabilisation	29.1	10.8	13.2	4.5	0.5	0.1	51.5
Cooling and Shading	26.3	8.2	8.2	7.1	2.3	0.5	88.6
Early Phase Assessments	2.4	0.4	0.5	0.5	0.5	0.5	4.7
Cryopreserving Biodiversity	4.7	1.2	0.8	0.9	0.9	0.9	14.3
Systems Engineering and Integrated Logistics	10.4	2.9	2	1.8	1.8	1.9	25.3
Automation	26.2	9	10.8	4.1	1.1	1.2	36
International Engagement	1.75	0.35	0.35	0.35	0.35	0.35	3.55
Total	215.6	68	65	40	23	20	541.8

Uncertainty of investment requirements

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

1. The R&D sub-programs have, by necessity, been presented as specific investment scenarios, actual investment would need to be more dynamic as the program adapts to the emerging state of the Reef and improved understanding of needs and benefits.
2. The sub-program investments make predictions as to the outcomes of stage-gate assessments and processes designed to refine and reduce the number of delivery methods being developed.
3. In each area, the teams have made assumptions about required resourcing and duration to achieve stated goals. These estimates were made based on the combined experience of the teams; however, at this early stage of the program, they are subject to medium-to-high levels of uncertainty.

The net outcome is that uncertainty increases rapidly beyond the first three years and years four to 10 have progressively increasing levels of uncertainty.

7.2 Government investment scenarios

The R&D program investment requirements were developed considering key criteria, including the breadth of interventions being initially progressed, R&D durations and how quickly interventions might be made deployment-ready and R&D investment risk appetite. As such, what can be achieved, and how fast, will be a function of the level of base government funding and the extent to which this can be leveraged into an overall investment profile.

In addition to the base (minimum recommended) investment case, two additional investment profiles were assessed:

- An enhanced government funding case
- A reduced investment case.

Each is discussed below:

Base (minimum recommended) investment case

This is the base case and the assumed investment profile for the R&D program detailed in this plan. It would be a five-plus-five-year program, with the first five years potentially funded assuming $100M in base government program funding via the Great Barrier Reef Fund Reef Trust Partnership, supplemented by $100M in third-party (corporate and philanthropic) funding and a further $100M in R&D provider in-kind investment. Additional base government investment would be sought for the second five-year period, dependent on findings and outcomes from the first five years.

Enhanced government investment case

Several options were examined for an investment case that would aim to manage risks and reduce the timeframes of interventions deployed on the Reef. These options would still commence with the same 43 targeted intervention-scale combinations and use additional base government investment in the first five years to lock in delivery of the proposed R&D program and bring forward development by developing prototype deployment systems.

Specifically:

a) **Increase base government funding.** This option increases the ratio of base government funding to supplementary funding (philanthropic, corporate, R&D provider) to support critical core cross-cutting aspects of the R&D program, including modelling and decision-making system development, deployment engineering, Traditional Owner and social engagement aspects, and project management and integration. Initial estimates suggest an additional $50M over five years would be sufficient. This model would reduce the risk that supplementary funding from philanthropic sources may take time to secure, delaying progress in the first few years of the program, may not be fully secured and/or would be burdened with specific caveats from philanthropic donors or research providers, skewing the intended R&D program.

b) **Early investment in prototype deployment.** Funding the development and operation of intervention deployment (infrastructure and operational systems) is beyond the scope of the R&D program. However, initial analysis suggests that a $100M investment over five years would allow no-regrets deployment prototyping facilities to be brought online and commence operations, significantly accelerating the prospect of early at-scale intervention. The prospective areas include the development of an aquaculture capability and field deployment platforms for larval slick coral restoration, cooling and shading and rubble stabilisation interventions.

Reduced investment case

Two options were assessed to manage the scenario of the minimum recommended investment not being available for the first five years of the R&D program. This could occur because of reduced government base funding or the levels of supplementary funding from other sources not being achieved.

c) **Reduced number of interventions–not recommended**. Reducing the number of interventions initially progressed would provide only minimal cost reductions and would force premature elimination of intervention objectives that may have turned out to be extremely valuable.

d) **Reduced rate of investment into each intervention–recommended in a reduced-funding scenario**. If the recommended minimum investment levels cannot be secured, the broad suite of current interventions should be retained within the R&D program. However, investment levels in larger-scale interventions could be reduced. This approach would delay future potential large-scale intervention benefits but would retain much-needed optionality while delivering early intervention deployment options. Additional funding would still need to be sought in the out-years to continue the required R&D. The trade-off is the potential additional Reef degradation that would occur while the intervention is developed at a slower rate, as illustrated in **Error! Reference source not found.**Figure 6. Additional funding would still need to be sought in the out-years to continue the required R&D.

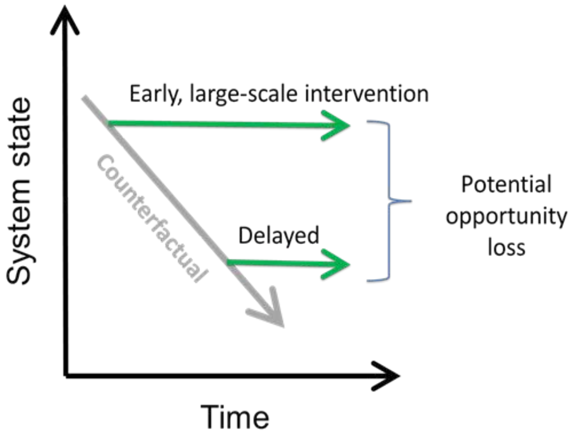

Figure 6: Potential impact of delaying the delivery of large-scale interventions.

Summary

It is recommended that the minimum overall investment level targeted is $326M over the first five years, with a subsequent second five years currently estimated at a further $216M.

As a minimum, this requires $100M of base government funding over the first five years. This funding would be supplemented by third-party and R&D provider (in-kind) funding. Subject to program outcomes, including levels for third-party funding secured, a submission to government during years three to five would be made for base government funding to continue the program into a second five-year period.

It is further recommended consideration be given to funding early deployment capability in the form of prototype systems and enabling resources. This would enable a combination of larger-scale testing, and working with stakeholders to assess benefits and risks, along with the earliest possible commencement of intervention deployment (subject to appropriate regulatory approvals). Preliminary estimates indicate that a further $100M in government investment would be required over the first five years of the program to secure this outcome. Further assessment of this option will occur early in the R&D program.

8. REFERENCES

The follow RRAP documents were used to produce this report:

R1: Engagement and Regulatory Dimensions

R2: Intervention Summary

R3: Intervention Analysis and Recommendations

T5: Future Deployment Scenarios and Costing

APPENDIX A – RRAP DOCUMENT MAP

APPENDIX B – R&D GOALS EXAMPLE

Several variants of aquaculture systems are being explored as delivery methods to seed corals to both restore degraded reefs (with natural unmodified corals) and increase resilience and rates of adaptation (with enhanced corals). The associated R&D sub-program therefore has two goals: to develop enhanced corals (with a focus on both the coral host <u>and</u> microbial treatments) and develop aquaculture systems that can produce and deploy very large quantities of corals to the Reef (natural or enhanced).

Ideally, the R&D program would deliver an outcome that moved the capability to the top right-hand corner of Figure B1. Should some technologies prove infeasible, or if there was a requirement for deployment before they were fully developed, the available technologies could be packaged into a reduced-scope capability for deployment.

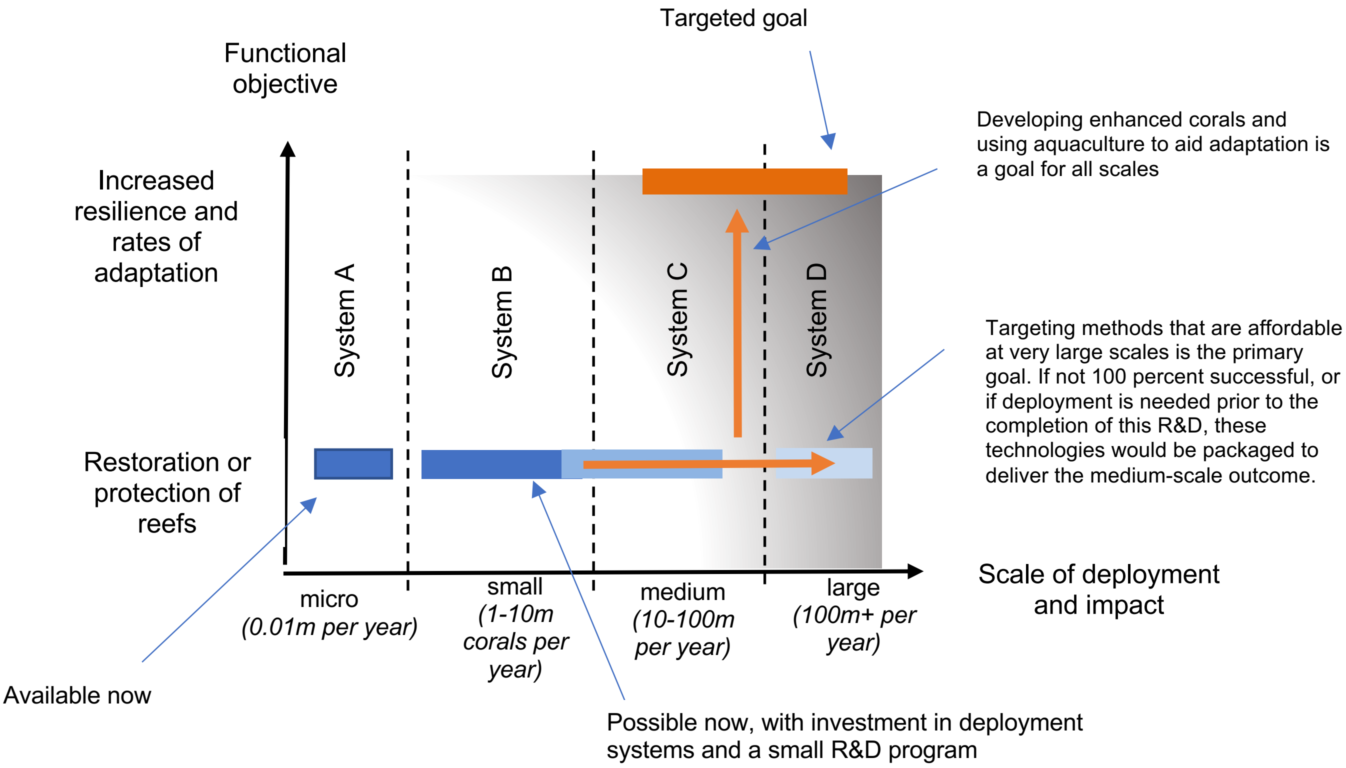

Figure B1: Different aquaculture systems and how the RRAP R&D Program would target a specific goal, with fall-back positions should not all technologies prove feasible.

APPENDIX C – DEPLOYMENT PHASE BUSINESS MODEL

The assumed business model for deployment is an important consideration in assessing the feasibility to deliver interventions and the extent to which the RRAP R&D Program seeks to develop and test methods prior to tendering for deployment.

Several implications were assessed as part of the broader and individual R&D strategies including:

A. Funding sources.

B. Investment entry hurdles.

C. Pricing and managing risk.

Funding sources

In an open market, those receiving value are best placed to fund the cost of an activity. The Great Barrier Reef context is complex, due to the wide range of stakeholders and lack of direct Reef adjacency. Reefs of the Great Barrier Reef are mostly remote from specific communities (unlike for example in the Caribbean/Pacific where the reef typically surrounds a specific community), most tourism-related companies and public stakeholders. Those operating reef trips have a direct adjacency to a specific reef; however, these operators represent a component of businesses deriving value from reef-based tourism.

This contrasts with the international context where direct adjacency to reefs and the benefits they provide, is driving several emerging commercial markets. In particular, two are gaining traction:

- **Storm surge protection:** Recent large infrastructure losses from Caribbean/Eastern US typhoons are leading to pricing the storm surge protection value provided by reefs into capital and insurance markets. This seeks to drive commercial investment in maintaining/restoring the height of reef crests and, therefore, reduce infrastructure damage caused by flood inundation damage. This is less relevant to Australia, due to the remote nature of reefs from coastal infrastructure. As such, it is difficult to see these mechanisms providing funding for Australian reef restoration activities in the near future.
- **Parametric reef insurance:** Several reef insurance products are in development. Currently, the offerings/uptake are limited and appear to be most applicable to large tourism developments with adjacent local reefs that need to be maintained. The operator pays an insurance premium, with a payout occurring if a weather event above a certain category occurs (irrespective of damage). This allows the operator to pay for the reef to be restored. It is uncertain if these products would be relevant to Australia, as there are limited locations with both reef adjacency and a customer with the financial ability to pay the insurance premiums.

In summary, there are no clear 'direct Reef stakeholders' with sufficient adjacency and/or scale to directly fund large-scale reef restoration and adaptation activities. There is a driver for tourism operators to maintain lease sites (assuming they cannot simply move operations to another site); however, this is a very small market.

Domestically, there are efforts to develop a 'Reef Credit' market. Others are exploring options that would seek to leverage investment currently located in hedge funds. These may develop in time; however, it is uncertain as to how quickly these might develop, what scale they might reach and what areas they may consider funding.

Currently, the most likely funding source would be the redirection of state and federal taxation revenue.

Investment entry hurdles

Based on the interventions identified to date, there is a strong correlation between the scale of deployment and initial investment requirements. While some interventions can be delivered on a project-by-project basis, as their scale of deployment increases, they reach a point where dedicated large-scale infrastructure is required. Others start with this need, requiring up-front capital investments of tens of millions to hundreds of millions. This is illustrated in Figure C1 for selected groups of intervention delivery methods. For example, under cooling and shading, the cloud brightening method is designed to only be deployed at scale; however, it requires a large up-front capital investment in infrastructure. Conversely, the surface film method would be deployed at small scale, on a case-by-case basis, using chartered vessels, with logistical constraints preventing it from being scaled to regional or system levels. Similarly, the different methods of aquaculture come with different scale potentials and investment entry hurdles.

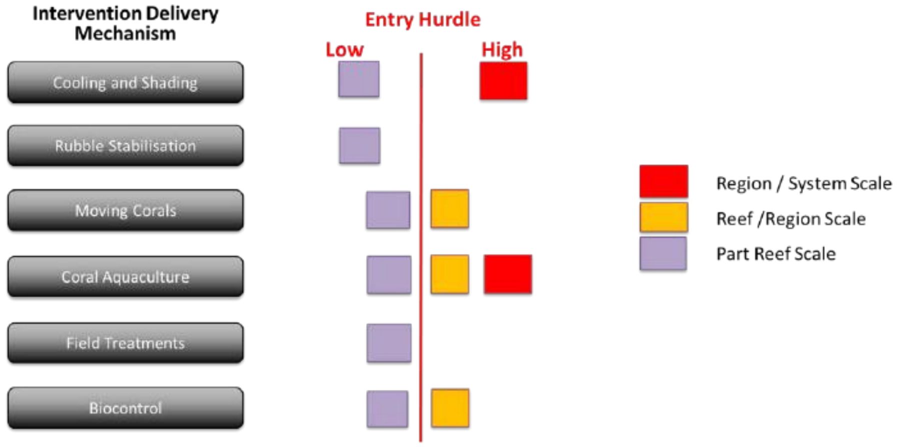

Figure C1: Intervention investment entry hurdles.

If private sector investment to establish infrastructure was to occur at large scales, it would require hedging with future revenue guarantees (contracts). Based on the current context, these guarantees could only occur if the state and/or federal governments were funding the services.

Pricing and managing risk

Risk cost is minimised when risk is carried by the entity best positioned to manage it. In the case of restoration and adaptation interventions, risk spans two dimensions:

- Functional outcome risk: this is multifaceted and comprises both upside (achieving benefits) and downside (adverse outcomes) and is scale dependent. For example, the difference between an average and a good intervention deployment strategy could be an order of magnitude difference in the level of impact achieved.
- Technical delivery risk: can the specific actions/products be delivered (as contracted) in the manner required?

These dimensions impact on what R&D should be government-funded versus that assumed to be undertaken by those contracting to deliver interventions. Due to the complexity of the ecological systems involved, as a generalisation, it is assumed that managing functional outcome risk needs to be centralised and managed by the government. Managing technical delivery risk is highly contingent on the intervention and this needs to be factored into individual intervention R&D programs.

Assumed intervention deployment business model

Based on the above, the following was assumed in designing the minimum recommended RRAP R&D Program:

A. The assumed Australian investment model for future deployment of interventions would be a public-private partnership. The government could raise funding through taxation revenue and tender delivery to private industry. This is the least restrictive assumption. It allows interventions with large initial capital investment requirements to be considered.

B. Functional outcome risk would be carried by the government, including decisions regarding intervention selection and deployment scale/location/timing. A large component of the minimum recommended RRAP R&D Program is therefore focused on developing these decision-making processes and the underpinning modelling and knowledge requirements.

C. Technical delivery risk is assumed to be shared and managed on a case-by-case basis, dependent on current technology readiness levels and industry-provider expertise. In each instance, RRAP would seek to determine the R&D required to develop and test methods prior to commercial transfer and tendering for deployment. Where appropriate and possible, the R&D program would seek to involve potential delivery providers in pre-tender R&D.

Case example: Rubble stabilisation

The production and delivery components of rubble stabilisation interventions are highly industrial, with high levels of cross over into other fields of industrial endeavour. For example, there is significant existing heavy engineering industry expertise in stabilising substrates and deploying artificial structures in remote marine locations. It is therefore reasonable to assume that industry can adapt this capability as needed when tendering for services.

However, there are major knowledge gaps relating to the need for rubble stabilisation and the methods that might be employed. These have major implications:

1. It is still uncertain where and when rubble stabilisation would provide an acceptable cost-benefit outcome and, therefore, the extent to which it should be used as an intervention.

2. Delivery methods such as stabilisation and 3D structure would be deployed in patterns (for example, with careful design, you might only need to directly stabilise 10 percent of a target area to effectively stabilise the full area). At this time, there is no knowledge as to the design/performance of different options. Clever designs could reduce costs by an order of magnitude.

3. It is not yet possible to set functional performance criteria for each delivery method.

Points 2 and 3 have tendering implications and the pricing of risk. There are many possible options to tender rubble stabilisation services to the commercial market. These would be bookended by the following two options:

	Option	Commentary
1	To stabilise area A, client directs company to undertake stabilisation method X in locations Y in quantities Z	Client carries risk that functional stabilisation objectives are not met. Client would need to tender additional/rectification stabilisation works if the first deployment was not successful.
2	Client tenders to company to stabilise a general area A with an overall functional performance guarantee.	Company forced to price very high functional delivery risk into tender. Client carries no risk, but costs are significantly higher.

Based on the current state of knowledge, both options would result in a very high risk-cost being carried/passed on to the client (government) if deployment was contracted immediately. Conversely, an R&D program to refine functional performance needs and parameters, such as spacing designs, prior to tendering, would significantly reduce risk and pricing. However, there would be little value in undertaking R&D into the detailed engineering methods to deliver at scale. There is sufficient existing industry expertise for this detailed engineering to be best delivered by the market when tendering for services.

APPENDIX D – DEVELOPMENT TIMELINE EXAMPLE

The RRAP R&D Program represents one of several stages that would be required to deliver a new intervention at scale.

This example (Figure D1) outlines the process to develop a large-scale aquaculture capability, such as that required to underpin interventions such as ER8, ER9, EE4, EE5, EN2 and EN3. It illustrates several key points:

- There is an initial R&D requirement to achieve critical performance parameters and develop and test critical aspects of the recommended method. R&D is likely to still be required beyond this point.
- Developing production prototypes would likely be a precursor to investment in production facilities, to confirm performance and undertake final design and development activities.
- Investment requirements ramp-up substantially from the point of developing production prototype facilities.

Production volumes would take time to ramp-up, as investment in infrastructure would be progressively staged, to manage risk. This staging might be due to facility replication, or staged development within a facility, or a combination of both, depending on the context.

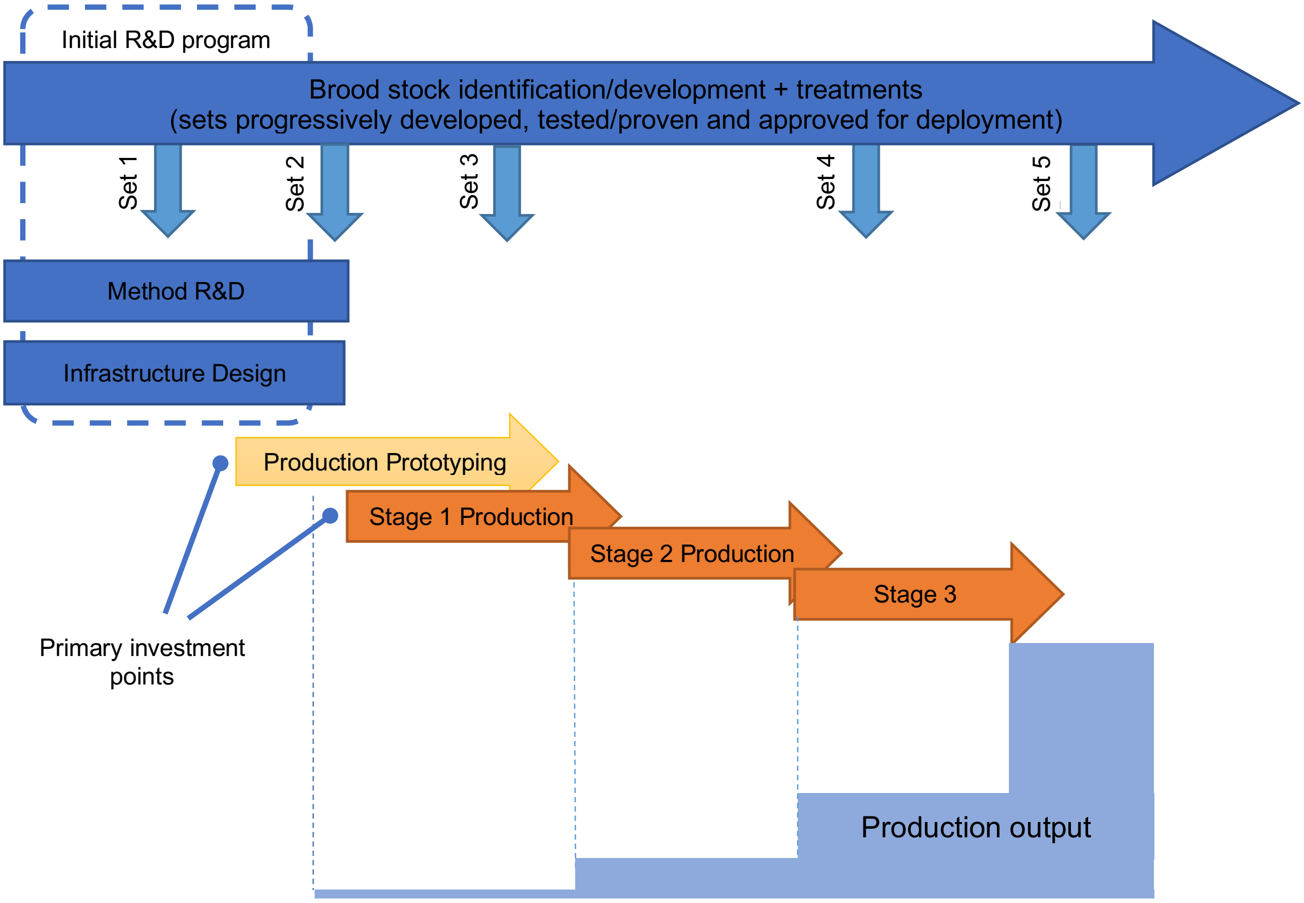

Figure D1: Development timeline example - developing an aquaculture capability.

APPENDIX E – R&D PROGRAM DESIGN CONSIDERATIONS

APPENDIX E1: INTERVENTION SYNERGIES

Functional synergies

Two primary synergies were assessed and factored into the R&D program recommendations:

- **Ecosystem functional synergies.** Where interventions support each other in achieving the desired ecosystem functional outcomes.
- **Deployment infrastructure synergies.** Common infrastructure requirements in which use could be combined or alternated.

Assessing these synergies is critical, as they impact on both fundamental viability and optimal design. Within the minimum recommended R&D program, they would be identified and assessed via three processes:

- **Ecosystem functional synergies** would be assessed on an ongoing basis by the Modelling and Decision Support R&D sub-programs.
- **Functional synergies** at the 'delivery method' level would be assessed inside the relevant intervention R&D sub-programs. Clustering these R&D sub-programs by delivery mechanism type facilitates the assessment of different delivery methods. Within each program, the teams would be assessing alternative methods, which would provide synergistic benefits if deployed in parallel.
- **Infrastructure synergies** would be identified and assessed in the Systems Engineering and Integrated Logistics R&D Sub-Program.

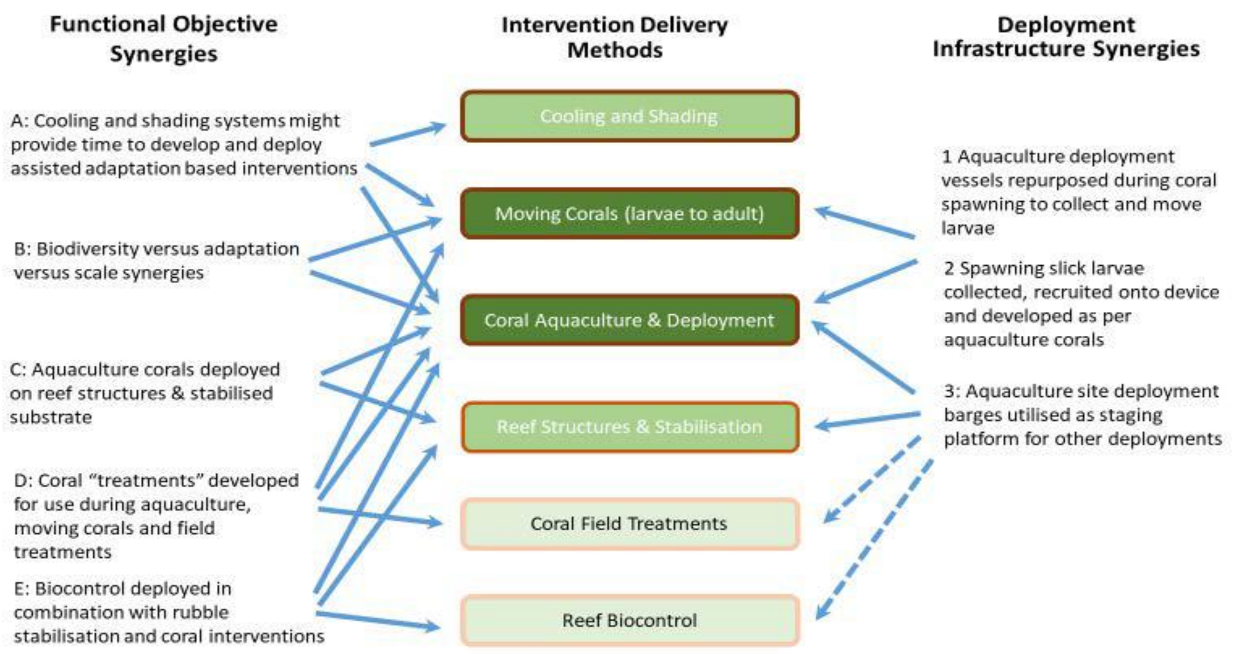

Figure E1.1: Functional and infrastructure synergies.

Figure E1.1 illustrates some of the more significant synergies. Further details are in **R3: Intervention Analysis and Recommendations** and **T5: Future Deployment Scenarios and Costing.**

A: Functional synergy: cooling and shading and adaptation: The cooling and shading interventions of cloud brightening, and ultra-thin surface films could be deployed at scale within a relatively short period (five to 10 years) should they be proven feasible (technically, environmental/social and costs). This is much quicker than interventions designed to assist the rate of temperature adaptation in corals (10 to 15 years), to achieve high aquaculture production rates, and then deployment and reproductive spreading of benefits: intra- and inter-reef (an estimated further 10 to 20 years). As such, the cooling and shading interventions might protect against the worst of the mass bleaching events in the shorter-term, buying time for the adaptation methods to take effect.

B: Functional synergy: moving corals (larvae) & aquaculture: Both moving corals and aquaculture are delivery methods for reseeding degraded reefs and/or enhancing the bleaching tolerance of local coral populations (Table E1.1). Each has distinct benefits and downsides. An integrated model partially offsets these downsides, with a significantly better outcome than if one method was used in isolation.

Table E1.1: The functional synergy between the moving corals and aquaculture methods.

	Benefits	Downsides
Aquaculture	Supports a wide range of interventions and methods to enhance performance	Practically, it can only support a subset of coral species and could impact on genetic and species diversity.
Moving corals (larvae)	Supports a wide range of coral species and genetic diversity	Only supports one approach to enhance performance (i.e. assisted gene flow by moving corals from warmer to cooler reefs). Scale is limited by the annual nature of mass spawning, slick formation and the availability of charter vessels.

C, D & E: functional synergies and combined interventions: These are three examples of the many possible combined interventions, designed to provide an ecological outcome that is greater than the individual outcomes.

1&2: Deployment infrastructure synergy and sequential use: This is different from the simultaneous use of infrastructure for more than one intervention. In this instance, the infrastructure would be repurposed (i.e. used sequentially) between two or more uses during the year. At this time, one specific use case has been identified: the repurposing of aquaculture deployment vessels to collect and move larvae during mass spawning periods.

3: Deployment infrastructure synergy and shared use: Many interventions require a product to be delivered from the shore to the reef. In these instances, transport and deployment logistics are a primary cost driver. Sharing infrastructure could result in significant cost savings.

R&D implications

Assessing, understanding and leveraging functional and infrastructure synergies will be critical if intervention benefits are to be maximised and costs minimised. These need to be considered and factored into decision-making from the commencement of the program.

For example, the program will need to identify optimal infrastructure configurations for different scenarios and strategies that provide the flexibility to progressively operationalise and scale the different intervention methods. The assessment and design will need to consider a wide range of factors including:

- Scale of deployment
- Number and type of delivery methods being deployed from common facilities
- The need for progressive scaling of deployment
- Investment hurdles.

The Systems Engineering and Integrated Logistics R&D Sub-Program was designed to drive this process.

APPENDIX E2: DEPLOYMENT SCALE AND DEVELOPMENT RISK

Based on the modelling (**T6: Modelling Methods and Findings**) and engineering studies of deployment scale (**T5: Future Deployment Scenarios and Costing**), an assessment of possible deployment scales for each delivery method was completed. Further assessment was then undertaken to estimate risk (technical development and regulatory approvals) and the time required to develop (R&D) and establish (procurement, construction, production ramping etc.) each method.

Details of the findings and methods are provided in **T5: Future Deployment Scenarios and Costing**. Further analysis is then provided in **R3: Intervention Analysis and Recommendations**.

Findings discussion and R&D implications

The scale of the Great Barrier Reef means that the required production and deployment quantities are anticipated to be large, even assuming 'smart' deployment and modest program objectives. This places a strong importance on methods that can be deployed at required scales for the lowest possible cost.

To assess the likely future feasible deployment scale and cost of each of the deployment methods, three key observations were made:

- **Scale/unit cost relationship.** Per unit costs do not necessarily reduce as scale increases; other factors can outweigh economies of scale benefits
- **Inherent scale ranges.** All delivery methods have upper- and lower-scale limitations driven by either logistics or cost
- **Scale/development time relationship.** Scale and development time are correlated.

Scale/unit cost relationship: As a generalisation, economies of scale should result in reduced unit costs as quantity is increased. However, with many intervention delivery methods, unit cost increased with scale, often with a large step increase at a specific point, as was the case for methods deployed on a seasonal basis, such as larval slick capture and release or ultra-thin surface films. Due to the short operational period each year, leasing equipment (for example vessels) and employing temporary staff provided the lowest-cost option. In this scenario, as more vessels were leased, unit costs progressively increased until the leasing market was exhausted. If further scale was required, vessels would need to be purchased. Seasonality means low infrastructure utilisation, creating a major step increase in cost.

Inherent scale ranges: Each delivery method has inherent upper- and lower-scale limitations, driven by either logistics or cost. For example, of the cooling and shading methods under assessment, some would only be viable at a small scale (for example ultra-thin surface films), while others would only work at a large scale by virtue of their operating mechanism (such as cloud brightening). Even in areas such as aquaculture, there are several very different concepts that might be developed. Each have optimal scale ranges that provide the lowest unit costs compared with alternatives. To minimise the cost for any deployment scale, the correct method needs to be used.

Scale/development time relationship: Delivery methods designed for large scales are logistically more complex and require higher levels of automation to drive unit costs down. These take longer to develop and test.

R&D implications:

- Quantifying unit cost relationships as a function of scale for each method will be critical.
- Delivery methods selected for development need to be well aligned for the target scale. For example, it should not be assumed that a method that works at the medium scale could be developed to work at small or large scales. In both instances, this could be highly suboptimal, and an alternative method would be a much better option.
- There are cross-over technologies between delivery methods and knowledge gained from one will offset future deployment costs and risk for others; however, the program cannot simply start with a delivery method that works at the small scale and expect over time to 'scale it up'. Once a specific delivery method is selected, it implicitly selects a deployment scale range with associated time and sunk cost implications if this initial decision was incorrect.
- Infrastructure synergies between interventions need to be carefully assessed if costs are to be minimised and outcomes maximised. There are significant potential cost reductions with careful design of shared production and deployment infrastructure.

APPENDIX E3: INTERVENTION TECHNICAL UNCERTAINTY AND RISK

Most interventions and associated delivery methods currently have medium-to-high levels of performance uncertainty. Given the complexity of the processes and goals, and the early stage of development, it is reasonable to assume a medium-to-high level of technical risk associated with the interventions and delivery methods.

Planning and managing areas of uncertainty and risk have been clustered into three groups:

1. Intervention efficacy risk.
2. Delivery method technical development risk.
3. Delivery method performance risk.

Engagement and regulatory environment risks are covered in **R1: Engagement and Regulatory Dimensions**. Ecological risks are outlined in **R2: Intervention Summary** and **T3: Intervention Technical Summary**.

1. Risk associated with intervention efficacy

If the intervention is delivered as designed (product/action delivered at the scale, location, timing targeted), will it have the functional outcome being targeted?

Risk in this area is driven by a range of factors including:

Ecology and genetic processes and knowledge gaps about process rates: intervention assessments and associated modelling highlighted some fundamental knowledge gaps that limit quantitative assessment of benefits and risks. Existing knowledge can be used to assess the short-term benefits and risks of small-scale interventions with reasonable accuracy; however, the longer-term outcomes of large-scale deployments have high uncertainty levels.

The Great Barrier Reef is a well-studied system; however, the analysis is seeking to assess impacts over long time frames, in a context of an uncertain climate future, with change occurring at unprecedented rates. Historically, Reef management decisions were made without the added pressures and uncertainty of climate change. Solutions to this problem require an active adaptive management approach, coupled with a decision-support strategy that filters viable from unviable options in a race against time:

- The interventions need to factor that the system is adapting to the changing conditions, to support this adaptation, increase resilience and allow the intervention to be eventually phased out.
- RRAP has system-level restoration and adaptation objectives. Outcomes that can only be practically achieved by interventions seed an outcome that is greater than the sum of inputs.

Required knowledge is context-specific; however, based on current knowledge, there is a high-risk that interventions could be deployed at a large scale (and great cost) for little or no benefit. Examples of knowledge gaps include:

- **Coral-centric interventions**
  - Extent of natural genetic diversity
  - Natural adaptation rates and heritability
  - Extent of natural trade-offs (for example bleaching resistance versus growth and fecundity) and to what extent there are exceptions (situations in which corals do not exhibit trade-offs)
- **Rubble stabilisation**
  - Existing formation processes/rates and the impact of climate change on these rates
  - Links between rubble and broader reef ecology (at what point does increasing rubble matter)
  - Stabilisation processes and requirements to improve natural rates
- **Cooling and shading** (cloud brightening, ultra-thin surface films)
  - Summer atmospheric data (required to drive models)
  - Relationship among temperature, light and water flow during ocean heat waves
  - Trade-off understanding: for example, if these methods were used to reduce mass bleaching, would it reduce adaptation rates and potentially create future issues?
- **Biocontrol**
  - To what extent will invasive species or native pests (other than crown-of-thorns starfish) likely be an issue?
  - Will macroalgae removal represent an opportunity?

<u>R&D implications:</u>

- Determining the information sufficient to guide intervention strategies would be addressed by the decision-support strategy. It would account for critical uncertainty, risk tolerance and likely benefit-cost ratios in both the short and long terms and at small and large scales. Knowledge and information would evolve over the program and the strategy would evolve with it.
- Deployments would likely need to be optimised spatially and temporally, and by leveraging intervention synergies to produce maximum ecological, social and economic return on investment.
- New interventions would need to be well integrated with conventional management strategies, particularly crown-of-thorns starfish control.
- Deployment quantities versus functional outcome: improved understanding of relationships between action and impact would be required as the program progressed. For example, what amount of coral cover, species and genetic diversity needs to be sustained on different reefs on the Great Barrier Reef to achieve program success? Under resource constraints, and growing pressure from climate change, is low coral cover and diversity on many reefs better than high cover and diversity on fewer reefs? While conceptually simple, this is a complex question that RRAP would need to address with the stakeholder community and which requires agreement or reconciliation at the level of program objectives. While the concept feasibility modelling simulated an adaptive strategy whereby corals were deployed on reefs in a connected network to support resilience, more optimal deployment in strategic locations and densities could well result in lower numbers of corals required for the same outcome.

1) Technical method development risk

Many of the proposed delivery methods are very early in their development lifecycle, with high levels of technical development uncertainty.

<u>R&D implications:</u>

- Favours retaining a broader suite of method options until the uncertainty is reduced.
- R&D programs need to have a priority focus on reducing this uncertainty.

2) Delivery method performance risk

This is a subsidiary of technical development risk, relating to conversion rates, i.e. what percentage of the product deployed is converted into a useful outcome. Examples include survival rates of deployed corals or larvae or the conversion rate of cloud brightening aerosols to reflective vapour droplets. As these occur at the end of the deployment process, unit cost rates are directly proportional to these conversion rates. For example, if only one percent of corals deployed from an aquaculture process survive to become a sexually reproductive adult, the cost per survivor is 100 times more than if all survive. In some areas, these conversion rates can have orders of magnitude uncertainty, resulting in a wide range of possible cost-benefit ratios.

<u>R&D implications:</u>

- Reducing uncertainty as to conversion rates needs to be a high priority. In some instances, consideration should be given to not undertaking other R&D related to that method until this is known.

APPENDIX E4: MODELLING SYSTEMS (PHYSICAL, ECOLOGY, VALUE, DECISION)

Simulating the long-term future Great Barrier Reef system state and values is an incredibly complex modelling challenge, compounded by the uncertainty over climate trajectories and their impacts. Seeking to then understand the impact of deploying interventions into the system adds new orders of complexity. The modelling undertaken during the RRAP Concept Feasibility Study was suitable for a feasibility assessment; however, significant improvements would be required as the program develops to ensure appropriately informed decisions are made.

R&D implications:

The R&D program would need to incorporate a focused model development program that addressed key shortfalls and occurred in parallel to other R&D areas, considering that:

- Some shortfalls are model design/architecture related. It is possible a new model(s) would need to be developed in addition to refining existing models.
- Some shortfalls relate to the ecology/process/rate uncertainty. Improvements would be contingent on R&D to generate the required underpinning knowledge
- Some shortfalls relate to the lack of intervention performance information. Improvements would be contingent on progressing aspects of the associated intervention R&D programs.

To the extent feasible, the modelling capability needs to be developed such that it reduces requirements for field testing. Intervention deployment would be an adaptive process; however, the feedback loop can be very slow. For example, it may take several years to undertake a restoration action and then five to 10 years to observe the outcomes. In a dynamic and changing system, this creates a risk that interventions are continually lagging behind Reef needs. Field testing would not be eliminated; however, as trust in models increases, they can guide the development and deployment of interventions.

APPENDIX E5: ECOLOGICAL RISK

The analysis to date has focused on assessing current knowledge and identifying gaps. Early in this process, it was apparent that quantitative assessments of benefits and costs would be feasible; however, there was insufficient knowledge to quantitatively assess ecological risks. Critical knowledge gaps around risks (likelihood and consequence) would need to be addressed early in the R&D program.

R&D implications:

- Quantitative assessments of risk need to be developed during early R&D program activities and used to filter interventions against a set of performance criteria. This would progressively focus investments on more prospective interventions and delivery methods.
- The cost-benefit analysis methods, levels of nuancing and uncertainty would all need to be improved as RRAP decisions grow more complex and involve greater levels of financial investment and risk.
- Predictive modelling suites, in combination with quantitative decision-support systems, would be required to facilitate R&D program insights into the risks of intervening and not intervening, in both time and space and under different environmental scenarios. This would help identify optimal strategies for multiple linked decision points.
- A risk assessment framework that builds on broad stakeholder engagement and consultation is required. Thus, both real and perceived risks can be accounted for in the projections of outcomes and decision-making. This is critical because perceived risk around a high-performing intervention that has low actual risk would lead to inaction and loss of opportunity. Conversely, green lights for an intervention with low perceived risks but high actual risks can lead to damage.
- Understanding how both perceived and actual risks can be minimised via R&D and engagement need to be joint activities, aimed at supporting transparent decision-making across the program. This would provide clarity around when an intervention under R&D could be expected to achieve higher benefits than risks when combined with other interventions in a strategy.

APPENDIX F – R&D SUB-PROGRAM SUMMARIES

APPENDIX F1: DECISION SUPPORT R&D SUB-PROGRAM

Background and objective

The recommended RRAP R&D Program includes a service-focused team that would use a decision-support system to guide effective decision-making at strategic, tactical and technical levels.

Program

The RRAP R&D Program would integrate with the Reef 2050 Plan and the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP). Key elements of the decision-support R&D program include:

- Inform complex investment choices to ensure RRAP is well positioned to deliver an effective R&D program.
- Characterise and compare (clearly, transparently and quantitatively) the performance of a rich set of intervention options against multiple (sometimes conflicting) objectives, within clear problem formulations.
- Facilitate processes that prioritise the development of the interventions with the highest likelihood of delivering positive outcomes for the Reef.
- Build on the well-tested problem-objectives-alternatives-consequences-trade-offs process for structured decision-making. The RRAP decision-support system would consist of nested implementations, from strategic to technical levels. This would enable analysis of how changes in the performance, risks and costs of single interventions and portfolios combine to affect decisions at the highest program level.
- Reconcile objectives across environmental, ecological, economic and social dimensions using rigorous elicitation and engagement approaches that account for group bias and stakeholder/agency interactions.
- Be fully integrated in the RRAP governance framework, bio-physical modelling, ecological responses, regulatory frameworks, and social and economic value assessments and the intervention R&D programs. All decision analyses would include consideration of the uncertainties arising from all information sources (e.g. via modelling, ecological intelligence or stakeholder engagement).
- Inform RRAP trade-off analyses at all program levels, including among objectives, values and scales. The Decision Support team would work with the Modelling team to analyse decision paths likely to lead to optimal Reef solutions over 10-, 20- and 30-year horizons. Path analyses would account for uncertainty associated with climate change trajectories, socio-economic scenarios, capacity for adaptation by people interacting with the Reef, industries and agencies, and development and maturation of interventions
- Form the basis for a decision-making support process that can be used, with confidence, during intervention pilot trials and the operational deployment phase.

Timing and investment requirements

Table F1.1: Summary of Decision Support Sub-Program investment requirements ($'000s).

Years 1–5				
2019/20	2020/21	2021/22	2022/23	2023/24
900	1300	1200	800	600

Years 6–10				
2024/25	2025/26	2026/27	2027/28	2028/29
400	400	400	400	400

APPENDIX F2: MODELLING R&D SUB-PROGRAM

Background

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

Objectives

1. Provide credible counterfactual projections for the Great Barrier Reef under climate change and business-as-usual management interventions.

2. Quantify the benefits of restoration activities in time and space.

3. Allow the benefits of restoration to be evaluated alongside those of other forms of management interventions, including the identification of synergies.

4. Support RRAP activities that require modelled scenarios (e.g. location of field activities).

5. Fill critical knowledge gaps that have a marked bearing on model projections and/or management decisions.

Strategy

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

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

Program

Although the future of the Great Barrier Reef is highly uncertain, it is important to clarify the intent of the modelling. While it is impossible to know the precise trajectory of Reef condition over successive decades, we can simulate feasible trajectories and ask how it might have changed had we managed the Reef differently. In other words, how much healthier would the Reef be had we implemented interventions A and B at specific locations and points in time? This would allow us to gauge the likely benefits of Reef management and their sensitivity to assumptions about future climate change, management efficacy and so on. To be clear, the modelling is not trying to undertake predictions such as the amount of coral at Reef X in 2032.

While reef modelling is challenging, Australia and Queensland in particular has an unprecedented opportunity to be successful. First, no other coral reef system in the world has a sophisticated physical and biogeochemical model of the environment: eReefs.

eReefs is at the heart of RRAP modelling and the ecological models explicitly link to it. Second, there is considerable momentum from which to model the effects of restoration. Models of reef ecosystems have been developing for more than a decade and are well established in the literature, with publications in top journals including *Nature* and *Science*. Third, other investments in coral reef management have all included modelling the response of reefs and the benefits of management. These programs include paddock-to-reef catchment modelling, an integrated pest management system for crown-of-thorns starfish and a resilience-based management guidance project (both funded by the National Environmental Science Program) and the Great Barrier Reef Marine Park Authority's Reef 2050 Integrated Monitoring and Reporting Program (RIMReP). RRAP could partner with this significant ongoing work.

The recommended program would proceed through a series of parallel activities including:

- End-user consultation (within RRAP, Reef managers, Traditional Owners, stakeholders)
- Core modelling of ecosystem dynamics
- Support for field data collection
- Linking model projections and ecosystem services
- Visualisation and decision support, including delivery method design (interface, speed/autonomy, scope, links with other tools)
- Project coordination.

Timing and investment requirements

Table F2.1: Summary of Modelling Sub-Program investment requirements ($'000s).

Years 1–5				
2019/20	2020/21	2021/22	2022/23	2023/24
1800	2800	300	1900	1200

Years 6–10				
2024/25	2025/26	2026/27	2027/28	2028/29
900	800	800	800	900

APPENDIX F3: ECOLOGICAL INTELLIGENCE AND RISK R&D SUB-PROGRAM

Background

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

The second goal of RRAP is to create 'deployment-ready' interventions that have an appropriate social and regulatory license. Several real and perceived unintended consequences of restoration have already been identified through the stakeholder engagement activities of the RRAP Concept Feasibility Study. Such issues need to be explored in parallel to intervention development to ensure RRAP recommendations have considered the safety of techniques and resolved regulatory and stakeholder concerns.

Objectives

1. To help identify, coordinate and investigate real and perceived ecological risks of restoration and communicate these to regulators, stakeholders and RRAP project teams. This would involve a coordinated field-testing program where individual R&D programs would converge on common field-testing sites to create economies of scale in terms of monitoring outcomes.

2. To resolve at least five core ecological knowledge gaps that support the realisation of RRAP objectives:

   - Where and when does natural larval supply limit coral recovery?
   - Where is coral recovery limited by early post-settlement mortality?
   - How important are adult coral cover and species diversity in promoting natural coral recovery?
   - What are the natural levels of fitness and demographic responses to minor and major thermal stress of dominant coral communities?
   - What is the innate capacity of corals for adaptive change, to increase thermal tolerance?

Strategy

1. Ecological risks would be identified and investigated in close consultation with regulators and RRAP teams focused on policy and engagement.

2. In identifying these risks, international expertise and novel approaches would be harnessed.

3. Ensure ecological questions being addressed have relevance across RRAP and a clear pathway to impact on management decisions.

4. Design a field sampling program that can be used by multiple R&D programs.

Program

The real and perceived risks already identified would be considered alongside those raised through a broader consultation with regulators and scientists from diverse disciplines. Risks of the highest priority and feasibility would be investigated.

The Ecological Intelligence and Risk Sub-Program would maximise efficient use of RRAP resources through activities such as early workshops to review priorities and eliminate activity duplication among research themes. This would include consideration of research programs outside RRAP, although differences in timelines and other factors may necessitate limited duplication of comparable activities beyond RRAP. As much of the field data as possible would be collected through an integrated field program that would benefit multiple RRAP activities and needs.

Timing and investment requirements

Table F3.1: Summary of Ecological Intelligence and Risk Sub-Program investment requirements ($’000s).

Years 1–5				
2019/20	2020/21	2021/22	2022/23	2023/24
2400	4400	4600	3900	2800

Years 6–10				
2024/25	2025/26	2026/27	2027/28	2028/29
1900	1700	1700	1700	1800

APPENDIX F4: ENGAGEMENT AND REGULATORY R&D SUB-PROGRAM

Engagement Framework

Background

The viability of interventions to preserve and restore the Great Barrier Reef would depend, to a large extent, on the social acceptability of these interventions, which in turn hinges on public trust in the implementing organisations and meaningful participation of stakeholders and rights-holders.

Objectives

1. Understand the social acceptability of proposed interventions or specific technologies.

2. Assess how proposed interventions (or non-intervention) may affect the diverse social and cultural values, uses and benefits associated with the Reef and reef-dependent communities and industries.

3. Identify appropriate ways to engage different groups and interests in the co-design, deployment and evaluation of proposed interventions or technologies over time.

Strategy

1. The current engagement architecture in the Reef is generally suitable to support RRAP access to trusted networks to socialise the program, scope interests and values, and plan for future engagement. However, additional, fit-for-purpose engagement activities would be required to meet the more challenging demands of:
   - Deliberation on specific technologies
   - Representation/participation in RRAP decision-making
   - Supporting transparency and co-design of interventions
   - Identifying co-benefits from the R&D program
   - Exploring broad trade-offs and uncertainties around future Reef states.

2. It is essential RRAP empowers Traditional Owners to exercise their unique rights and responsibilities. This would require facilitating:
   - Traditional Owner involvement in RRAP governance
   - Resourcing involvement in R&D activity through co-research or subcontracting field research
   - Education and accreditation opportunities during the R&D program.

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

Program

The overarching goal of the engagement R&D strategy is to achieve interventions and decision-making that are socially and culturally responsible and legitimate to stakeholders, rights-holders, managers and the public. The proposed sub-program has two components: a transitional program and an R&D program.

The transitional program would establish operational requirements, frameworks and capacities for social science and engagement. It would identify the objectives of the sub-program in operational terms, clarify how it would coordinate with other social science and engagement efforts outside RRAP and how the information would be used to inform technology decisions. The Engagement Framework R&D Sub-Program would advance the evaluation of technology options through five broad activity areas:

1. Demonstration sites and citizen science.
2. Monitoring public attitudes and social license to operate.
3. Participatory Technology Assessment Panels (citizen panels).
4. Co-benefit agreements.
5. Coordination, synthesis, and strategy setting.

Regulatory Framework

Background

The Great Barrier Reef regulatory and policy environment is robust, but not entirely fit-for-purpose to manage the proposed RRAP interventions. The environment is complex, fragmented and overlapping. Its capacity to assess novel risks and impacts associated with unconventional interventions is limited. The proposed RRAP interventions challenge the existing regulatory system in an unprecedented fashion.

Objectives

The regulatory component of the R&D program aims to develop options to help Australia achieve a world-leading regulatory environment and policy best practice for assessing reef restoration and adaptation activities, including the range of risks and impacts associated with novel reef restoration and adaptation interventions. This program would work with regulatory authorities, reef scientists and relevant stakeholders to achieve these objectives.

Program

The regulatory program would focus on the following areas:

1. **Regulatory capacity:** Identifying short-, medium- and long-term priorities to improve regulatory capacity to address RRAP interventions.

2. **Guidelines and training:** Preparing guidelines and delivering training to RRAP researchers to ensure they are fully aware of the regulatory environment pertaining to the Great Barrier Reef.

3. **Cooperation between regulators:** Facilitating further cooperation between the Great Barrier Reef Marine Park Authority and other relevant regulators, with expert input from RRAP scientists on RRAP interventions involving emerging technologies.

4. **Permission system:** Developing options to improve the permission system for reef restoration and adaptation interventions.

5. **Policy and regulatory innovation:** Developing options for regulatory and policy innovation.

6. **Whole-of-government reef restoration policy:** Preparing options for whole-of-government reef restoration policy development.

Timing and investment requirements

Table F4.1: Summary of Engagement and Regulatory Frameworks Sub-Program investment requirements ($'000s).

Years 1–5				
2019/20	2020/21	2021/22	2022/23	2023/24
2100	2800	2700	2700	2600

Years 6–10				
2024/25	2025/26	2026/27	2027/28	2028/29
1700	1400	1400	1400	1400

APPENDIX F5: ENHANCED CORALS, TREATMENTS AND AQUACULTURE R&D SUB-PROGRAM

Background

Experience from overseas (**T4: Current Practices**), laboratory or small field trials (**T3: Intervention Technical Summary**) and ecological modelling (**T6: Modelling Methods and Findings**) support the benefits of seeding degraded systems with corals. Effective methods to propagate corals (both sexually and asexually) are needed. Coral adaptation to increasing temperatures and more frequent and extreme bleaching events is also important. Reseeding with enhanced corals can substantially affect the risks and benefits of restoration and adaptation activities. Corals with enhanced performance can be achieved by breeding existing tolerant corals, by genetic engineering and/or by microbiome or hardening treatments. While early laboratory results are promising, significant research is required to confirm the functional benefits of seeding enhanced corals on reefs and to increase the survival of those corals post-deployment.

Objectives

1. Enhance coral performance and brood stock development including an assessment of the thermal tolerance, growth and survival and reproduction on receiving reefs.
2. Develop treatments (microbial and hardening) to be applied during the aquaculture production process to enhance growth, survival and heat tolerance.
3. Develop coral breeding and asexual propagation know-how to reliably produce coral juveniles or fragments.
4. Enhance growth and survival of coral spat (attached larvae) and (micro) fragments to juveniles, post settlement and deployment.
5. Design aquaculture facility prototypes, breakthrough developments and automation.

Strategy

The recommended R&D strategy initially focuses on measuring the functional benefits of seeding enhanced corals onto reefs and the know-how to achieve a large-scale aquaculture production and deployment capability. First, it would focus on identifying/generating enhanced corals via breeding, engineering or treatments, then on the breakthrough larval/polyp aquaculture method and deployment systems (such as those that enhance growth and survival) identified as essential to achieve large scales at low cost. Depending on the success of these areas, a decision would be made as to the target scale and methods to be used. This would refine the strategy and the residual R&D would deliver working options.

Program

This program aims to deliver the required knowledge for the ecological modelling to evaluate the benefits and risks of enhanced coral seeding and to develop and optimise methods to achieve scale and drive down cost in the aquaculture production of corals for reseeding purposes (Table F5.1). The aquaculture methods evaluated and developed here underpin and/or contribute to many other interventions including moving corals, rubble stabilisation and biocontrol. For example, this plan has strong links with moving corals by providing knowledge on the choice of coral stock, optimised settlement techniques and methods to maximise post-settlement survival. Similarly, the plan has links to ecological modelling by providing key parameters of fitness, thermal tolerance and trade-offs to input into models at the same time as developing and optimising tools to identify and breed enhanced corals.

Table F5.1: Summary of Enhanced Corals, Treatments and Aquaculture R&D Sub-Program.

Interventions to be assessed and developed	**Likely scale**	**Development risk**	**R&D plus establishment duration (years)**
ER7—Coral seeding by semi-automated aquaculture* EE3—Seeding enhanced corals bred from existing stock with semi-automated aquaculture* EN1—Seeding enhanced corals bred from engineered stock with semi-automated aquaculture*	Small	Low	5–10
ER8—Coral seeding by automated aquaculture* EE4—Seeding enhanced corals bred from existing stock with automated aquaculture* EN2—Seeding enhanced corals bred from engineered stock with automated aquaculture*	Medium	Medium	5–10
ER9—Coral seeding by larval/polyp aquaculture* EE5—Seeding enhanced corals bred from existing stock with larval/polyp aquaculture* EN3—Seeding enhanced corals bred from engineered stock with larval/polyp aquaculture*	Large	High	5–10

* These delivery methods have the potential to include additional treatments (including probiotics and hardening). There is a large overlap in the methods used to treat corals in the field and those that can be applied in the aquaculture or moving process to enhance corals' performance.

Method description and interventions supported

There are many possible ways in which corals can be enhanced through the selection of brood stock and with additional treatment (T3: Intervention Technical Summary), with aquaculture methods that vary across dimensions such as sexual/asexual reproduction, land/sea based, centralised/decentralised, manual/automated and age of the coral deployed. All would be used to either repopulate degraded reefs or to increase adaptation rates via the deployment of corals with enhanced performance ('enhanced corals'). Enhanced coral brood stock could be sourced from existing populations or species, produced using natural evolutionary processes or developed using methods such as synthetic biology or genetic engineering.

Development status and risks

Ability to enhance performance in corals: Aquaculture is proven as a restoration method; less well tested is its use to assist system adaptation. Research over the past seven years into its use to assist system adaptation is very promising (**T3: Intervention Technical Summary**). The uncertainty that would need to be addressed includes heritability of evolved traits (i.e. whether performance is maintained across generations), performance trade-offs (i.e. whether enhanced corals perform on receiving reefs), the extent of improved performance traits that can be achieved and the numbers and deployment methods required for beneficial impact as a function of the biological, ecological and environmental characteristics of receiving locations.

Sexual/asexual breeding: These methods are generally well understood. R&D would be required to develop methods for specific target species. This is not considered high-risk but would take time due to coral lifecycles (periodic reproduction and long generation times). Another key research area is focused on enhancing the growth and survival of sexually or asexually produced corals during the aquaculture process and post deployment on the Reef. Survival of deployed corals is a major driver of cost and scale.

Potential aquaculture production and deployment scale, cost and timing:

Based on knowledge from the Australian Institute of Marine Science's National Sea Simulator, the aquaculture facility design studies completed during the RRAP Concept Feasibility Study and existing micro-scale expertise, a small-scale (several million corals per year) shore-based facility with moderate levels of production and deployment automation could be developed immediately (subject to infrastructure and operational funding and a small associated R&D program).

Larger production scales would require a more extensive R&D program. A detailed engineering study of a high-automation, medium-scale capability indicated high feasibility, with some aspects needing development and performance confirmation (**T11: Automated Aquaculture Production and Deployment**). Extensive automation would reduce the cost per coral substantially; however, infrastructure investment costs may limit the production and thus the scale at which the method could be employed. Additionally, the post-deployment survival rate of corals would need to be increased for this to be a viable delivery method.

The study also highlighted options that could result in significant per coral cost reductions and higher throughput rates, potentially facilitating deployment scales in the hundreds of millions of corals per year. This would require moving to a different style of aquaculture (larval/polyp aquaculture). If proven feasible, this delivery method would likely be more cost-effective, even at smaller production numbers compared with the alternatives.

R&D strategy

Part A:

- Identify enhanced corals, improving early survival and measuring any potential performance trade-offs on receiving reefs (with support from the Ecological Intelligence and Risk and Modelling sub-programs).
- Breakthrough larval/polyp methods and deployment systems (in combination with the Automation Sub-Program).
- Centralised/dispersed facilities (in combination with the Systems Engineering and Integrated Logistics Sub-Program).
- Small program on sexual/asexual methods to produce the corals required for field tests of enhanced performance and early life survival.

Delay all other areas until the above outcomes are known.

Part B:

Based on the findings of Part A, decide:

- Whether the target is restoration and/or adaptation (i.e. aquaculture can produce corals with or without enhanced performance) and if the latter the specific methods to be progressed.
- Target deployment scales and methods of delivery:
  - Centralised or distributed
  - Extent of automation
  - Determine if larval/polyp-based to be used.

The R&D sub-program would then progress the required technologies and systems—including the R&D delayed from Part A—to develop the required corals with enhanced performance from aquaculture breeding and additional treatments, settlement, grow-out and fragmentation methods.

Investment requirements

Table F5.2: Summary of Enhanced Corals, Treatments and Aquaculture Sub-Program investment requirements ($'000s).

Years 1–5				
2019/20	2020/21	2021/22	2022/23	2023/24
7700	17 700	22 600	23 100	22 300

Years 6–10				
2024/25	2025/26	2026/27	2027/28	2028/29
15 400	9500	5500	3600	2800

APPENDIX F6: COOLING AND SHADING R&D SUB-PROGRAM

Background

Cooling and shading interventions offer the opportunity to preserve the current biodiversity and ecological functioning of the Reef across the full range of corals, reefs and associated organisms. Environmental modelling conducted during the RRAP Concept Feasibility Study, as well as by others, indicates large-scale solar radiation management has the potential to cool and shade vast portions of the Great Barrier Reef if the technology goals can be met (**T14: Environmental Modelling of Large Scale Solar Radiation Management**). Ecological modelling showed this cooling and shading would be sufficient to vastly improve ecological outcomes for the Reef under a range of future climate scenarios (**T6: Modelling Methods and Findings**). Smaller-scale applications of shading and cooling technologies show promise for protecting individual reefs or sites that have high value (**T13: Ultra-Thin Surface Films**). While the potential benefits are large, especially for large-scale shading and cooling techniques, the risks are also considerable, both in technical ability to achieve target rates and coverages for an acceptable cost, as well as social, regulatory and environmental risks. Thus, a concerted research program that addresses the technical development requirements and practical feasibility of each intervention, while deeply engaging in the regulatory, social and risk facets is required.

Objectives

1. Develop delivery technologies to meet the required parameters, particularly in terms of delivery rates, material specifications (e.g. droplet size distributions, surface film longevity, fog hang time), energy and other resource requirements, reliability and low environmental footprint.

2. Develop small-scale technologies ready for deployment to high-value sites while assessing and progressing those suitable for scaling up to regional application.

3. Develop a system design that considers climatological and prevailing conditions to enable the material to be delivered to the target locations with maximum efficacy.

4. Develop an enhanced ocean and atmospheric modelling capacity to support system design, assess efficacy and evaluate unintended impacts.

5. Engage with regulators, stakeholders and Traditional Owners to co-design the R&D process, as well as implementation and monitoring.

Strategy

The initial focus would be on quickly developing delivery methods (that have already passed desktop studies) to proof-of-concept experiments, to ascertain their real-world performance. The recommended program has a staged, sequential development stream for each delivery method type, progressing from desktop feasibility study, to engineering design and laboratory development/testing, to small-scale, proof-of-concept testing in real-world conditions. Following this, technologies would be developed through progressively larger-scale field trials if they were deemed suitable for regional, large-scale application. Alternatively, for those most suitable for Reef-scale application, the process would be refined through further testing under a range of conditions and a commercial technology transfer package compiled and provided to industry.

Simultaneous to developing the technical hardware and system, the interventions would be modelled at different scales to inform system design, evaluate efficacy and assess risk. While oceanic conditions on the Reef are well characterised and monitored, there is a paucity of data and monitoring of atmospheric conditions, particularly those related to atmospheric aerosols and albedo. The program would establish a monitoring activity to collect baseline atmospheric data and conduct intensive field surveys to calibrate atmospheric and cloud microphysical models.

Regulatory, social and Traditional Owner engagement would need to begin early and continue throughout the program. Many of the ideas within the cooling and shading interventions are novel and not well understood by stakeholders, regulators or the general public. While these methods may offer some of the largest benefits to the Reef (**T6: Modelling Methods and Findings**), the risks are also more significant than many other proposed methods being investigated by RRAP. For social license to be effective, stakeholders would need to be meaningfully engaged in the program design and implementation to facilitate buy-in and trust in the research and research providers.

Program

Table F6.1: Summary of the Cooling and Shading Sub-Program.

Interventions supported	Likely scale	Development risk	R&D plus establishment duration
C3—Shading by cloud brightening	large	high	Medium
C4—Shading by fogging	Medium	Medium	Medium
C5—Shading by misting	Medium	Medium	Short
C6—Shading by surface films C7—Shading by microbubbles	Small	Medium	Short
C9—Shading by algae and other methods yet to be identified and assessed	Not yet assessed		

Method description and interventions supported

Cooling and shading interventions seek to reduce the intensity of bleaching events by reducing water temperature and/or light intensity. The RRAP Concept Feasibility Study recommended no further investment in developing shade cloths or pumping and mixing methods, which seek to move deeper cooler water onto the Reef. Three potential medium-to-large-scale shading interventions and one small-scale intervention are recommended to be further assessed and developed (subject to passing R&D gateways). Two further shading ideas, which have not yet been formally evaluated (microbubbles and shading by algae) are recommended to undergo desktop feasibility assessment during the first 12 months of the R&D program, with the view to being incorporated if the outcomes are positive.

These methods may have an impact on reef adaptation, which may be positive or negative. Further R&D is required to understand whether using shading to reduce large mortality events would provide an overall reduction or increase in adaptation rates. This work would be undertaken in conjunction with the Ecological Intelligence Sub-Program.

Development status and risks

Currently, the only deployment-ready cooling and shading intervention is C5—shading by misting, with commercial units of the scale required available. Further design and testing are required to understand how these units would be deployed (numbers, patterns etc.) and to assess environmental, social and regulatory acceptability.

All other proposed interventions are early in their development lifecycle, with medium-to-high levels of technical development and implementation risk. It is expected that most (if not all) methods could work, with the primary source of uncertainty being the cost versus performance that could be achieved. As for C5, implementation risk is currently less well understood, with significant uncertainty around downside impacts, social acceptability and regulatory approval requirements.

Potential deployment scale, cost and timing

Of all the methods assessed under RRAP to date, C3—shading by cloud brightening is the most scalable and, in fact, would only work at large scales. It seeks to make a small adjustment to light reflection levels over a large area that, in turn, reduces overall water temperatures. C5—shading by misting would likely only work in small-to-medium-scale areas and would primarily reduce light levels, rather than cool the water. C4—shading by fogging could potentially be used to both shade and cool and provides a potential fall-back option for cloud brightening should it not prove technically feasible. C6—shading by surface films and C7—shading by microbubbles seek to shade and might only practicably be deployed over small areas, limiting its use to high-value 'site'-scale deployments. The proposed interventions are synergistic if large-scale deployment for ocean cooling is desired. That is, the total cumulative shading of all these interventions would set the amount of cooling achieved. Thus, small- and medium-scale cooling and shading interventions targeting high-value reefs would also contribute to the overall large-scale cooling of reef waters.

All methods (except C3) would be relatively quick to develop, test and potentially deploy at the small scale. They would either be proven viable/acceptable or not within five years. Misting, surface films and fogging could be operational within a few years. More time would be needed for constructing and deploying the operational systems and sufficiently understanding the total impact of cloud brightening and the large-scale implementation of fogging or misting.

R&D strategy

This recommended program aims to rapidly sift through all prospective cooling and shading interventions to resolve the key efficacy and applicability uncertainties of each. This parallel technology development approach aims to quickly identify which types are effective and the extent of their scalability. Some intervention types would likely drop out during this initial period of laboratory and field proof-of-concept testing. At the end of this initial period, it is expected that the cooling and shading interventions not ruled out would fall into one of two categories: either useful at small scales for shading individual or collections of reefs or potentially useful as part of a large-scale cooling and shading system. Subject to stakeholder and regulatory approval, technologies would be refined and further field-tested to demonstrate efficacy and improve understanding of operating conditions and potential drawbacks before commercial transfer. Subject to stakeholder and regulatory approvals, large-scale cooling technologies would undergo further development to prepare for a large-scale proof-of-concept field trial over a significant area. If field trials were successful, the technology for large-scale cooling and shading would undergo further refinement in a similar process to that of the small-scale technologies. In parallel to the technology development, a monitoring program to collect the necessary atmospheric baseline data would be established to support the significant modelling needed to inform the decision-support system, predict efficacy and evaluate unintended impacts of large-scale implementation.

Efficacy and risk R&D

- Establish atmospheric monitoring for baseline data and model calibration/verification.
- Develop modelling capability for assessing small- and large-scale cooling and shading intervention efficacy and impacts.
- Assess benefits and risks for all methods.
- Engage stakeholders, Traditional Owners and regulators.
- Support development of a multi-parameter, decision-support system to weigh risk versus benefits.

Method development R&D

- Quickly assess and either confirm or discard C5—shading by misting, C6—shading by surface films, C4—shading by fogging and C7—shading by microbubbles for site or single-reef applications.
- Assess and develop C3—shading by cloud brightening, C4—shading by fogging and other solar radiation management options found to be scalable. Fogging and cloud brightening are expected to synergise well, as both use seawater, are likely to be applicable at large scale and may complement each other under various atmospheric conditions (i.e. cloud brightening when low cloud present, fogging in clear skies).
- Logistics would be assessed by the System Engineering and Integrated Logistics R&D Sub-Program.

Table F6.2: Summary of parallel activity (shaded boxes) for recommended cooling and shading program.

Project	Year									
	1	2	3	4	5	6	7	8	9	10
1. Atmospheric field survey	■	■								
2. Atmospheric and meteorological monitoring	■	■	■	■	■	■	■	■	■	■
3. Modelling	■	■	■	■	■	■	■	■	■	
4. Impacts assessment and regulatory applications	■	■	■	■	■	■	■	■	■	
5. Systems engineering	■	■	■	■	■	■	■	■	■	
6. Technology development to proof-of-concept										
6a. Cloud brightening proof-of-concept	■	■								
6b. Microbubbles desktop study	■									
6c. Microbubbles lab and proof-of-concept	■	■								
6d. Misting proof-of-concept	■	■								
6e. Fogging proof-of-concept	■	■								
6f. Ultra-thin surface films proof-of-concept	■	■								
6g. Project 6 field support		■								
7. Prototype development and field testing										
7a. Regional scale			■							
7b. Individual reef scale			■							
7c. Project 7 field support			■							
Project 8. Regional-scale large field trial and technology optimisation				■	■	■	■	■	■	
Project 9. Reef-scale large field trials and technology optimisation				■	■					
Project 10. Logistics and evaluation	■	■	■	■	■	■	■	■	■	
Project 11. Project management and governance	■	■	■	■	■	■	■	■	■	

Investment requirements

Table F6.3: Summary of Cooling and Shading Sub-Program investment requirements ($'000s).

Years 1–5				
2019/20	2020/21	2021/22	2022/23	2023/24
5700	12 300	15 400	14 900	14 000

Years 6–10				
2024/25	2025/26	2026/27	2027/28	2028/29
8200	8200	7100	2300	500

APPENDIX F7: MOVING CORALS R&D SUB-PROGRAM

Background

During mass spawning events, large proportions of larvae float away and do not settle and recruit onto a reef. The moving corals concept is to collect some of these larvae and move them to a location where there is a need for corals and an increased probability of settlement. This activity can have two benefits:

- If corals or larvae are transferred from warmer northern reefs to more southern reefs it could lead to an increase the temperature tolerance and adaptive capacity of the Reef.
- For reefs that are—or will be—recruitment limited, assisting in larval settlement and recruitment or transplanting corals can lead to increased coral populations.

Ongoing research over the past 20 years has focused on scale-testing assisted larval transport. More recently, it has moved to slightly larger-scale testing (but still micro-scale). During the 2018/19 coral spawning period, the first trials of ER3—coral seeding by larval slick translocation were performed.

Objectives

This R&D program would assess the options to efficiently and effectively collect and relocate embryos and coral larvae, collected in natural coral spawn and larval slicks, at scale.

Strategy

Initially, two methods would be assessed:

- Moving coral larvae a short distance to aid recovery of a nearby degraded reef (ER2–coral seeding by larval slick movement)
- Transporting more naturally heat-resistant larvae from northern reefs to more southern reefs, to aid their adaptation to warming waters (EE1—seeding enhanced corals from existing stock by larval slick translocation).

Subject to the performance of the above methods, a third option may be to combine these collection and movement ideas with a deployment method being assessed under the aquaculture program. This may reduce the cost per coral and increase the effective scale of the method.

Based on assessments to date, ER2—coral seeding by larval slick and EE1—seeding enhanced corals from existing stock by larval slick translocation are likely to be successful in the small-scale range (a few million corals per year), assuming multiple simultaneous operations (10 to 70). However, this is contingent on the conversion rates (successful recruitment and new coral) these interventions can achieve. Uncertainty in these conversion rates creates a wide range in the estimated cost per new coral created.

It appears the collection and transportation components of both methods could work with an appropriate R&D program. Significant uncertainty over the release phase would need to be addressed: the extent to which new corals would be created and if EE1 has adaptation benefits. The outcomes would significantly impact the scale, cost and utility of the methods.

Program

Given the uncertainty in the release phase of the method—and its impact on scale, cost and functional use—R&D would initially focus on these areas. Subject to successful findings, efforts would revert to developing the residual aspects of the methods.

Phase A: Efficacy R&D

1. Developing concept designs for the release phase, testing and determining likely release-to-recruitment and new coral conversion rates.

2. Assessing reef connectivity and likely recruitment limitations, and hence performance of the methods (via this sub-program and the Ecological Intelligence and Risk Sub-Program).

3. Assessment of EE1—larval translocation: the extent to which it could support assisted adaptation rather than be limited to a restoration method (via a combination of activities occurring in this program, the Enhanced Corals, Treatments and Aquaculture and Ecological Intelligence and Risk sub-programs).

Phase B: Method development R&D

Subject to the outcomes of the above, and a positive stage-gate assessment, the R&D sub-program would broaden to cover the residual method development areas.

Subject to the outcomes of this and the Enhanced Corals, Treatments and Aquaculture Sub-Program, the option of creating a hybrid method using aquaculture deployment would be assessed.

Table F7.1: Moving Corals R&D Sub-Program summary.

Interventions supported	Likely scale	Development risk	R&D and establishment duration (years)
EE1—Seeding enhanced corals from existing stock by larval slick translocation ER3—Coral seeding by larval slick translocation	Small	Medium	5–10
EE2—Seeding enhanced corals from existing stock by settlement of larval slicks on devices ER4—Coral seeding by larval slicks settled on devices	Small	Medium	5–10
ER2—Coral seeding by larval slick	Medium	High	5

Investment requirements

Table F7.2: Summary of Moving Corals Sub-Program investment requirements ($'000s).

Years 1–5				
2019/20	2020/21	2021/22	2022/23	2023/24
2900	4800	5200	4600	4400

Years 6–10				
2024/25	2025/26	2026/27	2027/28	2028/29
4700	4100	1500	500	500

APPENDIX F8: RUBBLE STABILISATION R&D SUB-PROGRAM

Background

Major coral mortality events can cause extensive rubble, primarily from more fragile morphologies of corals including branching, plating and foliose structures. Rubble is caused by direct physical damage during storms but can also occur over time as corals killed by bleaching or predators such as crown-of-thorns starfish subsequently collapse and become eroded. The rate of these processes is mostly unquantified. Loose rubble presents a hostile settlement substrate for coral recruitment because periodic turnover of rubble fragments can smother newly settled corals and prevent growth. Coral recruitment generally requires a stable substrate. Some rubble stabilisation methods also provide a 3D structure that could be seeded with corals and provide a fish habitat. Reducing the time for rubble to stabilise would result in more rapid regrowth of coral in the stabilised area. To date, this has not been an issue on the Great Barrier Reef; however, it may become a restoration rate-limiting factor if mass mortality events increase in size and frequency.

Most of the many potential methods to stabilise rubble and facilitate 3D reef structure are at a high technology readiness level and could be deployed almost immediately (S1—stabilisation by natural bonding, a method that conceptually looks to be the most scalable, is the exception).

All methods identified (particularly the 3D-structure methods) have high per metre square costs. This is driven by field logistics and is unlikely to significantly reduce with scaling, as the industry methods used are already highly evolved. There is scope for cost reduction in the design of the deployment programs, e.g. only stabilising high-functional value areas on a reef and using deployment patterns to minimise the percentage of targeted areas treated.

Objectives

To speed reef recovery and improve reef resilience through stabilisation interventions, this program seeks to:

- Understand the impact of rubble stabilisation activities on the broader Reef
- Explore the viability of changing the rate of natural stabilisation—both now and under predicted conditions and reef states
- Analyse the process, timing and environmental factors of rubble ultimately binding and stabilising and subsequent coral regrowth.

Strategy

A multi-phase sub-program is proposed, with stage gates (continue or not) between each phase:

1. Detailed planning and program establishment.

2. Process and rate studies and improved modelling to confirm whether rubble stabilisation would be beneficial.

3. Delivery method development.

4. Proof-of-concept testing.

Sub-program

Table F8.1: Summary of Rubble Stabilisation R&D Sub-Program.

Interventions to be assessed and developed	Likely scale	Development risk	R&D and establishment duration (years)
S1—Stabilisation by natural bonding S2—Stabilisation by chemical bonding S3—Stabilisation by mesh S4—Stabilisation by removal	Medium	Medium	5–10
S5—Structure by consolidation S6—Structure by 3D frames S7—Structure by concrete shapes S8—Structure by massive corals S9—Structure by 3D printed shapes	Small	Medium	5–10

Development status and risks

There are many potential methods to stabilise rubble and facilitate 3D reef structure, the majority of which are at a high technology readiness level and could be deployed almost immediately (S1—Stabilisation by natural bonding, a method that conceptually looks to be the most scalable, is the exception).

While there is a clear benefit to the locally treated area, the broader Reef and system benefits and the viability of seeking to change the rate of natural stabilisation, both now and under predicted conditions and Reef states, are less understood. Similarly, the process, timing and environmental factors of rubble ultimately binding and stabilising, and subsequent coral regrowth, are not well understood. For example, rubble may only need a modest artificial improvement in 'bonding' to withstand high frequency/low intensity water movement events, providing natural processes the time to further bind the rubble to the level required. This information would have a flow-on effect on the efficacy and viability of the stabilisation methods identified.

Potential deployment scale, cost and timing

All methods identified (particularly the 3D-structure methods) have high per square metre costs. This is driven by field logistics and is unlikely to significantly reduce with scaling, as the industry methods used are already highly evolved. There is scope for cost reduction in the design of the deployment programs, e.g. only stabilising high-functional value areas on a reef and using deployment patterns to minimise the percentage of targeted areas treated. Even assuming these design methods, the 3D structure is only likely to be economical at high-value, site-scale restoration programs. Rubble stabilisation might extend to high-value Reef-scale deployments.

R&D strategy

The program is split into three phases, with stage gates (continue or not) between each phase.

Table F8.2: Rubble Stabilisation R&D strategy.

Phase A: Quantifying the value of rubble stabilisation and/or 3D structure interventions	
A1: Functional requirements assessment (Part A)	Field and laboratory program: rubble baselines, forecasts, stabilisation rates and hydrodynamic conditions. Initial trial of methods for long-term reference.
A2: Updated benefits modelling	Modelling the dynamics of rubble formation, structural changes and their ecological consequences to evaluate the benefits of restoration.
Phase B: Setting functional requirements and assessing methods	
B1: Functional requirements development (Part B)	Defining environmental conditions for stabilisation intervention (hydrodynamic, ecological and recovery rate baselines).
B2: Method selection and development	Optimising method configuration. Incudes long-term and R&D field trials.
B3: Cost-benefit risk assessment	Including updated modelling to design a decision-support tool to identify the method and extent required for intervention in specific habitats and environmental conditions.
Phase C: Final testing of most prospective methods	
C1: Proof-of-concept scale testing	Multi-site large-scale tests.
C2: Final cost-benefit analysis	Updated cost-benefit analysis and deployment planning.
Commercial transfer and deployment as needed	
Available	Commercial tender package and deployment design ready.

Investment requirements

Table F8.3: Summary of Rubble Stabilisation Sub-Program investment requirements ($'000). Excludes institutional overheads.

Years 1–5				
2019/20	2020/21	2021/22	2022/23	2023/24
2100	5900	6300	4800	3300

Years 6–10				
2024/25	2025/26	2026/27	2027/28	2028/29
10 800	13 200	4500	500	100

APPENDIX F9: EARLY PHASE INTERVENTION ASSESSMENTS R&D SUB-PROGRAM

Background

During the RRAP Concept Feasibility Study, several very early phase potential interventions were identified. While there is insufficient knowledge to determine whether an R&D program to assess and develop these interventions is justified, evidence indicates there may be potential value in developing these interventions and they should not be dismissed.

Objectives

To investigate the viability of very early phase interventions that show potential value in a timely and cost-efficient manner.

Strategy

It is recommended desktop studies be completed for each of these very early phase potential interventions to assess needs and associated benefits, possible deployment methods and their current state of development, and likely scale limitations and costs. Potential functional, structural and other synergies would be explored. This program is a cluster of existing ideas ready for desktop studies to occur and a budget allowance for an additional study to occur each subsequent year of the program. It is assumed that additional new ideas would be generated that warrant this next stage of investigation. On the completion of these studies, a decision would be made as to if and how they progress further through the development pipeline.

Program

At this time, two specific desktop studies are proposed:

- **(Bio)-control.** Active control of coral predation and/or competition such as macroalgae (B1) and other species with negative impact such as the *Drupella* sea snail (B2).
- **Application of field treatments to enhance coral survival (F1).** Treating *in situ* corals to aid them surviving a bleaching event. This treatment could include application of medicines, food or probiotics.

On the completion of these studies, a decision would be made as to if and how they progress through the development pipeline.

Table F9.1: Summary of Early Phase Intervention Assessments R&D Sub-Program.

Interventions to be assessed and developed	Likely scale	Development risk	R&D and establishment duration (years)
B1 – Biocontrol of macroalgae	Small	Unknown	Unknown
B2 – Biocontrol of species with negative impacts	Small	Unknown	Unknown
F1 – Application of field treatments to enhance coral survival	Medium	Unknown	Unknown

Timing and investment requirements

Table F9.2: Summary of Early Phase Intervention Assessments investment requirements ($’000s).

Years 1–5				
2019/20	2020/21	2021/22	2022/23	2023/24
600	500	400	400	400

Years 6–10				
2024/25	2025/26	2026/27	2027/28	2028/29
400	500	500	500	500

APPENDIX F10: CRYOPRESERVING BIODIVERSITY R&D SUB-PROGRAM

Background

With coral reefs around the world threatened by climate change, the need for innovative restoration tools to conserve and secure reef habitats and biodiversity is urgent. Through the development and application of innovative cryopreservation techniques for coral germplasm, tissues and symbionts, the cryobiology and biobanking[4] program would integrate with, and provide support for, several potential RRAP interventions. This would include cryopreserving reproductive products to assist the development and maintenance of coral brood stock for aquaculture and to support coral seeding programs, securing enhanced or engineered coral and Symbiodiniaceae for research and facilitating assisted gene flow through the movement of cryopreserved samples among coral populations. Additionally, biobanking is one of the most effective methods to secure biodiversity. Cryopreservation of living coral samples from healthy reefs could help mitigate the loss of genetic and species diversity caused by predation, natural disasters and bleaching events.

Objectives

The proposed program would aim to:

1. Develop and apply innovative and cutting-edge cryopreservation techniques that include all aspects of coral germplasm, tissue and symbionts.

2. Support RRAP partners by biobanking high-value species, populations, genotypes, phenotypes and broodstock from coral and Symbiodiniaceae.

3. Secure coral biodiversity on the Great Barrier Reef through targeted biobanking of coral germplasm, tissues and symbionts from vulnerable reefs, and build long-term stability for coral reef cryopreservation and biobanking.

Strategy

The cryopreservation program would be developed along the following lines:

1. Research on the cryobiology of coral larvae, adult tissues and symbionts, and develop cryopreservation methods to support aquaculture breeding and larval slick capture activities.

2. Proof-of-concept scale tests new cryopreservation methods and develops high-throughput technologies to permit up-scaling and decentralisation of aquaculture.

3. Develop pathways to use cryopreserved material for large-scale production and assess the deployment of coral recruits for restoration.

[4] Biobanking—the storage of cryopreserved genetic material at ultra-low temperatures in biorepositories—is routinely used for genetic and reproductive management in the agriculture and aquaculture industries and was recently identified by the United States National Academy of Engineering and Sciences as a key strategy for securing and restoring reefs globally.

4. Expand efforts to biobank coral germplasm using existing sperm cryopreservation methods with concurrent research to refine and optimise protocols to increase capacity.

5. Prioritise species, accession plan and assess existing coral material in the Taronga CryoDiversity Bank to ensure a targeted approach to biobanking efforts and integration with RRAP partners.

Program

The coral cryopreservation and biobanking program would build on the successful collaboration between the Smithsonian Institution and the Taronga Conservation Society[1], which since 2011 has built the largest biorepository of living coral genetic material in the world at the Taronga CryoDiversity Bank. The program would deliver important new capability to preserve and store coral reproductive material, larvae and adult tissues to support breeding programs in RRAP. It would also expand current biobanking efforts for coral on the Great Barrier Reef to secure the vast biodiversity of Great Barrier Reef coral. As such, this program could provide major scaling breakthroughs for other programs in RRAP (Table F10.1).

Table F10.1: Interventions that could be supported by an ability to cryopreserve coral reproductive material, larvae and/or adult tissues.

Interventions that could be supported by cryopreservation technology
ER3—Coral seeding by larval slick translocation ER7—Coral seeding by semi-automated aquaculture*
EE1—Seeding enhanced corals from existing stock by larval slick translocation EE3—Seeding enhanced corals bred from existing stock with semi-automated aquaculture* EN1—Seeding enhanced corals bred from engineering stock with semi-automated aquaculture*
ER8—Coral seeding by automated aquaculture* EE4—Seeding enhanced corals bred from existing stock with automated aquaculture* EN2—Seeding enhanced corals bred from engineering stock with automated aquaculture*
ER9—Coral seeding by larval/polyp aquaculture* EE5—Seeding enhanced corals bred from existing stock with larval/polyp aquaculture* EN3—Seeding enhanced corals bred from engineered stock with larval/polyp aquaculture*

* These delivery methods have the potential to include additional treatments (including probiotics and hardening). Cryopreservation can also support these approaches.

The recent successful cryopreservation of larvae from the mushroom coral *Lobactis scutaria* represents a major advance in coral cryobiology and has great potential to become a critical biobanking tool. The use of innovative cryopreservation and warming technologies to recover large and complex samples such as coral larvae can potentially also be applied to coral microfragments and adult tissue, which would greatly expand the capabilities of the coral reef cryobiology program and permit biobanking activities to occur year-round.

As new cryopreservation technologies are developed and refined, research would transition towards the development of high-throughput processes to permit up-scaling and application of cryopreservation at the scale required for aquaculture and restoration. The program would also work to train a new generation of coral cryobiologists and expand the biorepository facilities at the Taronga CryoDiversity Bank to ensure long-term program development and sample security.

The cryobiology and biobanking program would be unique in the world for wildlife in both its comprehensive scale and integration with critical conservation and restoration efforts. Because of this multifaceted approach, the proposed program stands to lead the world in embedding cryotechnology in animal conservation biology.

Timing and investment requirements

Table F10.2: Summary of Cryopreserving Biodiversity Sub-Program investment requirements ($'000).

Years 1–5				
2019/20	2020/21	2021/22	2022/23	2023/24
1100	1900	2100	2400	2100

Years 6–10				
2024/25	2025/26	2026/27	2027/28	2028/29
1200	800	900	900	900

[1]Taronga is a conservation society that is constituted under the Zoological Parks Board Act 1973 as a statutory authority owned by the people of New South Wales and administered by the Minister for the Environment and Heritage.

APPENDIX F11: SYSTEMS ENGINEERING AND INTEGRATED LOGISTICS R&D SUB-PROGRAM

Background

RRAP Concept Feasibility Study investigations, specifically the assessments completed in the concept-level deployment costing project (T5: Future Deployment Scenarios and Costing), identified that possible and likely intervention deployment strategies would be costly. This is unsurprising given the scale of the Great Barrier Reef and the challenge of increasing its resilience and adaptive capacity. Much of this likely cost is infrastructure-related; to procure and operate the required shore and marine production and deployment systems.

Detailed production and deployment concepts need to be developed and all associated engineering and technical challenges identified and (where appropriate) resolved. Importantly, these designs must be cost-optimised. This needs to occur at both the specific intervention/delivery method level and between interventions due to the many opportunities to integrate production and deployment systems across different interventions.

Objectives

R&D would be required to identify optimal and integrated deployment strategies and develop the required infrastructure use-cases and specifications. The Systems Engineering and Integrated Logistics Sub-Program would provide several core functions:

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

Strategy

The Systems Engineering and Integrated Logistics Sub-Program would provide concept and preliminary designs for technology and infrastructure, as well as socially-accepted methods for applying technology and infrastructure—independently and collectively—to achieve at-scale reef restoration.

This would be achieved by delivering the following outputs:

- Concept designs for each of the intervention delivery methods. These would be progressively developed to match the intervention R&D programs and stage gates
- Information to guide the most appropriate regional distribution of key reef restoration and adaptation infrastructure for optimal performance and environmental and social benefits
- An operational decision-support system to guide seasonal and operational decisions.

Program

The sub-program projects can be clustered as follows:

Table F11.1: Systems Engineering and Integrated Logistics R&D Sub-Program structure.

Project		Deliverables	Comments
1	Engineering and project planning support	Supporting capability and integration oversight	Across RRAP
2	Concept-level cost assessment	Concept-level deployment costs	First-cut estimates of deployment costs to inform research planning
3	Centralise vs de-centralise study	Assessment of logistics advantages of centralised versus decentralised shore-based aquaculture facilities	To inform planning of larger shore-based facilities
4	Economic impacts study	Companion to project 2; will assess regional impacts of major shore-based facilities	To inform planning of larger shore-based facilities
5	Preliminary deployment costing for each intervention	Preliminary engineering costing of deployment operations for individual interventions	More refined and detailed deployment costings for individual interventions to inform research and future operations
6	Logistics planning model development	A model that can be used for detailed integrated deployment planning	Would generate input data for specific infrastructure requirements (use case planning) and explore deployment synergies across interventions
7	Deployment infrastructure use case study	Detailed use-cases for specific deployment infrastructure	Core program deliverable– commencement of preliminary design and engineering phase
Program review: review outcomes and confirm methods have viability (cost/benefit/risk factors) before next stage/s			
8	Optimal deployment study	Apply model developed in project 5 to generate information on optimal logistics requirements	Results would guide infrastructure investment cases
9	Major field-testing program to assess deployment efficacy	On-water lessons learned	Results would guide refinement of infrastructure requirements
10	Develop operational decision support system	Decision-support system	Would guide optimal seasonal and day-to-day deployment
11	Develop infrastructure specifications and procedures	Specification and operating procedure documents	Key component of commercial transfer package
12	Test decision-support system	Refine decision-support system based on test results	key component of commercial transfer package
Program review: review findings and recommendations and finalise if/how these methods are transferred into production			
13	Commercial transfer package	Commercial transfer package	Detailed design post-RRAP

Timing and investment requirements

Table F11.2: Summary of Integrated Logistics Systems Engineering and Deployment investment requirements ($'000s).

Years 1–5				
2019/20	2020/21	2021/22	2022/23	2023/24
1600	2700	3000	3700	3900

Years 6–10				
2024/25	2025/26	2026/27	2027/28	2028/29
2900	2000	1800	1800	1900

APPENDIX F12: AUTOMATION R&D SUB-PROGRAM

Background

Even small-scale interventions on the Great Barrier Reef are major undertakings due to the massive scale of the system. Automation and mass production would be essential to deliver interventions at the scale required for a noticeable impact.

During the RRAP Concept Feasibility Study, several high-level concept designs were developed for different deployment methods. In addition, a more detailed preliminary engineering study was completed on an aquaculture system. These studies indicated a strong need for automation if methods were to be logistically- and cost-feasible. They indicated that in many instances, existing automation systems could simply be applied, while in others, development would be required.

Objective

To develop technology that could substantially increase the efficacy and productivity of interventions developed in RRAP.

Strategy

In most instances, it would be too early in the intervention delivery method development process to actively commence automation development programs. It is recommended that development activities occur only when concepts have stabilised, and in the following circumstances:

1. The delivery method is a priority development area and the concept design is sufficiently stable so the investment does not have a high sunk cost risk.

2. The automation cannot be procured for deployment (most automation requirements would simply be procured).

3. It is at low technology readiness level and would take time to develop, impacting the critical path.

4. It has a high-functional performance impact and needs to be proven as part of the investment case, prior to commercial transfer and deployment.

Based on the timelines in the proposed intervention and integrated logistics R&D sub-programs, more definitive automation R&D investment decisions would require a further 12 to 18 months, when there was sufficient clarity and stability in deployment methods.

Currently, two areas meet the investment criteria, where an immediate investment in automation is justified:

- Aquaculture deployment methods are more advanced/stable than the other areas and have a specific area of automation that meets criteria 3 and 4 above. The methods under consideration deploy corals using a small device that is released from the surface. Post-deployment survival rates are critical to an acceptable cost-benefit, and a driver of this is accuracy in coral device placement. This process would need to be automated, and it is not known how well this might work. High-resolution reef mapping, characterisation, path-planning and automated position systems need to be designed and tested. If proven feasible, this automation would open the way for increasing the outputs of coral seeding by larval slick movement, translocation and settlement on devices (ER2, ER3 and ER4), further strengthening the business case to invest in this area of automation R&D.

- High resolution in water monitoring of test and control sites would be critical to the success of the RRAP R&D Program and subsequent deployment. A fully diver-based delivery would be expensive. There are opportunities to reduce cost and risk via autonomous underwater systems. This is an area of broader reef technology development; however, it requires investment to increase progress and deliver a platform for RRAP in a timely manner.

An automation R&D strategy has been developed to fast-track delivery of these two critical areas; however, it delays major investment in other areas until around year four of the program. In years one to three, the Systems Engineering and Integrated Logistics team would work with each of the intervention areas to progressively refine concept designs and identify where additional automation R&D was justified.

Program

This program would develop and evolve as needs and opportunities became clearer. A logical way to cluster an automation program could be:

- Underwater autonomy
- At-surface autonomy
- On-shore and on-deck autonomy.

Two possible fast-tracked projects are envisaged:

- Mapping and coral or coral-settlement device deployment vessel positioning system
- Autonomous monitoring and coral planting platform.

Timing and investment requirements

The following timeline and budget include the simultaneous development of three technologies in addition to operationalisation of the two fast-track projects.

Table F12.1: Summary of Automation Sub-Program investment requirements ($'000s).

Years 1–5				
2019/20	2020/21	2021/22	2022/23	2023/24
1700	2500	1300	600	3700

Years 6–10				
2024/25	2025/26	2026/27	2027/28	2028/29
9000	10 800	4100	1100	1200

APPENDIX G – R&D STAGE GATES

Standard assessment criteria:

To standardise expectations and status assessment, a set of assessment/outcome descriptions were developed. Each includes five criteria.

Table G.1: Standard assessment criteria to determine R&D stage gates.

Criteria	Description
Concept description	To what extent has the intervention idea been described?
Cost/benefit/risk	How advanced are the cost/benefit/risk assessments for this intervention?
Method efficacy and performance	The extent to which the critical intervention method performance parameters have been identified and tested. For example, functional or cost parameters identified in modelling that need to be met for a method to have efficacy or be financially viable.
Method development	How developed is the method and what is needed to get it to a commercial transfer ready status (i.e. a tool available for use if needed)?
Stakeholder/regulatory	Status of stakeholder engagement and degree of approval to deploy.

These criteria were split from general ‘method development’ R&D activities to ensure the program was identifying and tracking the status of high technical delivery risk development activities and/or confirming high-risk (required and uncertain) performance criteria can be met.

For example, if modelling indicated an intervention only had potential efficacy if it:

- Achieves specific performance criteria (bond strength, degree heating week resistance…), and/or
- Does not have a specific downside risk of X, and/or
- Can be deployed at a scale of Y or greater, and/or
- Has a post-deployment success rate (survival in the case of corals) of Z or better, and/or any other criteria,

then it would be prudent to retain a special focus on these parameters and, in general, to rapidly test against these criteria and confirm they can be achieved. If they cannot, then an assessment as to if this area of development should continue is required.

Detailed stage descriptions

Table G.2: Detailed stage descriptions.

<table>
<tr><th colspan="2">Stage</th><th>Description</th></tr>
<tr><td>1</td><td>Idea</td><td>Documented but not yet assessed</td></tr>
<tr><td>2</td><td>First principles assessment

(unfunded)</td><td>Proponent to provide a first principles-based assessment covering:
<table>
<tr><th>Aspect</th><th>Indicative development level</th></tr>
<tr><td>Concept description</td><td>Simple description of recommended method/intervention and how it relates to those already in RRAP interventions table</td></tr>
<tr><td>Cost/benefit/risk</td><td>First principles assessment of how it could potentially assist in achieving RRAP functional objectives (P1 to P3)
First principles assessment of affordability (scale and cost)
Basic risk logic and documentation of any potential ‘show-stopper’ risks (ecology, social, regulatory, stakeholder)</td></tr>
<tr><td>Method efficacy and performance testing</td><td>N/A</td></tr>
<tr><td>Method development</td><td>N/A</td></tr>
<tr><td>Stakeholder/regulatory</td><td>N/A (covered by risk)</td></tr>
</table></td></tr>
<tr><td>3</td><td>Desktop study (funded)</td><td>Low-cost desktop assessment to develop early phase estimates of benefits and risks. The team undertaking this would be context-specific, but it would need to involve a centrally managed modelling assessment of costs/benefits to ensure consistency.
<table>
<tr><th>Aspect</th><th>Indicative development level</th></tr>
<tr><td>Concept description</td><td>• Detailed description including possible future production/deployment scenario descriptions with assumed methods and quantities suitable for scenario assessment of benefits and costs</td></tr>
<tr><td>Cost/benefit/risk</td><td>Semi-quantitative cost-benefit analysis factoring inputs at the level of:
• Quantitative benefits modelling based on currently known information and modelling capability. Accepted that some process/rates will not be factored. Accepted that some processes/rates will have wide possible ranges (i.e. not yet studied and verified)
• Deployment cost assessment via out-costing method (find something similar and estimate based on that) and inhouse costing framework
• Identification of basic deployment scale to cost relationships (trends and inflection points)
• Qualitative risk assessment completed
• Modelled ecology risks if feasible within existing models/knowledge limitations</td></tr>
<tr><td>Method efficacy and performance testing</td><td>• Key efficacy and performance criteria identified and factored into the early stages of the development program design</td></tr>
<tr><td>Method development</td><td>• Outline of development path documented
• Likely commercial transfer point identified
• Outline of R&D requirements by stage gate
• Development costs estimated</td></tr>
<tr><td>Stakeholder/regulatory</td><td>• Initial socialisation of idea with stakeholders and regulators, with key perceptions documented
• Potential ‘show-stopper’ stakeholder risks identified
• Potential ‘show-stopper’ regulatory risks identified</td></tr>
</table></td></tr>
<tr><td>4</td><td>Development</td><td>R&D program, including field testing. At the completion of this stage, a method should be ready for large-scale field trials (noting this may require significant Capex/Opex investment in production and deployment systems).
<table>
<tr><th>Aspect</th><th>Indicative development level</th></tr>
<tr><td>Concept description</td><td>• Detailed description including targeted future production/deployment scenarios and methods suitable for final proof-of-concept testing and validation.</td></tr>
</table></td></tr>
</table>

<table>
<tr>
<td></td>
<td></td>
<td>
<table>
<tr><td>Cost/benefit/risk</td><td>Quantitative assessment factoring benefits, cost and risk at the level of:
Cost:
Deployment cost assessment via a concept design for relevant scenarios (the equivalent of the Worley Parsons/AIMS concept design and cost assessment of large-scale land-based aquaculture and deployment)
Unit cost as a function of scale and inflection points quantified
Benefits:
Quantitative Reef system modelling, factoring key processes and rates
Underpinning ecosystem process/rate R&D completed, and outcomes incorporated into analysis as required to support analysis
Underpinning method performance R&D (field validated as required) completed and incorporated into benefits analysis
Risk:
Quantitative assessment of ecology risk via field trials and appropriate modelling
Detailed technical, stakeholder and regulatory risk assessment completed.</td></tr>
<tr><td>Method efficacy and performance testing</td><td>Key areas confirmed as achievable via laboratory and field testing</td></tr>
<tr><td>Method development</td><td>Methods and systems developed and tested to the point where they are ready for large-scale proof-of-concept deployment</td></tr>
<tr><td>Stakeholder/regulatory</td><td>Needs work, but at a point where stakeholders and the regulatory environment would support scale testing.</td></tr>
</table>

Notes:
Depending on the context, method performance would either be an input to the assessment or an output from the assessment:
Input: if method performance level X is assumed, what are the benefits, costs and risk?
Output: minimum method performance for efficacy is determined from this assessment and passed to the development team to assess if it can be achieved.
</td>
</tr>
<tr>
<td>5</td>
<td>Scale trials</td>
<td>Proof-of-concept scale testing ($10M to $100M scale field tests, i.e. the scale at which you want to be sure of the outcome before you undertake)

To be developed.</td>
</tr>
<tr>
<td>6</td>
<td>Production and deployment</td>
<td>Intervention-specific/not yet developed.</td>
</tr>
</table>

APPENDIX H – COSTING RATE ASSUMPTIONS

Costing of R&D programs was completed using the rates detailed below. In addition to these rates, cost indexation and overheads were factored as follows:

- Indexation was factored at two percent per year
- 50 percent overheads were allocated to the on-costed salary rates.

People	Code	Description	On-costed salary rates $'000/year
Project Leader	PL	AIMS/CSIRO 9+ Uni Academic E)	250
Senior Scientist	SS	AIMS/CSIRO 7/8 Uni Academic D)	200
Mid-Career Scientist/Engineer Specialist	MCS	AIMS/CSIRO 5/6 Uni Academic B/C	150
Junior/Post Doc Scientist/Engineer Specialist	PD	AIMS/CSIRO 3/4 Uni Academic A	120
Research Assistant	RA		80

Teams	Description	On-costed salary rates $'000/year
1 FTE	1*SS	200
3 FTE (single team)	1*SS, 2*MCS	500
5 FTE (single team)	1*PL, 1*SS, 1*MCS, 1*PD, 1*RA	800
10 FTE (several teams)	1*PL, 2*SS, 2*MCS, 2*PD, 3*RA	1430
15 FTE (several teams)	1*PL, 2*SS, 3*MCS,4*PD, 5*RA	1980
20 FTE (several teams)	2 x 10 person teams	2860

Vessel - research	Size	$'000 per day	Description	Notes
	Small	3	Trailable day vessel (30NM limit)	Bespoke vessels costed at specific quoted rates
	Medium	5	10m to 20m dive/light work vessel	
	Large	12	20m to 30m research vessel with specialist capabilities and laboratories	
Vessel - other	**Size**	**$'000 per day**	**Description**	**Notes**
	Small	3	Trailable day vessel (30NM limit)	Bespoke vessels costed at specific quoted rates
	Medium	5	10m to 20m dive/light work vessel	
	Large	20	20m to 40m medium work class vessel	
Plane	**Size**	**$'000 per day**	**Description**	**Notes**
	Small	2	Single engine, two to three passengers only (four hrs usage)	
	Medium	5	Twin engine - passengers and kit (four hrs usage)	
	Large	15	Twin Otter - 1500kg payload capable (four hrs usage)	

HP Computing	Size	$'000 per day	Description	Notes
	Small	0.2		
	Medium	0.5		
	Large	1		

Laboratory	Size	$'000 per day	Description	Notes
	Small	0.1	Single bench (5m long)	Typical general lab with fume hoods, gases, deionised water
	Medium	0.5	Five-person working area	
	Large	1	Whole lab with space for 10 persons	
Laboratory (PC2)	**Size**	**$'000 per day**	**Description**	**Notes**
	Small	0.2	Single bench (5m long)	Specialist laboratory (PC2 or chemistry or other) - as above with additional specialised fit-out and/or physical containment systems
	Medium	1	Five-person working area	
	Large	2	Whole lab with space for 10 persons	

Seawater controlled env room	Size	$'000 per day	Description	Notes
	Small	0.18	Small room (24*50l tanks)	Includes technicians to build and run technical systems, but not technicians to manage in-tank biology
	Medium	0.24	Medium room (36*50l tanks)	
	Large	0.36	Large Room (48*50l tanks)	
Experimental aquarium	**Size**	**$'000 per day**	**Description**	**Notes**
	Small	0.18	Single set of three tanks @ 3000l volume	Indoor or outdoor, includes technicians to build and run technical systems, but not technicians to manage in-tank biology
	Medium	0.9	Five sets of tanks	
	Large	1.8	10 sets of tanks	

Reef Restoration and Adaptation Program

GBRrestoration.org

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Reef Restoration and Adaptation Program, a partnership:

Australian Government
Australian Institute of Marine Science
Australian Government Great Barrier Reef Marine Park Authority
Great Barrier Reef Foundation
CSIRO
QUT
James Cook University Australia
The University of Queensland Australia