R2: INTERVENTION SUMMARY

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

Bay LK[1], Mead D[1], Boström-Einarsson L[2]
[1]Australian Institute of Marine Science
[2]TropWATER, James Cook University

October 2019

Inquiries should be addressed to:

Dr Line Bay
l.bay@aims.gov.au

This report should be cited as:

Bay L, Mead D, Boström-Einarsson L (2019) Reef Restoration and Adaptation Program: Intervention Summary. A report provided to the Australian Government by the Reef Restoration and Adaptation Program (21pp).

Copyright

Acknowledgement

This work was undertaken for the Reef Restoration and Adaptation Program, a collaboration of leading experts, to create a suite of innovative measures to help preserve and restore the Great Barrier Reef. Funded by the Australian Government, partners include: the Australian Institute of Marine Science, CSIRO, the Great Barrier Reef Marine Park Authority, the Great Barrier Reef Foundation, The University of Queensland, Queensland University of Technology and James Cook University, augmented by expertise from associated universities (University of Sydney, Southern Cross University, Melbourne University, Griffith University, University of Western Australia), engineering firms (Aurecon, WorleyParsons, Subcon) and international organisations (Mote Marine, NOAA, SECORE, The Nature Conservancy).

Disclaimer

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, ethical and financially responsible. They would be implemented if, when and where it is decided action is needed and only after rigorous assessment and testing.

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

RRAP is working with Traditional Owners and groups with a stake in the Reef as well as the general public to discuss why these actions are needed and to better understand how these groups see the risks and benefits of proposed interventions. This will help inform planning and prioritisation to ensure the proposed actions meet community expectations.

Coral bleaching is a global issue. The resulting reef restoration technology could be shared for use in other coral reefs worldwide, helping to build Australia's international reputation for innovation.

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

2. EXECUTIVE SUMMARY

At the core of the Reef Restoration and Adaptation Program (RRAP) are the potential actions that could be taken on the Reef interventions. This program used a no-stone-unturned approach to examine 160 possible interventions, described by three core attributes: the *functional objective*, the *delivery method* and the possible *deployment scale*, where:

- **Functional objective** is the specific Reef ecosystem objective being targeted to aid recovery or adaptation to a changing climate.
- **Delivery method** is the specific approach to deliver the intervention, typically comprising a production and deployment action.
- **Deployment scale** is the likely feasible maximum scale of the intervention, based on current knowledge and an assessment of logistics and costs.

For review purposes, the interventions were grouped and assessed by functional objective and delivery method. The program identified seven types of functional objectives that represent a comprehensive scope of possibilities:

- Type 1: Cooling and shading to reduce coral stress during acute events
- Type 2: Add reef structures and stabilisation to increase the rate of reef recovery, through substrate stability and 3D structure, following major disturbances
- Type 3: Enhance the reproduction and recruitment of corals on reefs for recovery following disturbance
- Type 4: Biocontrol to restore coral reef health and resilience
- Type 5: Increase coral survival and reef health following disturbance with probiotics, feeding, medicine or other treatment
- Type 6: Increase the health and tolerance of reef populations by seeding corals with enhanced performance derived from existing stock
- Type 7: Increase the health and tolerance of reef populations by seeding corals with enhanced performance derived from synthetic biology and genetic engineering approaches.

For each functional objective, many more potential delivery methods were identified that represent alternative ways to meet the functional objective with different production, deployment or scale implications. This resulted in a total of 160 interventions that were carried forward for further evaluation in the intervention analysis (**R3: Intervention Analysis and Recommendations**).

This document describes the process to characterise, describe and catalogue interventions, a summary of the interventions identified, and an outline of the terminology employed throughout the RRAP reports. More detailed intervention descriptions are provided in reports **T3: Intervention Technical Summary** and **T4: Current Practices**.

3. BACKGROUND

The identification of interventions assessed under the RRAP Concept Feasibility Study included a mix of methods (Figure 1) from which an initial long list was identified:

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

This long list was refined and categorised as the costs, drivers of success and other considerations became more apparent during the concept feasibility study (Figure 1). Within seven intervention functional objective types, 160 unique delivery methods were categorised, based on the steps involved in their development (i.e. the product), production and deployment scale. For simplicity, where an intervention could be obtained by multiple methods, these were combined (as described in Section 4.3) resulting in the presentation of 43 interventions.

Potential benefits were modelled at the level of efficacy of the functional objective (e.g. level of cooling or degree of temperature tolerance in corals), factoring the specific approach to achieve this objective, where possible. Deployment costs were assessed by the delivery method. Existing knowledge and risks were identified for all interventions. Research and development (R&D) programs, priorities and estimated costs were defined for interventions recommended to progress to the RRAP R&D Program.

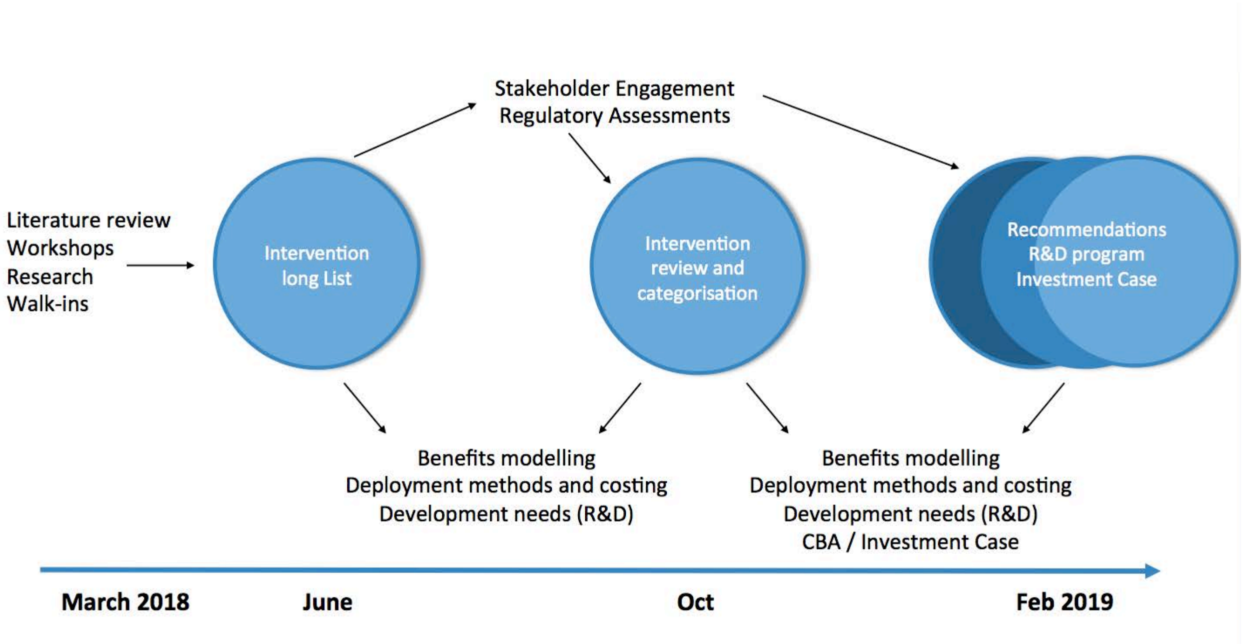

Figure 1: Process for identifying the potential interventions assessed by RRAP.

4. CHARACTERISATION OF INTERVENTIONS

The interventions being investigated are described as 'end-to-end approaches to achieve stated benefits for the Reef'. They have been characterised and documented by three attributes: their functional objective, delivery method and deployment scale. The knowledge and gaps surrounding the benefits and risks of the interventions and their specific production and deployment were documented at the level of the delivery method in the technical reports (T3: Intervention Technical Summary and T4: Current Practices).

The following definitions and terminology have been used (Table 1):

Table 1: The intervention terminology adopted by RRAP. Further definitions and a glossary are provided in T3: Intervention Technical Summary.

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

4.1 Overview of interventions

Table 2 provides a summary of the interventions examined during the RRAP Concept Feasibility Study. The interventions are grouped under functional objective types and delivery methods. In some instances, delivery methods can have alternative approaches.

For example, field treatments to enhance recovery following disturbance can consist of medicine, food or probiotics. The full matrix of approaches within delivery methods is described in Section 4.3.

Table 2: Overview of interventions grouped by objective and delivery methods. Code: C = cooling and shading; S = structure and stabilisation, ER = enhanced reproduction and recruitment, B = biocontrol, F = field treatments, EE = enhanced performance from existing species or populations and EN = enhanced performance from novel coral stock resulting from genetic engineering and/or synthetic biology. Additional descriptions of interventions including matrix approaches EEa–f and ENa–b are found in Section 4.2.

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

C8	Shading by structure	Suspending physical shade structures (e.g. cloth) at or near the surface of local reef areas via structure floats and/or anchors. Intended for intermittent operation during summer conditions to reduce incoming solar radiation and minimise coral bleaching.	Shade-cloth deployments
C9	Shading by algae	Farming suspended macroalgae above reefs to provide localised shade and/or remove nutrients. Requires fixed or moored structures. Not assessed or described in T3: Intervention Technical Summary. This intervention is scheduled to be assessed in the first year of the R&D program.	Macroalgal shading
C10	Ocean fertilisation	Deploying iron sulphate (or other nutrients) onto the ocean surface to stimulate phytoplankton growth. Described primarily as a method to capture and sequester CO_2, it can also provide shade. As this approach carries significant ecological risk, it was not considered for the Reef and not described in T3: Intervention Technical Summary. *Eliminated based on risk, not assessed further*	Ocean fertilisation
C11	Cooling by high altitude aerosols	Adding sulphate aerosols to higher atmospheric altitudes to globally cool Reef waters. This hypothesised intervention was not described in T3: Intervention Technical Summary. *Eliminated based on risk, not assessed further*	Sulphate aerosols
Type 2: Adding reef and 3D structures to increase substrate stability, and therefore the rate of reef recovery, following major disturbances			
S1	Stabilisation by natural bonding	Enhancing substrate consolidation by promoting natural bonding agents (including crustose coralline algae or other taxa or biological adhesives) from organisms such as bivalves to help increase the rate of reef recovery following a disturbance. Bonding agents/organisms would be produced/cultured in land-based facilities and deployed from barges and small vessels.	Assisted natural bonding
S2	Stabilisation by chemical bonding	Adding manufactured chemical bonding/grouting agents to enhance substrate consolidation to aid reef recovery. The bonding/grouting agents would be produced in land-based facilities and deployed in a semi-automated manner from barges and small vessels.	Chemical bonding and grouting
S3	Stabilisation by mesh	Stabilising substrate by fixing mesh over unconsolidated material to aid reef recovery. The mesh would be produced on land and fixed to the reef using a large barge or floating platform.	Mesh fixing
S4	Stabilisation by removal	Removing unconsolidated substrate via a surface-operated suction device to aid reef recovery. This approach has been successfully applied to reefs affected by ship and boat strikes. It requires a large barge/floating platform and is most effective where rubble beds are relatively thin veneers on top of consolidated coral reef substrate.	Suction removal
S5	Structure by consolidation	Consolidating rubble with gabion baskets to stabilise substrate and provide 3D structure to aid reef recovery. The mesh baskets would be filled with rubble, providing limited structure and habitat. They would be fabricated and filled onshore and deployed using large barges.	Gabion baskets

S6	Structure by 3D frames	Deploying small manufactured structures, such as the Mars™ spiders, onto the seafloor in areas of damaged reef to aid recovery. The spiders are modular and can be individually tied together by divers, or pre-attached into a chain or strip, prior to deployment. They are constructed onshore and could be deployed from small and large barges and vessels.	Mars™ Spiders and other smaller 3D structures
S7	Structure by concrete shapes	Deploying large, manufactured structures such as Bioballs™ or Subcon Mushrooms to facilitate ecological processes such as coral recruitment, survivorship, herbivory, fish diversity and growth of immobile organisms. They would be deployed from large barges.	Bioballs™ or Subcon Mushrooms
S8	Structure by massive corals	Deploying, or *in situ* reskinning, natural coral shapes. Artificial massive corals are concrete structures with a coral skin attached. The corals are grown separately, attached to the structures, which are deployed from large and small barges and deployment vessels.	Massive corals (coral-skinned shapes)
S9	Structure by 3D printed shapes	Deploying 3D printed structures that recreate structural complexity and facilitate ecological processes such as coral recruitment, survivorship, herbivory, fish diversity and growth of immobile organisms. The structures would be printed and deployed from large barges.	3D printed complex structures
Type 3: Enhance coral reproduction and recruitment on recovering reefs, following disturbance			
ER1	Coral seeding by *in situ* coral movement	*In situ* movement of whole coral colonies or large fragments within reefs to cluster them and increase fertilisation during natural spawning events (i.e. avoid Allee effects). Existing methods are well-developed and require divers, small and large vessels.	*In situ* movement of corals within reefs to increase fertilisation during natural spawning
ER2	Coral seeding by larval slick movement	Coral seeding by collecting natural, seasonally produced coral spawn/larval slicks in floating enclosures and towing them short distances to adjacent, high-priority areas for release. This aims to increase the number of corals from the spawning slick that ultimately recruit into reef populations.	Assisted larval movement
ER3	Coral seeding by larval slick translocation	Coral seeding by capturing natural, seasonally produced, coral spawn/larval slicks into tanks and transporting them via large vessels for release onto local or regional high-priority reefs. This aims to increase the number of corals from the spawning slick that ultimately recruit into reef populations.	Translocation of larval slicks
ER4	Coral seeding by larval slicks settled on devices	Settling coral slick-captured larvae onto devices and deploying onto local or regional reefs. This merges the larval slick and aquaculture methods and is designed to increase the number of corals created within the short annual spawning periods.	Translocation of larval slicks and device-based settlement
ER5	Coral seeding by *in situ* harvested fragments	Field-based harvesting of coral (micro) fragments (from areas of high coral cover or using fragments broken off in weather events) and delivery and planting in high-need areas. It would require automation of established manual methods. Additional treatments with microbes and hardening may be applied.	Direct harvest of coral (micro) fragmentation
ER6	Coral seeding by hatchery or	Optimising existing manual hatchery and nursery methods using local, unselected coral stock to seed reefs. Facilities	Optimised existing hatchery and nursery methods

	nursery aquaculture	could be land or sea-based, using diver-based deployment, supported by barges and small vessels.	
ER7	Coral seeding by semi-automated aquaculture	Semi-automated, shore-based aquaculture propagation, using either sexual or asexual methods and local brood stock, to seed corals onto reefs. This approach would amalgamate current aquaculture and automation technology with a combination of diver and semi-automated deployment methods from barges and small vessels.	Semi-automated shore-based aquaculture
ER8	Coral seeding by automated aquaculture	Automated, either sexual or asexual, mass production of corals in shore-based aquaculture, using local brood stock and field deployment from the surface and automated systems (no divers) to seed reefs. This method is based on deploying young corals (or small coral fragments) attached to a small device using barges and small vessels.	Automated, mass production shore-based aquaculture, field delivery systems
ER9	Coral seeding by larval/polyp aquaculture	Significant breakthrough larval/polyp-based sexual or asexual aquaculture that provides a step change in production rates and cost reductions, using local brood stock to seed reefs. These methods seek to vastly reduce production durations (from months/years to hours/days) and deployment success (via advanced active deployment devices) to facilitate much larger deployment quantifies at an affordable cost.	Breakthrough larval/polyp-based aquaculture
Type 4: Biocontrol to restore coral reef health and resilience			
B1	Biocontrol of macroalgae	Manual, automated or biological removal of macroalgae from reefs to promote coral recruitment, growth and survival. The removal methods may require *in situ* or land-based propagation of biocontrol agents. Existing manual methods require divers, robots and small and large vessels.	Biocontrol of macroalgae
B2	Biocontrol of species with negative impact	For example, managing the predatory sea snail *Drupella* using push-pull technology, biocontrol or genetic engineering. Push technologies (e.g. harnessing chemicals released by *Drupella* predators) deter the snails, while pull technologies (e.g. pheromones) attract the snails to specific locations where they can be removed. Biocontrol agents or genetic engineering control methods do not currently exist.	Biocontrol
Type 5: Increase coral survival and reef health following disturbance with probiotics, feeding, medicine or other treatment			
F1	Application of field treatments to enhance coral survival	*In situ* application of medicines, food or probiotics (treatments) to corals or reefs to enhance survival during natural stress events. Treatments are grown, cultured or manufactured on land and applied to colonies or reefs during or following stress. A viable deployment method is yet to be identified but could involve small and large vessels, aeroplanes or drones.	Field treatments
Type 6: Increase the health and tolerance of reef populations by seeding corals with enhanced performance, derived from existing stock			
EE1	Seeding enhanced corals from existing stock by larval	As in ER3, but using coral stock selected to promote adaptation or fitness in receiving populations, under changing conditions, using methods outlined in Section 4.3 EEa. May include additional treatments such as	Translocation of larval slicks

	slick translocation	microbial treatments or hardening (Section 4.3 Fc, EEe, EEf).	
EE2	Seeding enhanced corals from existing stock by settlement of larval slicks on devices	As in ER4, but using coral stock selected to promote adaptation or fitness in receiving populations, under changing conditions (as per Section 4.3 EEa–EEb). May include additional probiotic or hardening treatments (Section 4.3 Fc, EEe, EEf).	Translocation of larval slicks and device-based settlement
EE3	Seeding enhanced corals bred from existing stock with semi-automated aquaculture	As in ER7, but using coral stock selected to promote adaptation or fitness in receiving populations, under changing conditions (as per methods in Section 4.3 EEa–EEd). May include additional probiotic or hardening treatments (Section 4.3 Fc, EEe, EEf).	Semi-automated shore-based aquaculture
EE4	Seeding enhanced corals bred from existing stock with automated aquaculture	As in ER8, but using coral stock selected to promote adaptation or fitness in receiving populations, under changing conditions (as per methods in Section 4.3 Fc, EEa–EEd). May include additional probiotic or hardening treatments (Section 4.3 Fc, EEe–EEf).	Automated, mass production shore-based aquaculture
EE5	Seeding enhanced corals bred from existing stock with larval/polyp aquaculture	As in ER9, but using coral stock selected to promote adaptation or fitness in receiving populations, under changing conditions (as per methods in Section 4.3 4.3 Fc, EEa–EEd). May include additional probiotic or hardening treatments (Section 4.3 Fc, EEe–EEf).	Breakthrough larval/polyp-based aquaculture
Type 7: Increase the health and tolerance of reef populations by seeding corals with enhanced performance, derived from synthetic biology and genetic engineering approaches			
EN1	Seeding enhanced corals bred from engineered stock with semi-automated aquaculture	As in ER7 but using genetically engineered or synthetic coral stock and treatments. May include additional probiotic or hardening treatments (Section 4.3 EEe–EEf).	Semi-automated shore-based aquaculture
EN2	Seeding enhanced corals bred from engineered stock with automated aquaculture	As in ER8 but using genetically engineered or synthetic coral stock and treatments. May include additional probiotic or hardening treatments (Section 4.3 Fc, EEe–EEf).	Automated, mass manufacturing shore-based aquaculture
EN3	Seeding enhanced corals bred from engineered stock with larval/polyp aquaculture	As in ER9 but using enhanced coral stock derived from genetic engineering or synthetic biology. It may include additional probiotic or hardening treatments (Section 4.3 Fc, EEe–EEf).	Breakthrough larval/polyp-based aquaculture

4.2 Descriptions of functional objectives

The interventions being investigated by RRAP can be categorised into seven functional objectives (i.e. types):

Functional objective 1: **Cooling and shading** interventions to alleviate acute heat and light stress on coral reef organisms by temporarily reducing their exposure. Methods employ strategies to cool and/or shade reef waters by blocking some of the sun's energy or by pumping/mixing cooler water from depth.

Functional objective 2: **Reef structures and stabilisation** interventions to facilitate reef recovery through the addition of physical devices/processes designed to modify the reef structure. Methods include artificial reef surfaces (which range from settlement surfaces to artificial reefs) and stabilising rubble.

Functional objective 3: **Reproduction and recruitment** actions to enhance reproductive success, recruitment and recruit survival to facilitate recovery following disturbance. Methods include ecological manipulation of the density of corals for optimal health and survival and seeding native, non-selected corals.

Functional objective 4: **(Bio)-control** non-coral-focused actions to manage predators and competitors to facilitate recovery and maintain reef health and resilience. Methods include removing coral predators such as *Drupella* snails or competitors such as macroalgae[1].

Functional objective 5: **Probiotics and treatments** interventions that use bacteria, fungi or viruses to enhance desirable traits and/or the recovery of corals. Methods include manipulating the existing symbiosis of corals, forming novel associations with selected partners and developing disease treatments. Deployment methods include feeding, inoculation, medication and symbiotic manipulations with beneficial microbes during development.

Functional objective 6: **Enhanced coral performance** interventions that seed reefs with corals with enhanced performance to facilitate the adaptation of populations to environmental change. Methods use naturally tolerant or selectively bred corals as seed sources. Production and deployment methods include translocation of wild-caught material and propagation of selected stock in an aquarium facility.

Functional objective 7: **Engineered coral performance and reef health** synthetic biology and genetic engineering approaches to enhance the performance of corals and/or to accelerate reef recovery following environmental disturbance. Methods that target the coral animal and/or its symbiotic microbial partners are included.

[1] Please note that while crown-of-thorns starfish removal is considered in RRAP benefit models, it is not included in the proposed interventions as there are existing research and development programs dedicated to this method of intervention. Please consult Babcock et al. (2016), Westcott et al. (2016) and Pratchett et al. (2017) for further information on this topic.

4.3 Descriptions of delivery methods

Each of the seven intervention functional objectives contains single to multiple delivery methods. Intervention functional objectives two (reef structures and stabilisation) and three (reproduction and recruitment) target reefs post-disturbance, to facilitate recovery and resilience (i.e. they are treatments), while the others aim to prevent stress occurring (i.e. they are preventative).

For some delivery methods, a matrix of possible approaches exists (briefly described in Table 3 and covered in detail in **RRAP Reports: T3: Intervention Technical Summary** and **T4: Current Practices**. Production and deployment details are also explored in **T11: Automated Aquaculture Production and Deployment**.

Table 3: Matrix of delivery method approaches. Codes: F = field treatments, EE = enhanced corals, EN = enhanced novel engineered corals, Fa = treating coral disease, Fb = alternative foods, Fc = probiotics, EEa = assisted gene flow, EEb = assisted migration, EEc = marker-assisted breeding, EEd = interspecific hybridisation, EEe = manipulate symbionts, EEf = stress hardening, ENa = genetic engineering and ENb = synthetic biology.

Delivery method	Approach alternatives									
	Fa	Fb	Fc	EEa	EEb	EEc	EEd	EEf	ENa	ENb
F	X	X	X							
EE1				X			X	X		
EE2				X	X		X	X		
EE3			X	X	X	X	X	X		
EE4			X	X	X	X	X	X		
EE5			X	X	X	X	X	X		
EN1			X						X	X
EN2			X						X	X
EN3			X						X	X

Functional objective 1: cooling and shading to reduce coral stress during acute events

C1 **Cooling by mixing**: Mixing shallow reef waters to reduce local seawater temperature using slow-moving impellers on moored or attached structures. Intended for intermittent operation during summer doldrums conditions to minimise coral bleaching.

C2 **Cooling by pumping**: Pumping deeper colder waters either directly onto the reef or passed through heat exchangers to reduce seawater temperatures using permanent and attached structures. Intended for intermittent operation during summer conditions to minimise coral bleaching.

C3 **Shading by cloud brightening**: Adding nano-sized salt (or other) particles to the lower atmosphere (< 1000m) to change the water droplet size distribution in clouds, enhance the reflectivity of clouds and restrict the amount of light reaching reefs over distances large enough to also reduce heat. Particles would be added via devices mounted on moored platforms and vessels or via aerial dispersal of dry material. Intended for intermittent operation during summer conditions.

C4 **Shading by fogging**: Artificial 'sea-fog' created by spraying seawater into the air from dispensing devices on moored or attached platforms or vessels. Intended for intermittent deployment during summer conditions to reduce the amount of solar radiation reaching reefs and provide evaporative cooling to minimise coral bleaching.

C5 **Shading by misting**: Adding vaporised biogenic oil to the lower atmosphere via devices mounted on moored platforms or vessels. Intended for intermittent operation during summer conditions to form a mist of reflective smoke particles, and thus reduce incoming solar radiation to minimise coral bleaching.

C6 **Shading by surface films**: Adding ultra-thin surface films, manufactured from natural products, to surface waters via moored dispensers and/or aerial dispersal. Intended for intermittent deployment during summer conditions to reduce solar radiation and minimise coral bleaching.

C7 **Shading by microbubbles**: Creating nano-sized bubbles in reef surface waters to reflect light via temporary or permanently moored platforms. Intended for intermittent operation during summer conditions to reduce incoming solar radiation, and thus minimise coral bleaching.

C8 **Shading by structure**: Suspending shade structures (e.g. cloth) at or near the surface of local reefs via structural floats and/or anchors. Intended for intermittent operation during summer conditions to reduce incoming solar radiation, and thus avoid/minimise coral bleaching.

C9 **Shading by algae**: Farming suspended macroalgae above reefs to provide shade and/or remove nutrients. Requires fixed or moored structures. Not assessed or described in [T3: Intervention Technical Summary](). Scheduled to be assessed in the first year of the R&D program.

C10 **Ocean fertilisation**: deploying iron sulphate (or other nutrients) onto the ocean surface to stimulate phytoplankton growth. Described primarily as a method to capture and sequester CO_2, it can also provide shade. As this approach carries significant ecological risk, it was not considered for the Reef and is not described in [T3: Intervention Technical Summary]().

C11 **High altitude aerosols**: cooling by adding sulphate aerosol to higher atmospheric altitudes. This hypothesised global cooling intervention was eliminated based on risk and is not described in [T3: Intervention Technical Summary]().

Functional objective 2: Add reef structures and stabilisation to increase the rate of reef recovery, through substrate stability and 3D structure, following major disturbances

S1 **Stabilisation by natural bonding**: Enhancing substrate consolidation by promoting natural bonding agents, including crustose coralline algae or other taxa, or biological adhesives from organisms such as bivalves. Bonding agents/organisms would be produced/cultured in land-based facilities and deployed from barges and small vessels.

S2 **Stabilisation by chemical bonding**: Enhancing substrate consolidation by adding manufactured chemical bonding/grouting agents. The bonding/grouting agents would be produced in land-based facilities and deployed in a semi-automated manner from barges and small vessels.

S3 **Stabilisation by mesh**: Stabilising substrate by fixing mesh over unconsolidated material. The mesh would be produced on land and fixed onto the reef using a large barge or floating platform.

S4 **Stabilisation by removal**: Removing unconsolidated substrate via a surface-operated suction device. This approach has been successfully applied to reefs affected by ship and boat strikes. It requires a large barge or floating platform and is most effective where rubble beds are a relatively thin veneer on top of consolidated coral reef substrate.

S5 **Structure by consolidation**: Consolidating rubble with gabion baskets to stabilise substrate and provide 3D structure. The mesh baskets are filled with rubble and provide limited structure and habitat. They would be fabricated and filled onshore and deployed using large barges.

S6 **Structure by 3D frames**: Deploying small manufactured structures such as the Mars™ spiders on the seafloor of areas of damaged reef. The spiders are modular and can be individually tied together by divers or pre-attached into a chain or strip prior to deployment. They are constructed onshore and could be deployed from small and large barges and vessels.

S7 **Structure by concrete shapes**: Deploying large manufactured structures such as Bioballs™ or Subcon Mushrooms to facilitate ecological processes such as coral recruitment, survivorship, herbivory, fish diversity and growth of immobile organisms. They would be deployed from large barges.

S8 **Structure by massive corals**: Deploying, or *in situ* reskinning, of natural coral shapes. Artificial massive corals would have a coral skin attached on the structure prior to deployment. The corals would be grown separately, and the structures deployed from large and small barges and vessels.

S9 **Structure by 3D printed shapes**: Deploying 3D printed structures that recreate the structural complexity that facilitates ecological processes, such as coral recruitment, survivorship, herbivory, fish diversity and the growth of sessile organisms. The structures are printed onshore and deployed from large barges.

Functional objective 3: enhance the reproduction and recruitment of corals on reefs for recovery following disturbance

ER1 **Coral seeding by *in situ* coral movement**: *In situ* movement of whole coral colonies or large fragments within reefs to increase fertilisation during natural spawning events (i.e. avoid Allee effects). Existing methods are well-developed and require divers and small and large vessels.

ER2 **Coral seeding by larval slick movement**: Coral seeding by collecting natural, seasonally produced coral spawn/larval slicks in floating enclosures that are towed short distances to adjacent high-priority areas and released. This aims to increase the number of corals from the spawning slick that recruit into reef populations.

ER3 **Coral seeding by larval slick translocation**: Coral seeding by capturing natural, seasonally produced, coral spawn/larval slicks in tanks, transported by large vessels and released onto local or regional high-priority reefs. This aims to increase the number of corals from the spawning slick that recruit into reef populations.

ER4 **Coral seeding by larval slicks settled on devices**: Settling coral slick-captured larvae onto devices and deploying on local or regional reefs, thus merging the larval slick and aquaculture methods. This is designed to increase the number of corals created within the short annual spawning periods.

ER5 **Coral seeding by *in situ* harvested fragments**: Field-based harvesting of coral (micro) fragments (from areas of high coral cover or fragments broken off in weather events) and delivery and planting in high-need areas. Requires automation of established manual methods. Additional treatments with microbes and hardening may be applied.

ER6 **Coral seeding by hatchery or nursery aquaculture**: Optimising existing manual hatchery and nursery methods using local unselected coral stock to seed corals onto reefs. Facilities could be land- or sea-based and use diver-based deployment methods, supported by barges and small vessels.

ER7 **Coral seeding by semi-automated aquaculture**: Seeding corals onto reefs via semi-automated, shore-based aquaculture propagation (sexual and/or asexual methods), using local brood stock. This method would be an amalgamation of current aquaculture and automation technology and a combination of diver and semi-automated deployment methods from barges and small vessels.

ER8 **Coral seeding by automated aquaculture**: Seeding corals onto reefs via automated, sexual and/or asexual mass production of corals in shore-based aquaculture, using local brood stock and field deployment from the surface via automated systems (no divers). This method is based on deploying young corals (or small coral fragments) attached to a small device, distributed onto reefs using barges and small vessels.

ER9 **Coral seeding by larval/polyp aquaculture**: Seeding corals onto reefs using significant breakthrough larval/polyp-based sexual and asexual aquaculture methods that provide a step change in production rates and cost reductions, using local brood stock. These methods seek to vastly reduce production durations (from months/years to hours/days) and deployment success (via advanced active deployment devices) to facilitate much larger deployment quantifies at an affordable cost.

Functional objective 4: (bio)-control to restore coral reef health and resilience

B1 **(Bio)-control of macroalgae**: Manual, automated or biological removal of macroalgae from reefs to promote coral recruitment, growth and survival. The removal methods may require *in situ* or land-based propagation of biocontrol agents. Some methods for mechanical removal exist and require divers, robots and small and large vessels.

B2 **Biocontrol of species with negative impact**: For example, *Drupella* management to reduce predation using push-pull technology, biocontrol or genetic engineering. Push technologies (e.g. chemicals released by *Drupella* predators) deter the snails, while pull technologies (e.g. pheromones) attract the snails to a specific location where they can be collected. Biocontrol agents or genetic engineering methods do not currently exist.

Functional objective 5: increase coral survival and reef health following disturbance with probiotics, feeding, medicine or other treatment

F1 **Application of field treatments to enhance coral survival**: *In situ* application of medicines, food or probiotics (treatments) to corals or reefs to enhance survival during natural stress events. Treatments are grown, cultured or manufactured on land and directly applied to colonies or reefs during, or following, stress. A viable method of deployment is yet to be identified, but could involve small and large vessels, aeroplanes or drones.

Alternatives for field treatments

Fa **Treating coral disease**: Treating or preventing coral disease to enhance the growth and survival of corals during the propagation phase or to aid the recovery of impacted corals. Potential approaches include antioxidant and anti-microbial biological systems, as well as phage therapy (using a virus to treat a bacterial disease).

Fb **Alternative foods**: Providing alternative foods to optimise health, growth and survival of corals in captivity, during transport and on the reef following stress. Foods can be derived from bacteria, plants and animals, and can be pure or formulated.

Fb **Probiotics**: Manipulating the abundance or ratios of existing microbes in the coral holobiont (the entire community of living organisms that make up a healthy coral head) to enhance desirable traits such as good health, growth, survival and stress tolerance. Treatments can be applied to corals during rearing, to settlement and deployment devices or directly to the reef.

Functional objective 6: Increase the health and tolerance of reef populations by seeding corals with enhanced performance derived from existing stock

EE1 **Seeding enhanced corals from existing stock by larval slick translocation**: As in ER3, but using coral stock selected to promote adaptation or fitness in receiving populations under changing conditions, using methods outlined in EEa. It may include additional treatments such as microbial treatments or hardening (Fc, EEe and EEf).

EE2 **Translocation of larval slicks and device-based settlement**: As in ER4, but using coral stock selected to promote adaptation or fitness in receiving populations under changing conditions, as per EEa-b. It may include additional probiotic or hardening treatments (Fc, EEe and EEf).

EE3 **Seeding enhanced corals bred from existing stock with semi-automated aquaculture**: As in ER7, but using coral stock selected to promote adaptation or fitness in receiving populations under changing conditions as per methods in EEa–d. It may include additional probiotic or hardening treatments (Fc, EEe and EEf).

EE4 **Seeding enhanced corals bred from existing stock with automated aquaculture**: As in ER8, but using coral stock selected to promote adaptation or fitness in receiving populations under changing conditions as per methods in EEa–d. It may include additional probiotic or hardening treatments (Fc, EEe and EEf).

EE5 **Seeding enhanced corals bred from existing stock with larval/polyp aquaculture:** As in ER9, but using coral stock selected to promote adaptation or fitness in receiving populations under changing conditions as per methods in

EEa–d. It may include additional probiotic or hardening treatments (Fc, EEe and EEf).

Alternatives for enhanced coral holobionts

EEa **Assisted gene flow**: Facilitating the movement of genes between coral populations for enhanced performance in traits such as heat tolerance, growth and fecundity among reef populations. Other approaches may also consider genetic diversity to increase the adaptive potential of receiving populations. This method can be employed by EE1–6.

EEb **Assisted migration and colonisation**: Facilitating the movement of genes for enhanced performance, as well as the movement of tolerant species from other reef systems into the Great Barrier Reef, to enhance tolerance of sensitive populations and species. *Eliminated based on risk. Not assessed further.*

EEc **Marker-assisted selective breeding**: Facilitating an increase in corals with enhanced heat tolerance (or other desirable traits) to changing conditions on receiving reefs. Breeding stock is selected by genomic markers and may originate from local or regional sources. This method could be applied in EE3–6 but not EE1–2.

EEd **Interspecific hybridisation for novel genomics**: Intentionally crossbreeding separate species to produce novel (i.e. hybrid) genomic combinations that have higher fitness than parental species under changing conditions. It could only be applied in aquaculture propagation (EE3–6).

EEe **Manipulate symbionts**: Manipulating the abundance of symbiotic microalgae (Symbiodiniaceae) or other microbes to enhance the performance for future conditions, through experimental selection. The microbial treatments could be applied as probiotics, as part of the coral movement and aquaculture processes (EE1–6) or as a field treatment (F1).

EEf **Stress hardening**: Increasing coral tolerance to a stressor (e.g. heat exposure) through priming from short-term stress exposures. This could be applied as a primary product or a secondary treatment. The hardening treatment could be applied as part of the coral movement and aquaculture propagation method (EE1–6).

Functional objective 7: Increase the health and tolerance of reef populations by seeding corals with enhanced performance from synthetic biology and genetic engineering approaches

EN1 **Seeding novel enhanced corals with semi-automated aquaculture**: As in ER7 but using genetically engineered or synthetic coral stock and treatments (ENa and ENb). It may include additional probiotic or hardening treatments (Fc, EEe and EEf).

EN2 **Seeding novel enhanced corals with automated aquaculture**: As in ER8 but using genetically engineered or synthetic coral stock and treatments (ENa and ENb). It may include additional probiotic or hardening treatments (Fc, EEe and EEf).

EN3 **Seeding novel enhanced corals with larval/polyp aquaculture**: As in ER9 but using enhanced coral stock derived from genetic engineering or synthetic biology (ENa and ENb). It may include additional probiotic or hardening treatments (Fc, EEe and EEf).

Alternatives for novel enhanced coral holobionts

ENa **Genetic engineering**: Using technologies to manipulate the hereditary genetic material of corals to alter a characteristic of interest (e.g. thermal tolerance) in a target organism. Techniques include CRISPR/Cas9 where guide RNA and proteins are used to find, cut and edit DNA containing the guide RNA sequence in the genome of the target organism.

ENb **Synthetic biology**: Approaches for engineering tolerance of corals such as bacteria or reef health and other biological entities with desirable traits to enhance coral for reef-based treatment.

5. ADDITIONAL INTERVENTIONS

The following ideas (Table 4) were provided to the RRAP team late in the concept feasibility study and are yet to be assessed. Some were eliminated after the initial description and analysis (described in Table 2 and Section 4.3). As the RRAP planning and R&D progress, intermittent reviews and horizon scans will identify and describe additional interventions for potential further analysis.

Table 4: Interventions not yet fully described or analysed.

Title	Description
Geomorphic adjustments	Adjusting water flows onto reefs, or subsections of reefs, by changing the reef/shelf morphology Adjusting reef morphology to provide coral habitat in cooler zones and/or to control rubble movement

6. TERMINOLOGY AND GLOSSARY

The RRAP Concept Feasibility Study required many disciplines to collaborate to produce reports for different audiences. As each discipline has its own specific language and jargon, a shared understanding of terminology is important. Discipline-specific language is particularly evident in the RRAP technical reports (**T1 - T12**). A glossary of key RRAP intervention and method delivery terms can be found in **T3: Intervention Technical Summary**, which was developed from the following resources:

- **T3: Intervention Technical Summary** and references therein
- http://www.coralsoftheworld.org/page/glossary/
- https://www.coris.noaa.gov/glossary/

REFERENCES

Babcock RC, Dambacher JM, Morello EB, Plagányi ÉE, Hayes KR, Sweatman HPA, Pratchett MS (2016) Assessing different causes of crown-of-thorns starfish outbreaks and appropriate responses for management on the Great Barrier Reef. PloS One 11:e0169048.

Pratchett M, Caballes C, Wilmes J, Matthews S, Mellin C, Sweatman H, Nadler L, Brodie J, Thompson C, Hoey J, Bos A, Byrne M, Messmer V, Fortunato S, Chen C, Buck A, Babcock R, Uthicke S (2017) Thirty years of research on crown-of-thorns starfish (1986–2016): Scientific advances and emerging opportunities. Diversity 9:41.

Westcott DA, Fletcher CS, Babcock RC, Plaganyi-Lloyd E (2016) A strategy to link research and management of crown-of-thorns starfish on the Great Barrier Reef: An integrated pest management approach. Report to the National Environmental Science Programme. Reef and Rainforest Research Centre Limited, Cairns (80 pp).

APPENDIX A – RRAP DOCUMENT MAP

Reef Restoration and Adaptation Program

RRAP Investment Case

- **R1 | Engagement & Regulatory Dimensions**
  - T1: Stakeholder, Traditional Owner & Community Engagement Assessment
  - T2: Regulatory Assessment Findings
- **R2 | Intervention Summary**
  - T3: Intervention Technical Summary
  - T4: Current Practices
- **R3 | Intervention Analysis & Recommendations**
  - T5: Future Deployment Scenarios & Costing
  - T6: Modelling Methods & Findings
  - T7: Decision Support Findings
  - *T8: Consolidated into other reports*
  - T9: Cost Benefit Analysis
  - T10: Benefit Streams
  - T11: Automated Aquaculture Production & Deployment
  - T12: Cool Water Injection
  - T13: Ultra Thin Surface Films
  - T14: Environmental Modelling of Large Scale Solar Radiation Management
- **R4 | Research & Development Program**
- **R5 | International Engagement & Partnering**
- **R6 | Governance & Program Delivery**

KEY:

- Investment and R&D Strategy
- Summary of findings and key recommendations
- Technical process and detailed findings

Reef Restoration and Adaptation Program

GBRrestoration.org

Dr. Line Bay
Australian Institute of Marine Science
l.bay@aims.gov.au