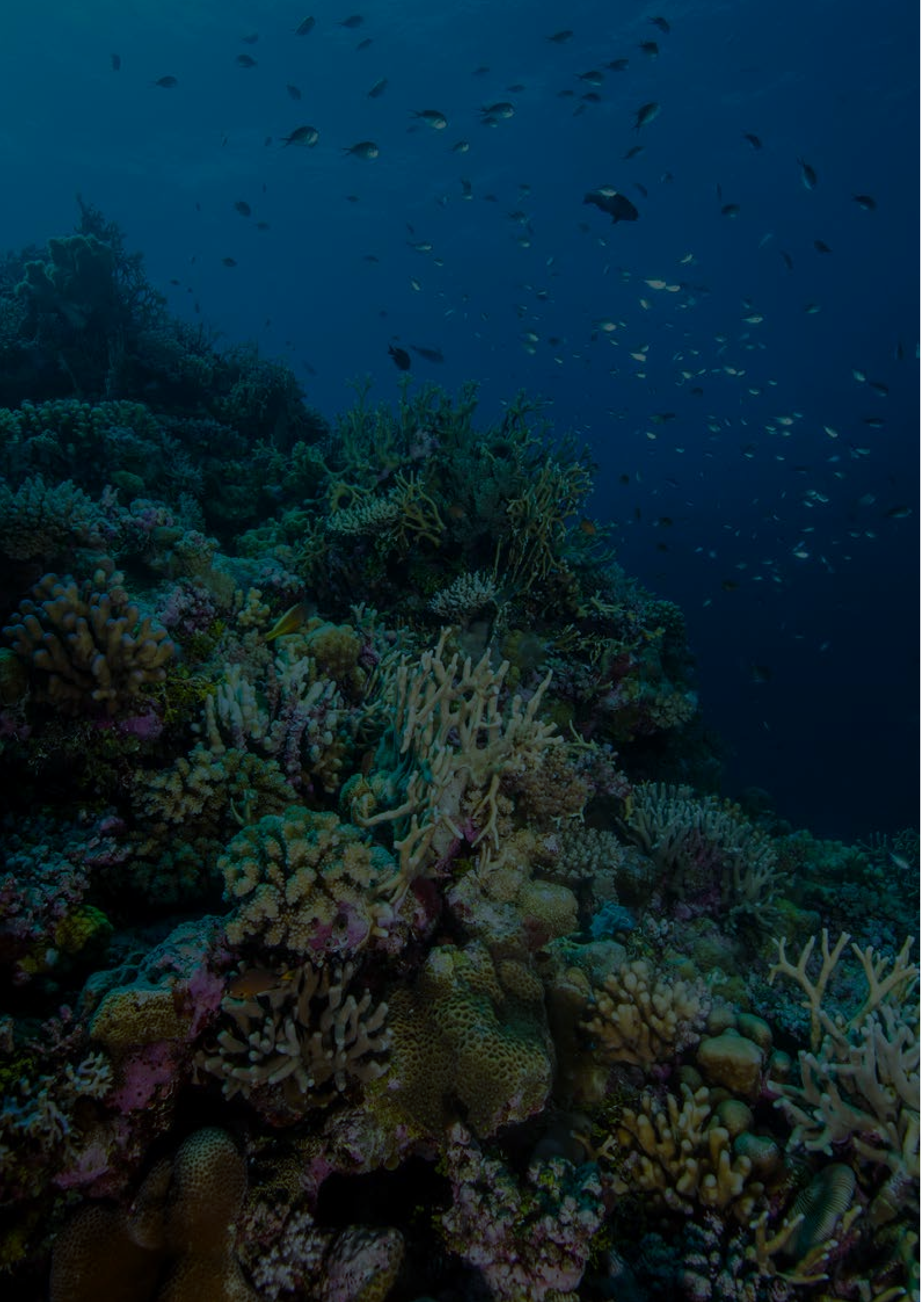
REEF RESTORATION & ADAPTATION PROGRAM

SYNTHESIS REPORT 2020–2025

Australian Government
REEF TRUST
Great Barrier Reef Foundation
Australian Government
Australian Institute of Marine Science
CSIRO
James Cook University Australia
QUT
Southern Cross University
The University of Queensland Australia



The Reef Restoration and Adaptation Program (RRAP) acknowledge Aboriginal and Torres Strait Islander Peoples as the first reef scientists and carers of Country. We acknowledge the Traditional Owners of the places where RRAP works, both on land and in Sea Country. We pay our respects to elders; past, present, and future; and their continuing culture, knowledge, beliefs, and spiritual connections.

We specifically acknowledge and thank the following Traditional Owners of Country where RRAP research was conducted and/or who contributed to RRAP research and development.

Location	Traditional Owner Group
Brisbane	Turrbal, Yuggera
Gold Coast	Yugambeh
Torres Strait	Masigalgal, Porumalgal, Warraberalgal (Poruma & Iama)
Northern Great Barrier Reef	Wuthathi, Kuuku Ya'u, Lama Lama, Cape Melville and Howicks Peoples, Nguurruumungu, Dingaal, Thanil
Central Great Barrier Reef	Eastern Kuku Yalanji, Gunggandji, Yirrganydji, Gimuy Walubara Yidinji, Manbarra, Wulgurukaba, Bindal, Nywaigi, Ngaro
Southern Great Barrier Reef	Darumbal, Woppaburra, Bailai, Gurang, Gooreng Gooreng, Taribelang Bunda
Canberra	Ngunnawal
Hobart	Muwinina, Palawa
Melbourne	Wurundjeri Kulin, Bunurong
Perth	Whadjuk Noongar
New South Wales (Sydney and Dubbo)	Cammeraygal, Wiradjuri

This work was undertaken for the Reef Restoration and Adaptation Program, funded by the partnership between the Australian Government's Reef Trust and the Great Barrier Reef Foundation. Partners include: the Australian Institute of Marine Science, CSIRO, the Great Barrier Reef Foundation, Southern Cross University, the University of Queensland, Queensland University of Technology and James Cook University.

Cover image credit: Gary Cranitch, Queensland Museum

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Numbers following authors names indicate their institutional affiliation relevant to the work they conducted for RRAP and this may differ from their current institutional affiliation.

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3. Great Barrier Reef Foundation
4. Commonwealth Science and Industrial Research Organisation (CSIRO)
5. The University of Queensland (UQ)
6. Queensland University of Technology (QUT)
7. Southern Cross University (SCU)
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Image credit: Matt Curnock, Ocean Image Bank

FOREWORD

Global warming is accelerating, and marine heatwaves are becoming more frequent and acute, threatening coral reef ecosystems across the world. Although nations are committed to reducing carbon emissions to net zero in the second half of this century, further ocean warming is inevitable over the next few decades. It is thus vital that we develop strategies to assist coral reefs to survive through this transitional period.

This report summarises progress made by the Reef Restoration and Adaptation Program (RRAP) in developing such strategies, with a particular focus on the Great Barrier Reef (GBR).

Our modelling of the future state of the GBR demonstrates that interventions will be needed to assist coral reefs in coming decades, under all realistic carbon emissions trajectories the world could follow. Without interventions, coral reef cover and diversity in the GBR will decline significantly and critical ecological, social, cultural and economic values will be lost.

Over the last five years RRAP has been researching interventions that could give coral reefs a chance to survive as the global climate system stabilises. We have made excellent progress and we have growing confidence that at least some of the interventions we have been examining can be implemented at scale to benefit high priority assets on the Great Barrier Reef.

Other than the interventions investigated by RRAP, we are not aware of any other management levers that could help to directly protect the Reef from the further ocean warming that lies ahead. Efforts to improve catchment water quality, arrest Crown-of-thorns starfish incursions and protect fisheries are also vital management actions, but these efforts in themselves cannot protect the GBR from worsening marine heatwaves.

We have just completed the first phase of RRAP research and have commenced a program of trial deployments to test the efficacy and practicality of some RRAP interventions at scale.

RRAP was conceived as a long-term endeavor and more research remains necessary, as are strengthened partnerships with traditional custodians of Sea Country, reef communities, and businesses operating in the GBR. Continued innovation is critical to achieving the efficacy and cost-efficiency that will make RRAP interventions viable and affordable at the scales required. Without significant and sustained investment in targeted research and development, simply scaling up the current interventions would be neither cost-effective nor sufficient to deliver the improvements in reef resilience needed as the impacts of climate change intensify.

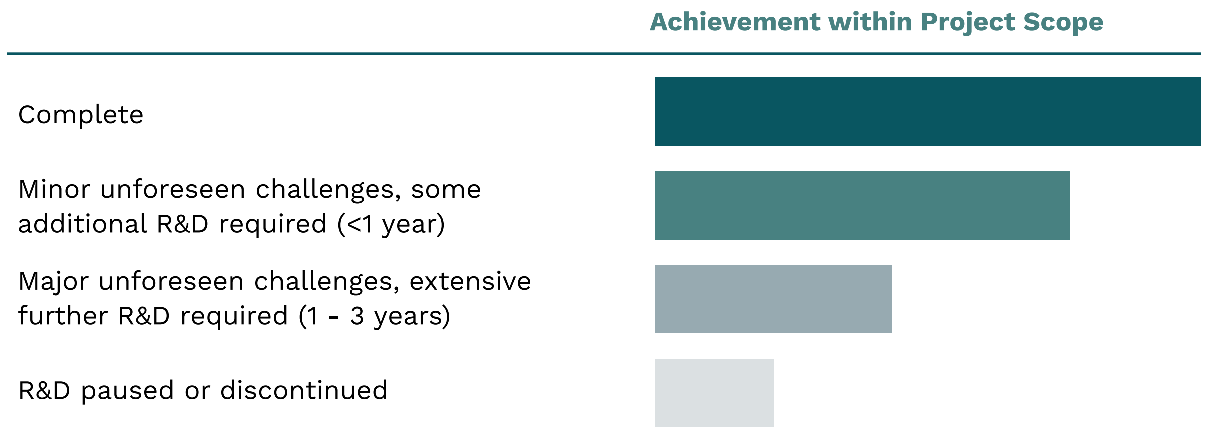
RRAP partners will continue working with government and reef stakeholders to develop the next phase of partnership research that will ensure that reef managers have options to protect the GBR in the years ahead.

HOW TO USE THIS REPORT

This report provides a point-in-time synopsis of activities, methods, findings and outcomes from RRAP completed in accordance with the program scope between 2020 and 30 June 2025.

Information contained in this report reflects program, subprogram and project scope, knowledge and outcomes as of May-June 2025. This report should be read alongside associated technical reports, datasets, and publications for full detail. Links to project reports, standard operating procedures and the full list of RRAP publications are embedded throughout this report. This report does not provide scientific inferences, policy guidance or operational instructions beyond RRAP's defined scope and duration.

Progress toward RRAP's original approved objectives is illustrated in a diagram similar to the one below for each of the 13 RRAP subprograms and major areas of work. The colour bar adjacent to each subprogram objective illustrates the level of completion of the agreed scope of work, as follows:



Case studies illustrating how RRAP has successfully developed and tested a suite of complementary tools and approaches to support coral reef restoration and climate adaptation are interspersed throughout this report. Together, these examples demonstrate the breadth of the RRAP "toolbox", spanning community engagement, social support, Traditional Owner partnerships, research, engineering, monitoring and deployment approaches, and how these capabilities can be applied in different operational contexts. The case studies also highlight how RRAP activities align with the objectives and priorities of the Reef 2050 Long-Term Sustainability Plan, particularly in advancing reef resilience, supporting evidence-based management, and enabling scalable restoration and adaptation responses for the Great Barrier Reef.

ACRONYM LIST

ADRIA	Adaptive Dynamic Reef Intervention Algorithms
AGF	Assisted gene flow
AI	Artificial intelligence
AIMS	Australian Institute of Marine Science
APCRS	Asia Pacific Coral Reef Symposium
ARIEL	Aerosol Radiation and their Interactions Experimental Laboratory
ASV	Automated surface vessels
BCF	Biocultural Framework
B4C	Boats4Corals
CAD	Coral Aquaculture and Deployment RRAP Subprogram
CADs	Coral Attachment Devices
CCA	Crustose coralline algae
CCIP	Crown-of-thorns starfish (COTS) Control Innovation Program
CGRAS	Coral Growout Robotic Assessment System
CORDAP	Coral Research and Development Accelerator Platform
COTS	Crown-of-thorns starfish
CS or C&S	Cooling and Shading RRAP subprogram
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSLICS	Coral Spawn and Larvae Imaging Camera System
DHW	Degree heating week
EcoRRAP	Ecological Intelligence for Reef Restoration RRAP subprogram
ECRS	European Coral Reef Symposium
ECT	Enhanced Corals and Treatments RRAP subprogram
ENG	Stakeholder and Traditional Owner Engagement RRAP subprogram
FPIC	Free, prior and informed consent
GBR	Great Barrier Reef
GBRF	Great Barrier Reef Foundation
GBRMP	Great Barrier Reef Marine Park
GBRMPA	Great Barrier Reef Marine Park Authority (Reef Authority)
ICRS	International Coral Reef Society
IP	Indigenous Partnerships cross-cutting program of work
IRRG	Intervention Risk Review Group
IUCN	International Union for Conservation of Nature
JCU	James Cook University
LTMP	Long-Term Monitoring Program
MCB	Marine Cloud Brightening
MC	Moving Corals RRAP subprogram
M&DS	Modelling and Decision Support RRAP subprogram
NOAA	National Oceanic and Atmospheric Administration
NRM	Natural Resource Management
PDP	Pilot Deployments Program
QUT	Queensland University of Technology
REG	Regulatory and Policy Environment RRAP subprogram
RISK	Intervention Risk Management cross-cutting program of work
RRAP	Reef Restoration and Adaptation Program
RRAP IS	Reef Restoration and Adaptation Program Information System
RRAS	Reef Restoration and Adaptation Science
RS	Rubble Stabilisation RRAP subprogram
RTP	Reef Trust Partnership
R&D	Research and Development
SCU	Southern Cross University
SeaSim	Australian National Sea Simulator (at AIMS)
SHAMS	General Organization for the Conservation of Coral Reefs and Turtles in the Red Sea
SOP	Standard Operating Procedure
SRM	Solar Radiation Management
TRL	Technology Readiness Level
T2D	Translation to Deployment RRAP subprogram
UAV	Unmanned Aerial Vehicle
UNOC	United Nations Ocean Conference
UQ	The University of Queensland
USGS	United States Geological Survey

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MISSION

RRAP'S MISSION IS TO DEVELOP INNOVATIVE SOLUTIONS THAT CAN SUPPORT THE RESILIENCE OF THE GREAT BARRIER REEF TO THE IMPACTS OF CLIMATE CHANGE, AND TO SHARE OUR KNOWLEDGE FOR THE BENEFIT OF CORAL REEFS GLOBALLY.

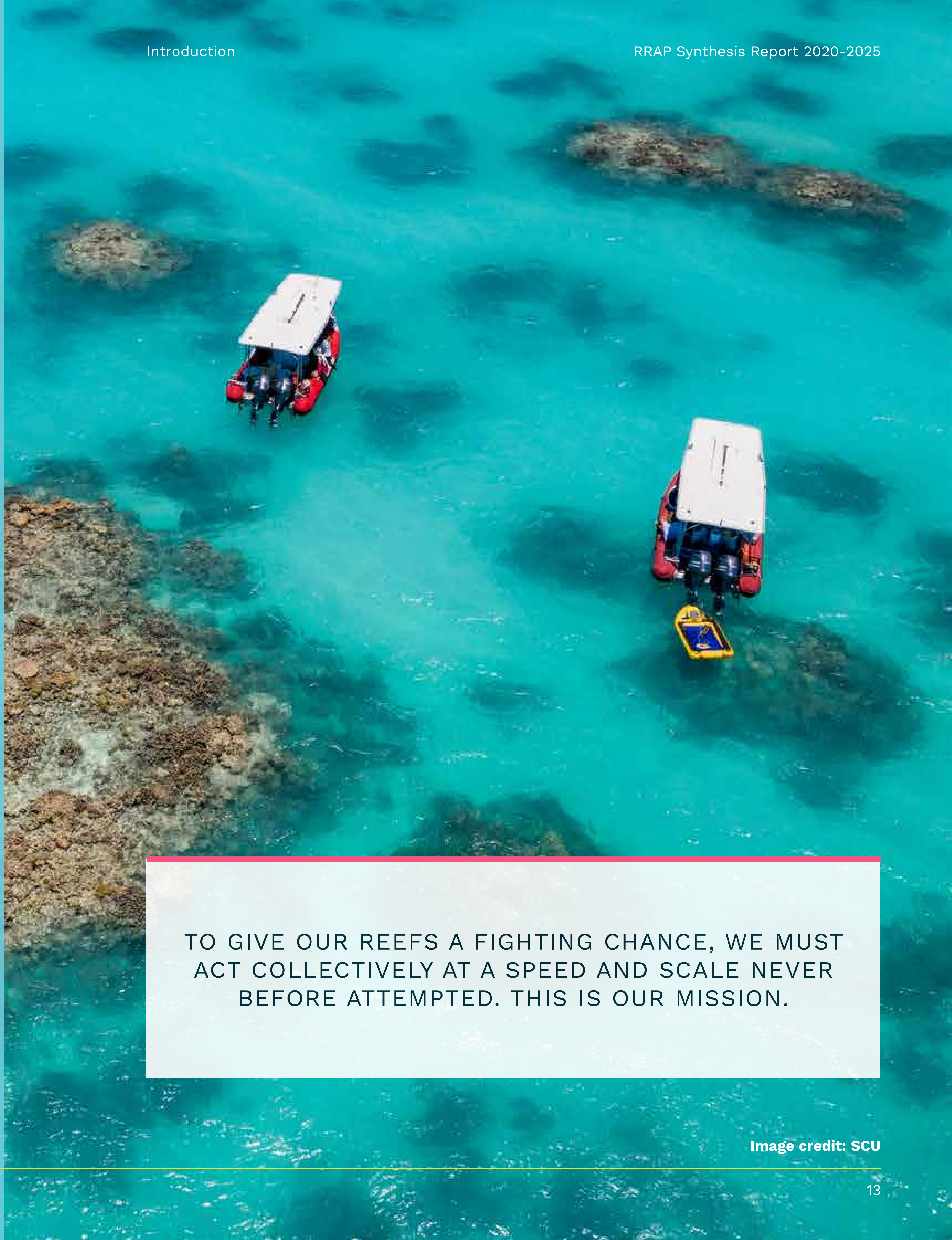
RRAP's mission is to develop and test novel scientific solutions to help coral reefs survive in the decades ahead, as emissions reduction targets are reached. These solutions have been developed and delivered in partnership with Traditional Owners, recognising their ancestral knowledge and the benefits of seeing the Great Barrier Reef as a cultural landscape beyond its biophysical features.

RRAP supports the consensus that addressing climate change and drastically reducing greenhouse gas emissions is the absolute priority for the long-term survival of coral reefs. This is alongside context-specific management activities which are essential to support reef resilience and recovery, such as actions to improve water quality, prevent overfishing and contain coral predator outbreaks.

Yet this is not enough. Emissions reductions and current management actions alone will not safeguard the Great Barrier Reef and coral reefs around the globe. Based on coral declines already attributed to climate change and further ocean warming locked in, our modelling of the future state of the Great Barrier Reef clearly shows that new solutions will be needed in coming decades. The record ocean temperatures and declaration of a fourth global mass bleaching event in 2024 highlight the increased urgency to prepare and respond to the impact of marine heatwaves. The speed at which climate change impacts are unfolding is alarming. We are in a race against time to protect our coral reefs.

A landmark investment from the Australian Government through the Reef Trust has enabled RRAP to develop innovative restoration interventions to the pilot deployment stage. We have propagated corals with enhanced thermal tolerance and developed methods to deploy them at scale. We have designed and trialled world-first cooling and shading technologies that could protect priority reefs during marine heatwaves. We have also identified how to introduce interventions such as these to the Great Barrier Reef in ways that are acceptable to environmental regulators, Traditional Owners of Sea Country and the broader Australian community.

This report synthesises the advancements made by the program since its inception and how some of the interventions we have been examining are now being tested at scale on the Great Barrier Reef. Continued R&D is essential for achieving the efficacy and cost-efficiency that will make RRAP interventions viable and affordable at the scales required in the future.



TO GIVE OUR REEFS A FIGHTING CHANCE, WE MUST ACT COLLECTIVELY AT A SPEED AND SCALE NEVER BEFORE ATTEMPTED. THIS IS OUR MISSION.

Image credit: SCU

REEF RESILIENCE TOOLKIT

Since inception, RRAP's mission has been to accelerate the translation of scientific discovery and technology innovation to real-world applications, with a focus on increasing scale, improving efficacy and reducing cost. To achieve this goal, RRAP systematically considered the range of possible technology solutions and pursued the development and testing of interventions that had the highest potential to deliver impact at scale and within the window of time available. RRAP developed an integrated program architecture with a culture of knowledge sharing and collaboration that transcends disciplinary silos and translates research and development into real-world benefits.

RRAP aims to deliver innovative, safe, reef solutions at scale. To date, RRAP intervention development subprograms have: identified and developed corals and coral symbionts that can survive at warmer temperatures (Enhanced Corals and Treatments); designed and automated innovative processes and strategies to produce and seed corals at low cost and with high survival (Coral Aquaculture and Deployment); developed and applied new techniques to bank coral sperm and larvae, securing genetic diversity and supporting coral conservation aquaculture (Cryopreservation); scaled up the collection of wild coral spawn before rearing and resettling larvae on priority reefs to assist natural reef recovery processes (Moving Corals); studied coral rubble formation in order to design strategies to stabilise damaged reef substratum prior to restoration (Rubble Stabilisation); developed and trialled innovative seawater spraying techniques to reduce coral stress due to heat and solar radiation (Cooling & Shading).

RRAP cross-cutting subprograms have: developed and applied innovative monitoring techniques to build the fundamental knowledge as to the 'how, where, and when' of natural reef recovery and future interventions (Ecological Intelligence for Reef Restoration); guided investment and action by projecting the condition of the Reef with or without interventions using comprehensive physical, ecological, value and risk modelling (Modelling and Decision Support); translated science to practice by automating innovative technologies, working with government and industry to create new opportunities and build capacity and develop a pathway for adoption of new interventions on a large scale (Translation to Deployment).

The intervention development and cross-cutting subprograms were embedded within work to ensure Traditional Owners and stakeholders, including Reef communities, are better able to benefit from and adapt to the outcomes of interventions by: developing foundational social science, exploring engagement and partnership models, and co-designing and piloting a biocultural value framework alongside targeted investment in Traditional Owner training and capacity building. (Stakeholder and Traditional Owner Engagement, Indigenous Partnerships); evaluating regulatory pathways for legitimate application of interventions at scale (Regulatory and Policy Environment); and through comprehensive appraisal of the social, environmental, cultural and heritage risks associated with potential large-scale use of interventions (Intervention Risk Management).

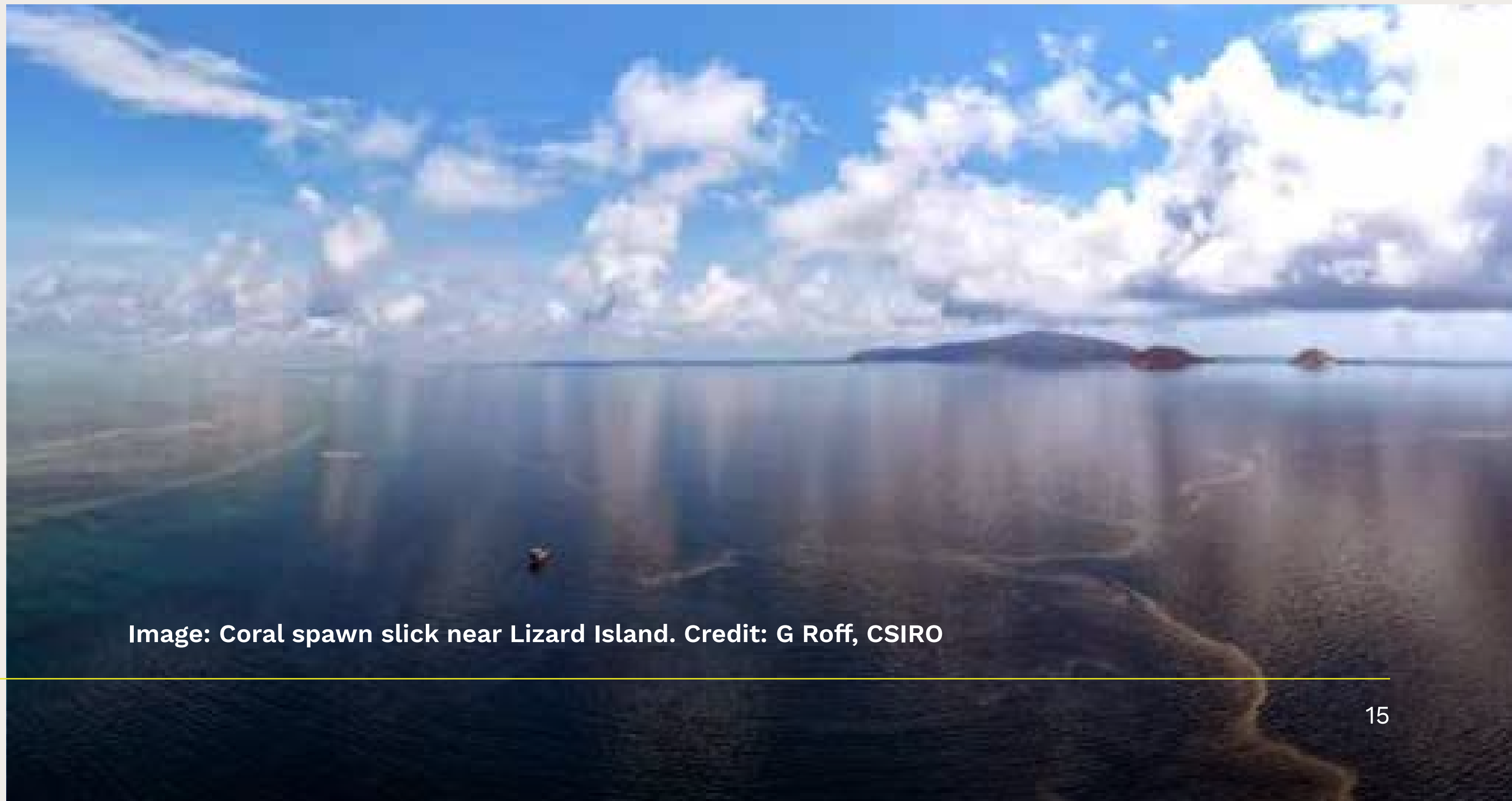


Image: Coral spawn slick near Lizard Island. Credit: G Roff, CSIRO

CASE STUDY: JOINING FORCES TO CREATE COST-EFFECTIVE TECHNOLOGIES

RRAP IS A MULTIDISCIPLINARY PROGRAM THAT INTEGRATES ECOLOGY AND ENGINEERING TO DELIVER SIMPLE, LOW-COST TECHNOLOGY THAT CAN BE EASILY ADOPTED BY TRADITIONAL OWNERS, LOCAL COMMUNITIES, MARINE OPERATORS, AND RESTORATION PRACTITIONERS. THREE FLAGSHIP INNOVATIONS SHOWCASE THIS PHILOSOPHY:

CryoMesh

CryoMesh improves the success of coral larvae cryopreservation and reanimation. It's a lightweight and low-cost mesh that allows coral larvae to be more successfully frozen and then revived. Portable and low-tech, CryoMesh could be used even in remote or resource-limited settings.

Larval seedboxes

Collaboration between modellers and coral ecologists has optimised larval delivery to the reef using a low-cost and easy-to-assemble 'larval seedbox'. In 2024, just five larval seedboxes released ~14 million coral larvae across two hectares of reef, with settlement rates up to 24-times higher than natural recruitment. Larval seedboxes have potential as a practical and scalable tool for coral restoration without needing land-based facilities.

Underwater Bioadhesives

Under RRAP's Coral Aquaculture and Deployment and Rubble Stabilisation subprograms, chemists, earth and material scientists and coral biologists worked together to develop new underwater bioadhesive materials that could help stabilise reef rubble and improve settlement conditions for baby corals. This new adhesive is biodegradable and can replace the use of plastics and cement in reef restoration.

Image: Researcher deploys a SeedBox.
Credit: L. Hardiman, CSIRO

TOGETHER, THESE TECHNOLOGIES ARE INTENTIONALLY DESIGNED TO BE PRACTICAL, ACCESSIBLE, AND SCALABLE, SO THAT SOLUTIONS CAN BE MORE EASILY ADOPTED BY THOSE WHO LIVE NEAR REEFS AND RELY ON THEM.

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PROGRAM OUTCOMES AND IMPACT

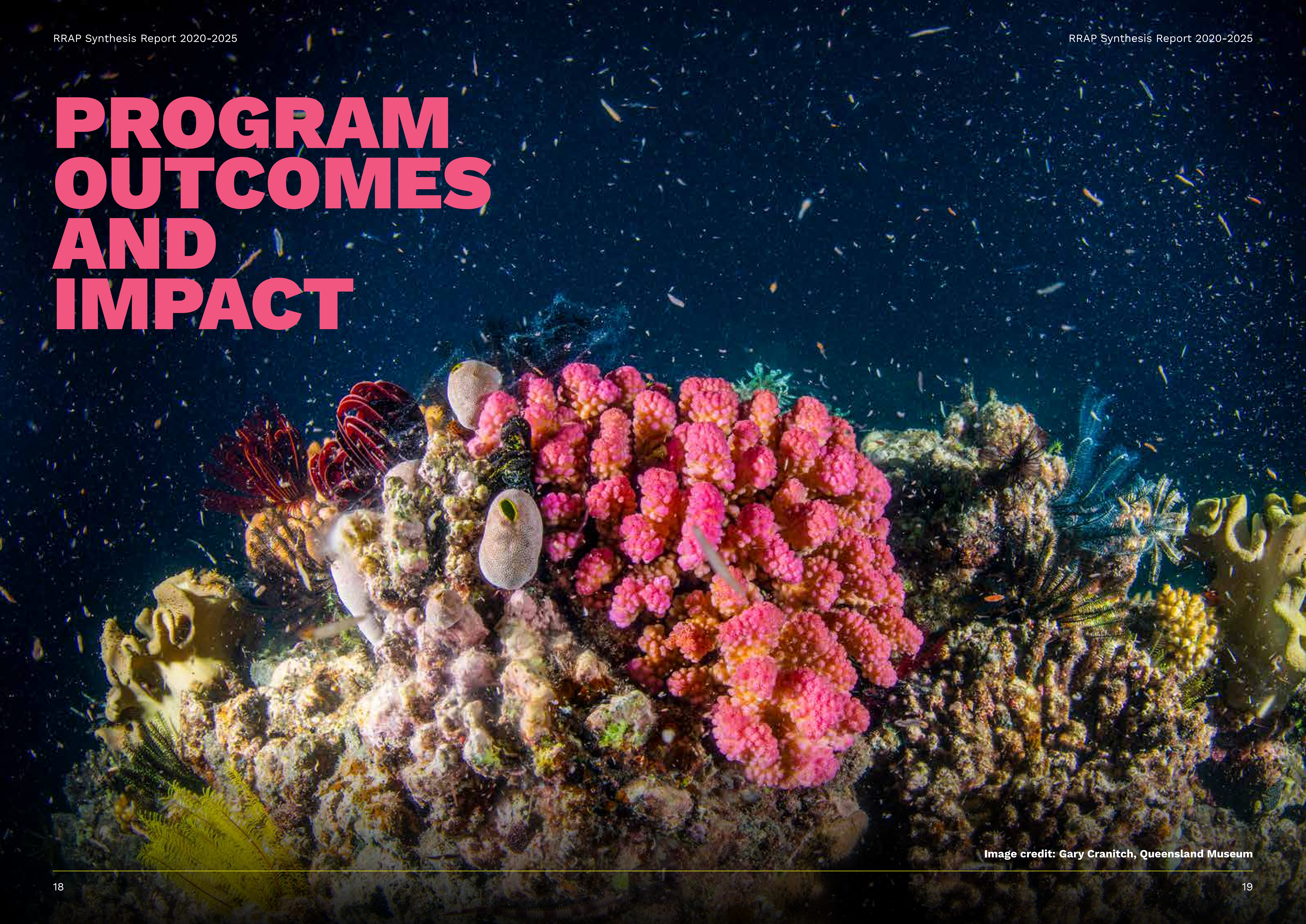


Image credit: Gary Cranitch, Queensland Museum

DESIGN AND OUTCOMES

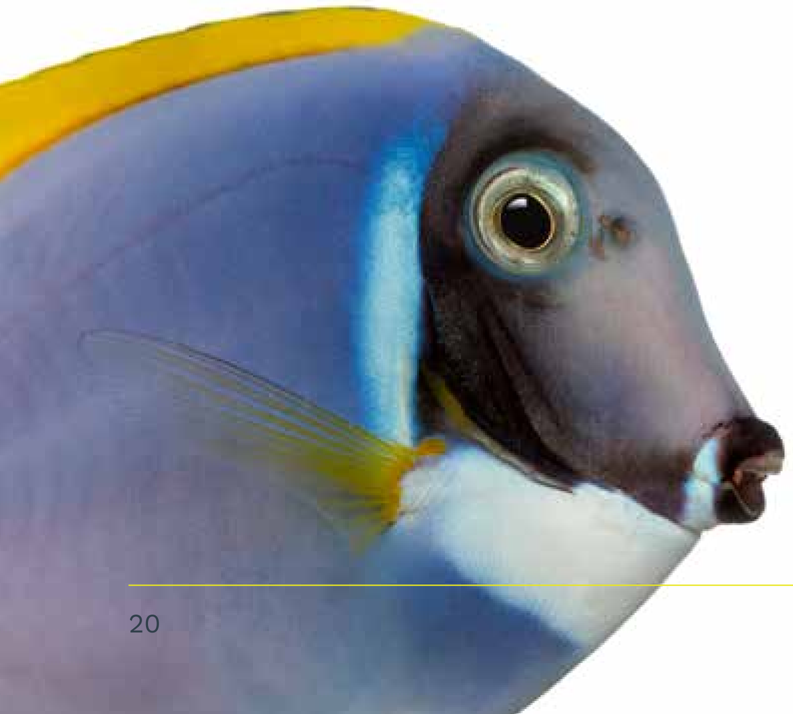
Following the 2016 and 2017 mass coral bleaching events, a consortium of research agencies, universities and non-government organisations proposed RRAP as a 10-year integrated research and development (R&D) program to provide decision-makers with scientifically demonstrated, ecologically-effective, socially-acceptable, technically-feasible and economically-viable options to help the GBR adapt to climate change.

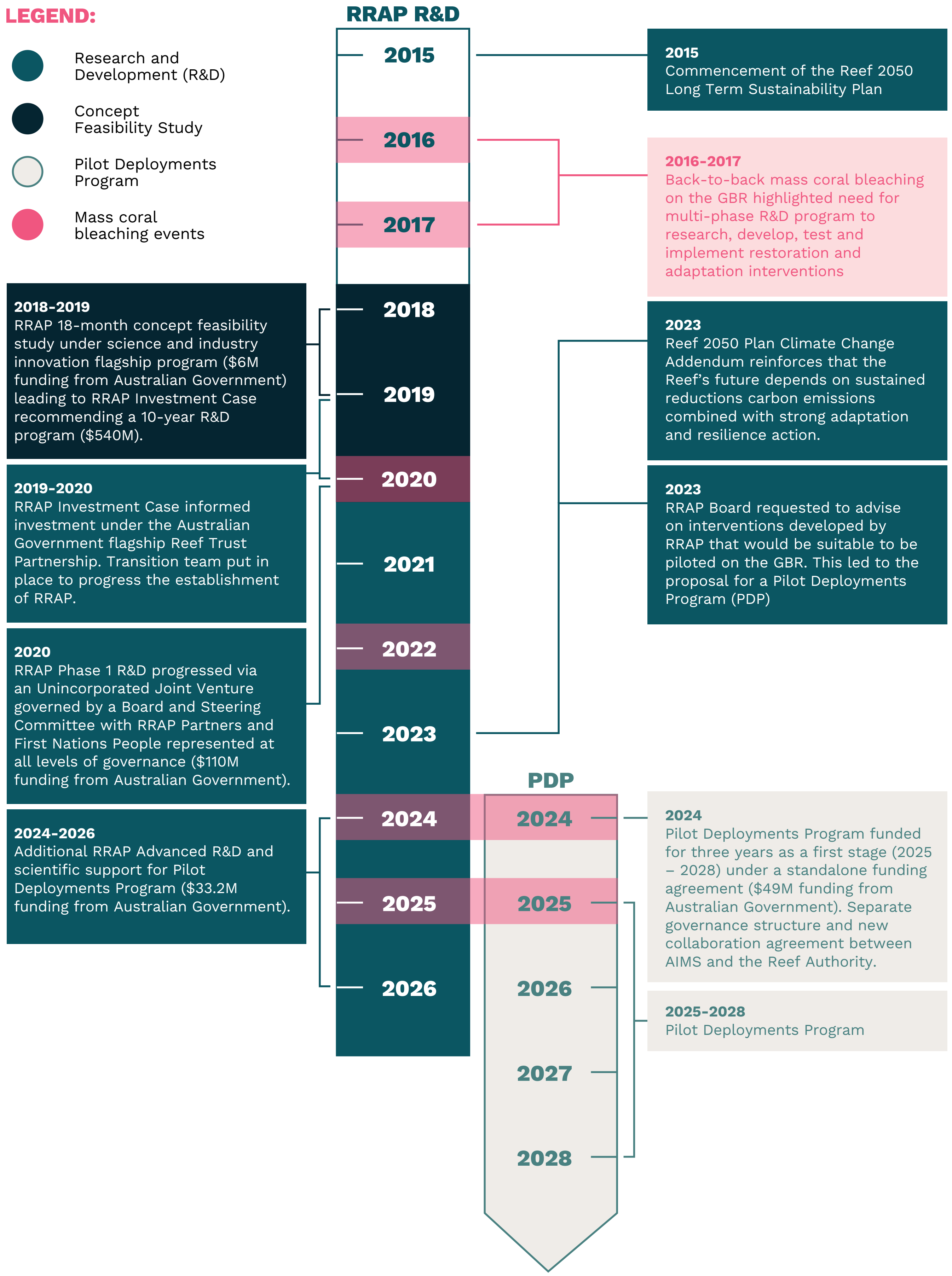
In 2018, the Australian Government funded a Concept Feasibility Study which led to the RRAP Investment Case and a suite of strategic and technical reports. The RRAP Investment Case informed investment under the Australian Government's flagship Reef Trust Partnership. An Executive Committee was formed to oversee the development, negotiation and execution of a Collaboration Agreement to govern RRAP as an Unincorporated Joint Venture (UJV). In parallel, the Executive Committee developed standards and expectations for the engagement of scientists with Traditional Owners and their work on Country.

The RRAP Board was formally established on execution of the UJV Collaboration Agreement in December 2020. The RRAP Steering Committee was established at the same time as well as the Program Management Team (comprised of subprogram leaders and co-leaders). The R&D program was progressed between 2021 and 2024, with regular planning and contracting processes to review status across the portfolio of integrated projects, assess available funding, and vary Project Agreements where required.

In 2023, the Australian Government requested that the Board advise on interventions developed by RRAP that would be suitable to be piloted on the GBR. This led to the Pilot Deployments Program which commenced in parallel with, and was supported by, RRAP R&D between 2024 and 2026. The Pilot Deployments Program is currently funded to 2028.

RRAP INVESTMENT CASE 2019





EVIDENCE THAT INTERVENTIONS ARE NEEDED, WORK AND ARE SAFE

Understand current perceptions and, ultimately, reach alignment between R&D providers, industry, community, Traditional Owners and government

Partnerships developed with Traditional Owners with agreement as to the need for interventions	Identified pathway for regulatory approval to deploy at required scale, location and timing	Stakeholders support the need for interventions, and the timing and methods proposed

Co-designed and co-developed a new **biocultural framework** for Traditional Owners to evaluate reef intervention risks and benefits in their Sea Country. Traditional Owner representation at all levels of RRAP governance and Indigenous Partnerships Team with process for obtaining **Free, Prior and Informed Consent**. Engagement grounded in advice from stakeholders, industry and the reef community. Broad **social support for GBR conservation and intervention research and development** among the Australian public.

SUPPORT BUILDS CONFIDENCE AND RATIONALE FOR INVESTMENT

Establish value-based framework, investment to foster industry and funding for protection, adaptation and restoration of reefs.

Ongoing funding to complete intervention development/ and testing (15–20 yrs)	Project-based deployment funds for operations by Community and industry	Funding for industry to establish and implement new infrastructure and operations

Significant **leveraged investment** into intervention R&D and funding for aligned research. **Additional funding** for the first tranche of scaled deployment of RRAP interventions through the Pilot Deployments Program in **partnership with the Reef Authority, Traditional Owners and industry.** Substantially decreased costs per 1 year old coral deployed on the reef through optimising culture methods, enhanced coral survival and **technological automation.**

Understand the counterfactual, benefits and risk of interventions as a function of type, scale, location and timing of deployment

Manageable risks of deploying at the target scale, location and timing	Reef projected to follow negative trajectory under counterfactual	Interventions provide benefits for reef health and resilience at an appropriate scale

Counterfactual models consistently predict widespread decline in coral cover on the GBR under relevant climate scenarios. Models with realistic incorporation of intervention strategies and tactics predict that **interventions can sustain coral populations** and buffer decline of coral cover. Intervention risk analysis shows that Conservation Aquaculture and Slick Collection and Release (reef-based larval re-seeding) are **low risk at pilot deployment scales**.

R&D into interventions, targeted effects on reef functioning (restoration, adaptation, protection), and approach and scale of deployment

Intervention-specific technology, materials, designs and processes	Intervention-specific deployment tactics accounting for scale and method of deployment	Concept designs for production and deployment at required scale by industry actor

Conservation Aquaculture and **Slick Collection and Release (reef-based larval re-seeding)** have been demonstrated on the reef and are being trialled at scale. **Cryopreservation** has been demonstrated on the reef for coral gametes and there is proof-of-concept for coral symbionts and larvae. A novel **bioadhesive** and **Fogging** have been demonstrated on the reef, and there is proof-of-concept for **Marine Cloud Brightening**. **Coral symbiont with enhanced heat tolerance** have been cultured and inoculated into corals and shown to persist within corals on the reef. There is experimental proof-of-concept for **enhanced heat tolerance for corals**with some aspects validated in the laboratory.

LARGE FIELD TRIALS AND PILOT DEPLOYMENTS BUILD THE EVIDENCE BASE

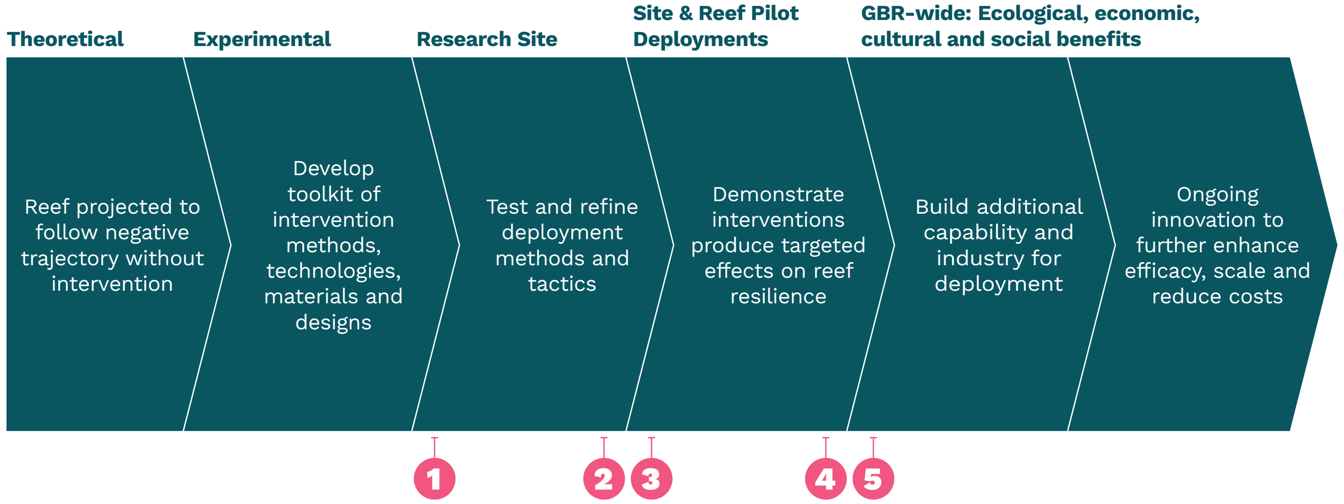
INVESTMENT ALLOWS FURTHER R&D AND DEPLOYMENTS TO OCCUR

RRAP INNOVATION AND LEARNING CYCLE

The RRAP R&D program was designed as an innovation and learning cycle whereby investment into R&D drives innovation of new methods that are subsequently trialled and piloted on the Reef to provide evidence of efficacy. Data, modelling and intervention risk management provides evidence that interventions are needed, work and are safe. This in turn, builds public confidence and social licence for further investment in intervention deployment along with industry- and capability-building. Additional and sustained investment in R&D is needed to achieve the efficacy and cost-efficiency that will make RRAP interventions viable and affordable at larger scales, and deliver the improvements in reef resilience needed as the impact of climate change intensifies.

The central boxes show RRAP achievements and impact to date. In summary, intervention specific technologies, materials and tactics have been designed, developed and tested alongside new coral biology, ecology and evolution data to provide the evidence base for ecological efficacy. Counterfactual modelling, intervention benefits modelling and intervention risk analysis has established that interventions are needed, work and are safe. Collaboration with Traditional Owners, industry, government and regulatory bodies, along with both deep and broad engagement with the reef community and Australian public, has demonstrated support for reef restoration and adaptation research and development. Significant additional investment from government, Traditional Owner groups, industry, research providers, corporate partners and non-government organisations has been leveraged to fund the RRAP mission along with future pilot deployments and reef restoration and adaptation research and development.

PATHWAY TO DEPLOYMENT



1. **Manageable risks of deployment at small site scale underpins regulatory approval for intervention research**
2. **Manageable risks of deployment at moderate (reef) scale underpins regulatory approval for pilot deployments**
3. **Collaborations developed with Traditional Owners and industry for deployment operations**
4. **Stakeholders support the need for interventions and the timing and methods proposed**
5. **Manageable risks of deployment at large scale (GBR-wide) underpins use of interventions in resilience-based adaptive management**

Future operational use of RRAP's toolkit of interventions can be built upon the cycle from theory through laboratory experiments to field testing in RRAP R&D, with ongoing learning through piloting at scale in the PDP. Research to develop and refine the intervention methods, technologies and materials is a critical initial step. Please see pages 25-26 for a technology readiness assessment of RRAP intervention methods.

As intervention methods mature, the transition from experimental proof-of-concept to field-testing 1, and again from field-testing to large scale pilot deployments 2, depends on risk evaluation and regulatory approval. Please see page 27 for risk and regulatory readiness of RRAP intervention methods.

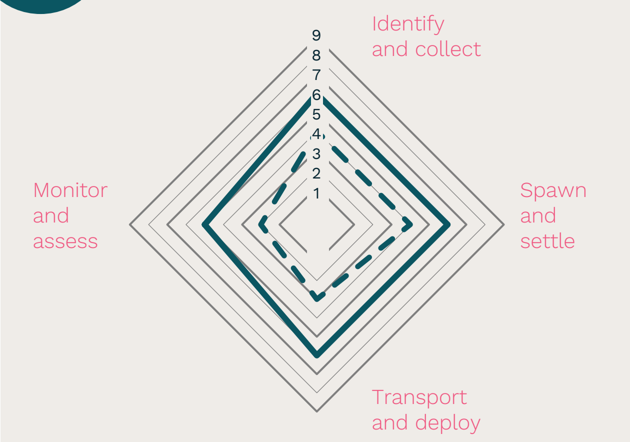
Partnerships with Traditional Owners and industry 3 facilitate broader access to benefit sharing with the community as well as reduced costs for pilot deployments. Please see Indigenous Partnerships and Stakeholder and Traditional Owner Engagement sections for more information.

Demonstrating that interventions produce targeted effects on reef resilience, and making defensible decisions about when, where and how to deploy, requires a mature modelling and decision support suite underpinned by robust ecological, environmental, economic, social and cultural information. Please see page 27 for readiness assessment of RRAP M&DS.

Moving beyond pilot deployments to operational use of RRAP interventions that expands options for reef management requires the support of managing agencies and other organisations who undertake reef stewardship activity. 4 and further assessment of risk linked to the increased spatial footprint of deployment 5. Please see pages 28-30 for RRAP Roadmap to 2040 which outlines key actions to be taken to embed reef restoration and adaptation interventions in the toolkit of management actions being deployed to enhance the resilience of Australia's reefs.

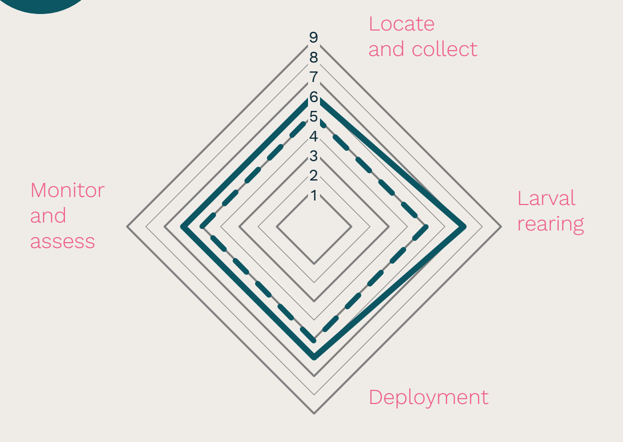
Over the duration of the R&D program, RRAP substantially increased the technology readiness levels (TRL) of 8 intervention methods between 2020 (dashed lines) and 2025 (solid lines). Lines further away from the centre of the plot show increasing technology readiness for scaled deployments on reefs in Australia or other reefs around the world. Two of these methods, conservation aquaculture and reef-based larval reseeding (or slick collection and release), are currently being used in the PDP.

CONSERVATION AQUACULTURE



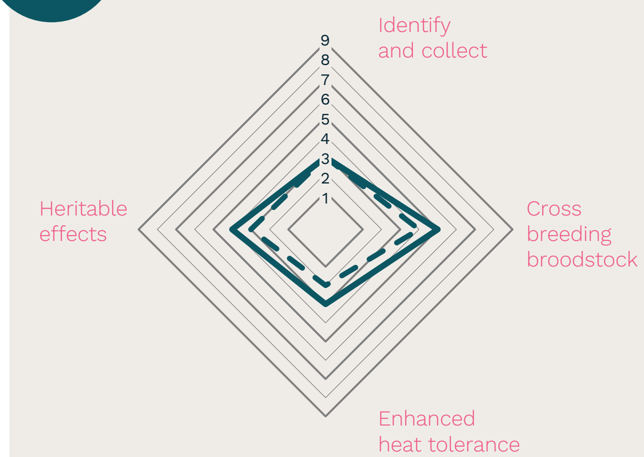
Future R&D focus: Reduced cost per coral, consistent and higher survival, increased coral diversity, rapid assays for pest detection.

REEF-BASED LARVAL RESEEDING



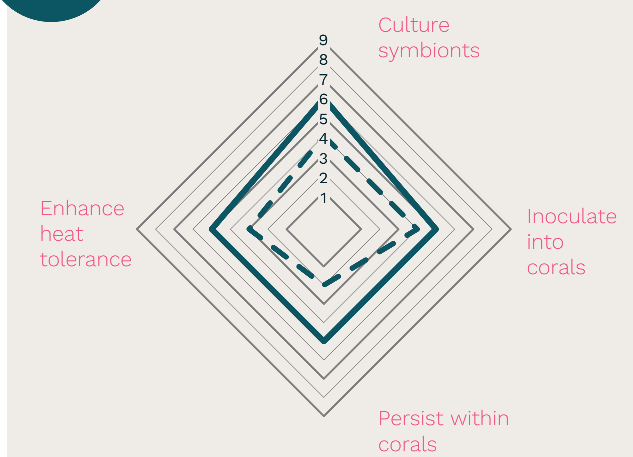
Future R&D focus: Deploying climate-resilient larvae, measuring benefits for reef biodiversity, increasing scale and cost-effectiveness.

CORALS WITH ENHANCED HEAT TOLERANCE



Future R&D focus: Genetic architecture of heat tolerance, selective breeding strategies, rapid phenotyping & genotyping, assisted gene flow.

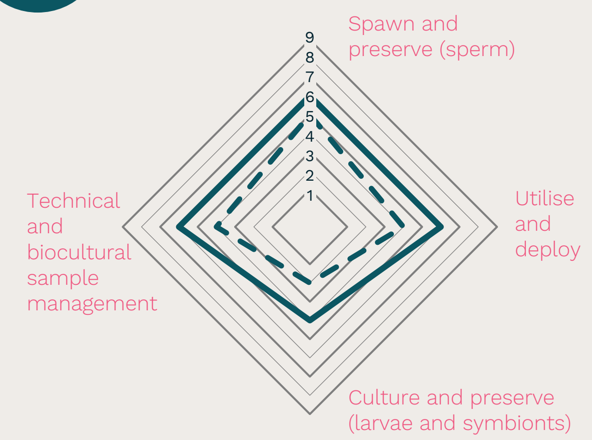
SYMBIONTS WITH EHNANCED HEAT TOLERANCE



Future R&D focus: Environmental spread, stability, effect size and variability in the field, naturally heat tolerant symbionts.

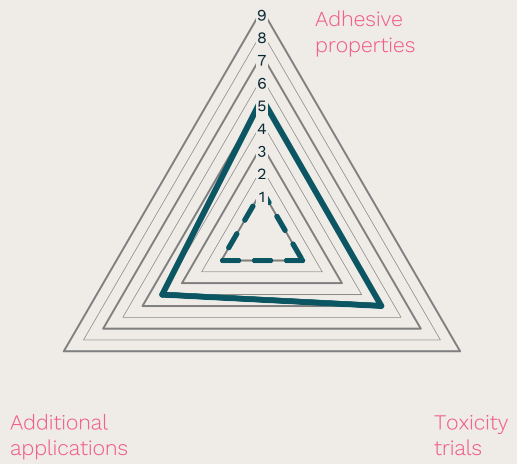
Axes on the plots on pages 25 and 26 show increasing technology readiness levels moving from the centre to the edge of the plot. Numbers correspond to the following descriptions: 1) Foundational principles observed; 2) method concept formulated; 3) proof-of-concept through modelling and/or demonstration of underpinning concepts; 4) method validated in the lab or in land-based trials; 5) method validated on the reef in small scale experiment; 6) method validated on the reef in large field trials; 7) method validated through multi-year field trials; 8) method complete and qualified; 9) method proven viable for full-scale deployment.

CRYOPRESERVATION

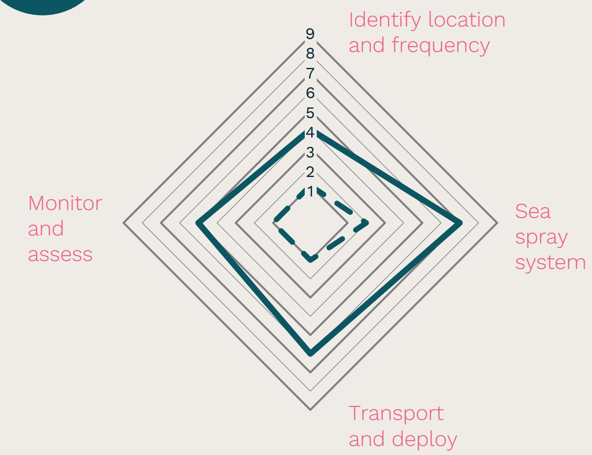


Future R&D focus: Diverse coral larvae and symbiont cryopreservation, high-throughput methods, cultural biobanking protocols.

BIOADHESIVE

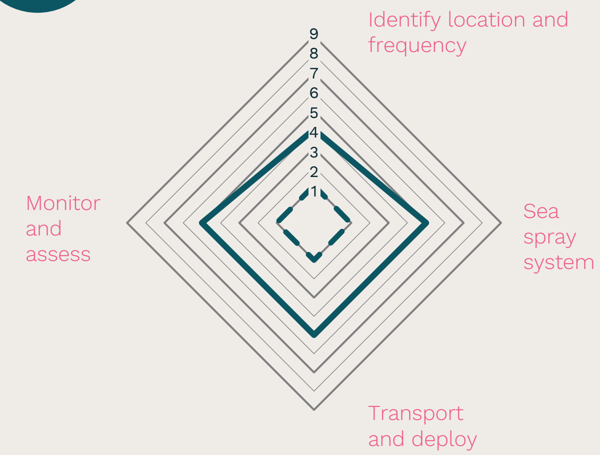


FOGGING

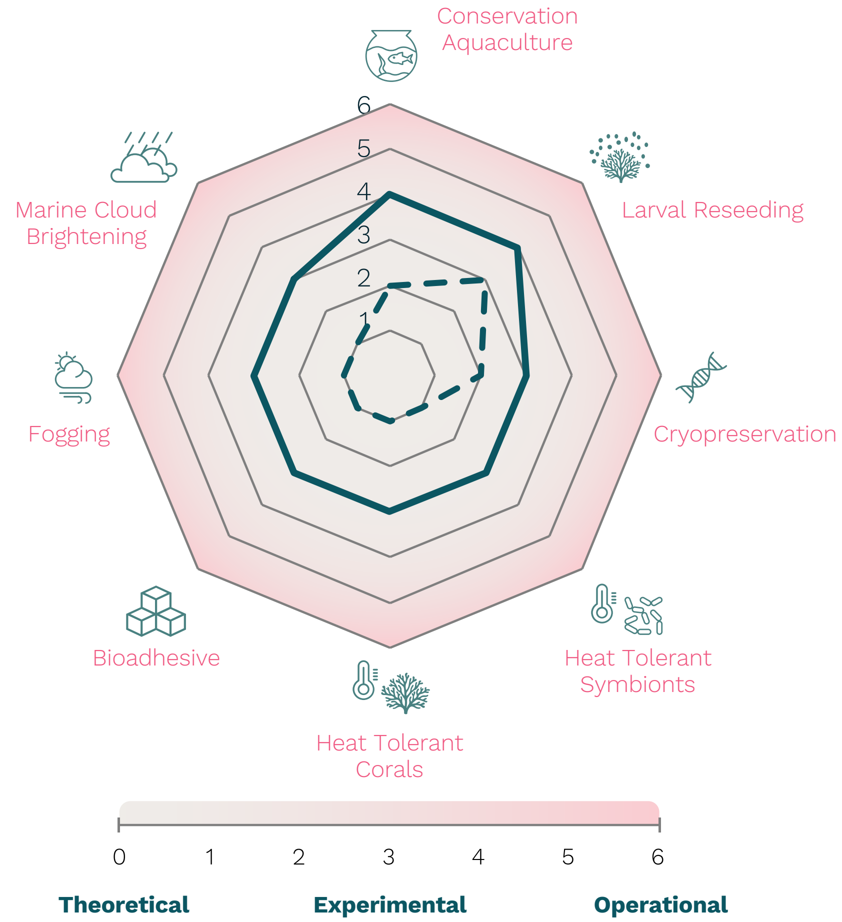


Future R&D focus: Reef scale pilot testing during bleaching event, automation and cost reduction, use of biogenic oils.

MARINE CLOUD BRIGHTENING

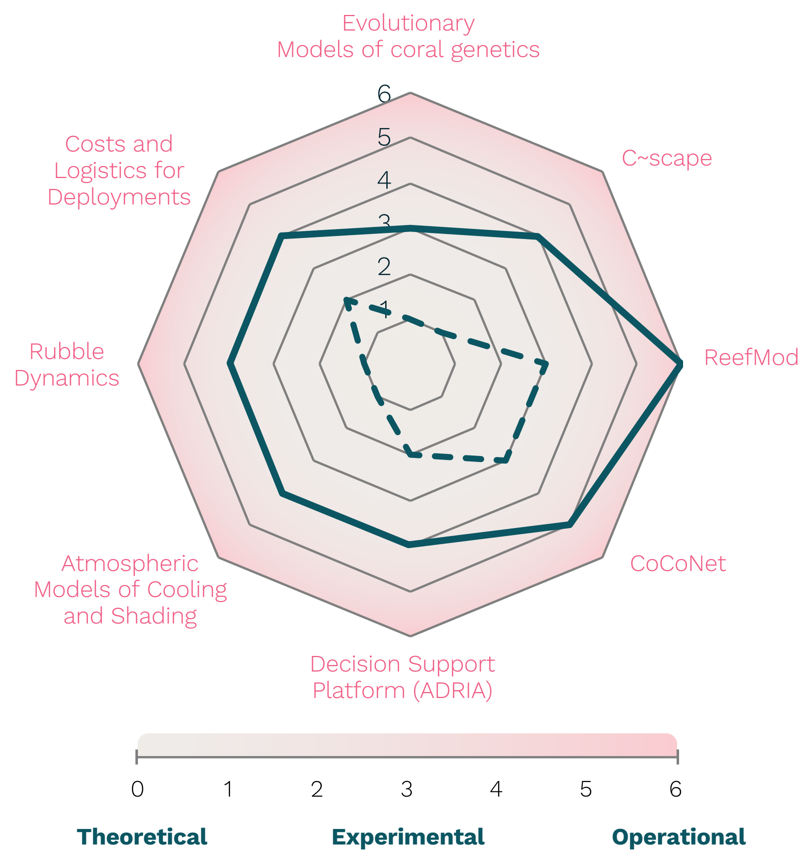


Future R&D focus: Improved nozzles for aerosol production, closely linking upscaled experiments with models to improve predictability.



INTERVENTION RISK AND REGULATORY APPROVAL

1. Intervention is insufficiently defined for meaningful risk assessment
2. Risk screening to identify hazard types and pathways
3. Regulatory approval for research-scale activities
4. Conditional approval for pilot deployments
5. Regulatory approval for operational use on the GBR
6. Intervention embedded in adaptive management with continuous learning and improvement



RELATIVE MATURITY OF RRAP MODELLING AND DECISION SUPPORT SUITE

1. Conceptual or exploratory for hypothesis framing
2. Broad option screening and awareness raising
3. Scenario evaluation to understand system responses under uncertainty
4. Decision analytics to compare and prioritise interventions
5. Operational support of real-world management actions
6. Supporting continuous improvement of decisions through learning

REEF RESTORATION AND ADAPTATION ROADMAP TO 2040

Globally, emissions reduction efforts are occurring too slowly to protect reef systems to 2040 and beyond. Despite the significant progress that RRAP has made, current coral seeding and larval reseeding interventions lack the thermal tolerance enhancement that is needed as waters continue warming. Moreover, the scale of interventions remains too small to match the magnitude of climate impacts. Research innovation is needed to decrease the costs of interventions and to optimise production and development methods that maximise the survival of deployed baby corals throughout their lifecycles. This includes technological and engineering research and development along with fundamental research to understand natural reef recovery rates in different environments and how baby corals from heat-tolerant parents disperse among reefs over time.

Scaling existing interventions without additional R&D would yield mixed results. Current methods could establish social licence for interventions and demonstrate quantifiable return on investment. Deployments could protect some high-value sites through repetitive actions and training programs could build workforce capacity.

However, without enhanced thermal tolerance, deployed corals would remain vulnerable to recurring marine heatwaves. Cost constraints around coral grow-out and deployment would persist thereby limiting pace of uptake and applicability on a larger scale.

System-level implementation of reef interventions requires unification of intervention R&D, piloting and deployment under a single program aligned with both state and federal priorities. Regional hubs should be established to coordinate place-based actions while maintaining focus on GBR-wide and Traditional Owner priorities. Monitoring programs and modelling frameworks must be shared across all Reef-associated conservation and management activities. An innovation-action learning model should be developed and applied instead of sequential translation of R&D-to-deployment. Collaboration amongst scientists, managers, Traditional Owners and stakeholders will be critical to the success of such a model. Finally, adaptive and agile regulatory frameworks are required, and it is essential to define a social contract that allows calculated risk-taking.

In 2040, a radically successful reef restoration and adaptation program would feature:

Technological Capability: Technologies to increase effectiveness by 10-fold at 10% of current costs. Thermal tolerance achieving 10-15 DHW capacity.

Operational Model: Dual-mode operations combining ongoing resilience-building industry with emergency response capability. Decentralised, community-accessible deployment operations led by Traditional Owners. Trigger-based proactive interventions with sophisticated decision support systems.

Industry and Finance: Thriving restoration economy with equitable Traditional Owner access. Multiple SMEs driving innovation and cost reduction. Blended public-private investment based on outcomes and underpinned by sustainable financing.

Governance and Coordination: Improved sharing of learnings and technologies across the Pacific region. Australia-wide approach, including harmonisation and streamlining of regulatory pathways. Transparent, equitable decision-making with public accountability.

Knowledge and Capacity: Two-track science supporting new interventions and adaptive management. Rapid innovation-to-deployment cycles. Integrated monitoring, modelling and risk decision systems.

Social and Ecological Outcomes: Healthy, growing reefs providing broad social-ecological benefits. Strong First Nations communities on Country with cultural and economic alignment. Sustained biodiversity and strengthened reef-economy connections supporting regional development.

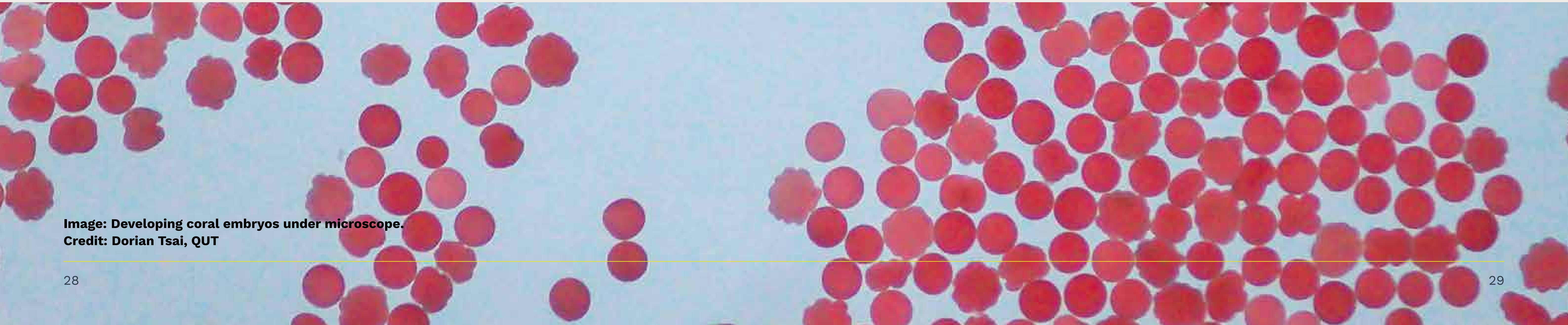


Image: Developing coral embryos under microscope.
Credit: Dorian Tsai, QUT

CRITICAL GAPS

Emissions reduction too slow	Insufficient thermal tolerance	Intervention scale too small	Fragmented operations and capacity shortfall	Limited access to Sea Country	Restricted funding and resources

2025-2030 Breaking Existing Limitations

Technical Advances

- 5-10DHW heat tolerance
- Increased efficacy
- Integrate modelling, risk monitoring & decision support
- Ongoing research and innovation.

System Integration

- Unite R&D and deployment
- Establish regional hubs with TO groups
- Coordinate with COTS and water quality actions
- Joint state-federal approach
- Embed biocultural lens in Reef management.

Foundation Building

- Demonstrate return on investment
- Build social licence
- Engage Tourism sector
- Adaptive regulatory framework
- Embed Cultural Values in practice
- Include indigenous pedagogies
- Determine risks and benefits.

2030-2035 Bridging to Scale

Technical Breakthroughs

- 10-15DHW heat tolerance
- 10x efficiency gains
- Cost reduced to <$1/coral
- Energy efficient cloud brightening
- Improve decisions about where to deploy to maximise benefits.

Industry Development

- Restoration economy emerges
- TO enterprise and workforce development with cultural governance
- Train workforce
- Multiple SME's operating
- Strengthen Ranger Capacity.

Finance Evolution

- Outcome-based funding
- Future funds established
- Nature markets active
- Public-private blended finance
- Broader social and economic benefits to community and TOs.

2035-2040 Transformed System at Scale

Operational Excellence

- 100M surviving corals at 1 year post deployment
- 100 km2 cloud brightening
- 15 DHW thermal tolerance
- Emergency response ready that includes TO workforce.

Integrated Governance

- Australia-wide coordination
- Pacific-wide shared learnings
- TO-led operations
- Harmonised regulations
- Transparent decisions inclusive of TO knowledge, values and practices.

System Outcomes

- Healthy growing reefs
- Thriving Reef economy
- Global tech leadership
- Cultural preservation
- Community-led stewardship
- TO-led and/or co-managed actions.

CRITICAL SUCCESS ENABLERS

Integration:	Unification:	Thermal Tolerance:	Governance Evolution:	Social Contract:	Inclusivity:
Break down silos between R&D, deployment and Reef management	Embed cultural heritage within environmental values	Critical for long-term coral survival under climate change	Transition to anticipatory and adaptive modes of governing	Implement shared risk-taking and benefit-sharing model	Amplify TO leadership, embed Traditional Ecological Knowledge with intergenerational training and knowledge sharing

Image credit: Jodi Salmond, Reef Check Australia

CASE STUDY: PILOTING RRAP INTERVENTIONS AT ECOLOGICALLY RELEVANT SCALES

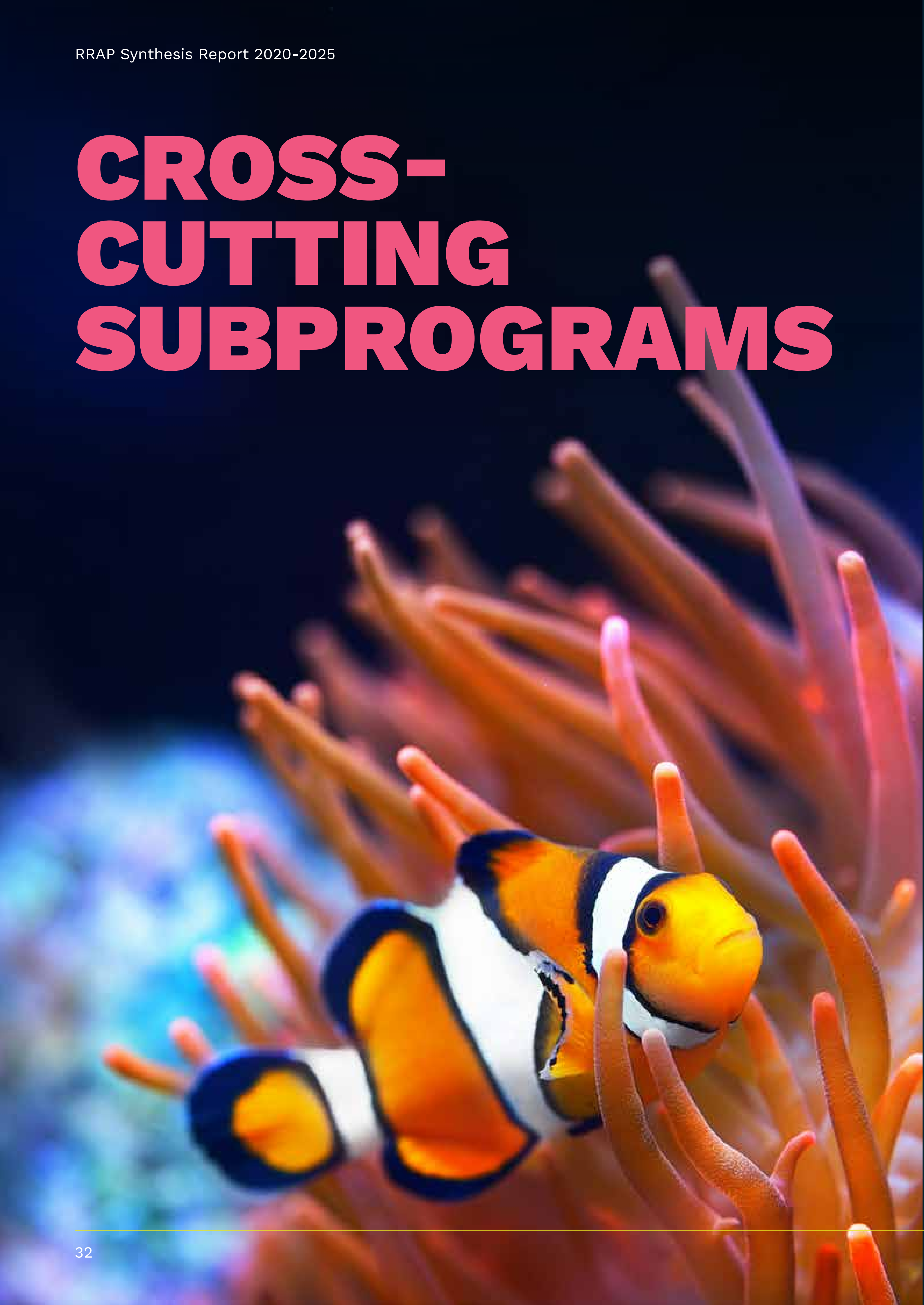
The Pilot Deployments Program (PDP) aims to further demonstrate and improve the feasibility, cost efficiency, scalability, safety and acceptability of RRAP interventions.

The PDP is the operational testing component of RRAP that is deploying a subset of RRAP interventions at scale – a critical step on the path to adoption and scaling of interventions on the Great Barrier Reef.

The Program is led by the Australian Institute of Marine Science in collaboration with the Reef Authority, RRAP Partners and activating reef delivery partners.

As interventions advance in their technology readiness, they can be transitioned into the PDP for larger operational trials. In the future, a structured feedback loop should then return information to research teams, allowing them to refine, adapt, or scale technologies based on new knowledge of intervention efficacy. This iterative information flow can ensure continuous improvement and accelerate intervention development.

The RRAP R&D Program recommended two types of interventions for pilot deployment in 2025, coral seeding (see CAD subprogram) and larval re-seeding (see Moving Corals subprogram). These interventions were selected based on their more advanced technology readiness and modelled potential benefits to the Reef.



CROSS-CUTTING SUBPROGRAMS

STAKEHOLDER AND TRADITIONAL OWNER ENGAGEMENT

ENSURE THAT DECISIONS ABOUT INTERVENTIONS ALIGN WITH PUBLIC PERCEPTIONS, AND ARE SOCIALLY AND CULTURALLY RESPONSIBLE

The Stakeholder and Traditional Owner Engagement subprogram ('ENG') designed and evaluated a best-practice engagement program to meet RRAP, community, Traditional Owner and stakeholder needs.

Between 2020 – 2025, **ENG** focused on three main goals:

- Understand **public perceptions of reef restoration and adaptation** including views about risks, opportunities and benefits arising from intervention research and development.
- Design and evaluate **best-practice, place-based, engagement** opportunities for GBR communities and the public.
- **Involve stakeholders, GBR Traditional Owners and communities** in co-design, evaluation and adaptive management of the subprogram.

Throughout Phase 1 of RRAP, ENG worked closely with the Regulation subprogram, the Intervention Risk project, and with the six Intervention Development subprograms, to help ensure that decisions about interventions are socially and culturally responsible, and legitimate to stakeholders, rights-holders, reef managers and the public. Key outcomes from the subprogram included: new understanding of social, cultural and economic risks and opportunities to inform intervention technology evaluation and design; critical knowledge to leverage co-benefits from research and possible future deployment so that people are better able to benefit from and adapt to the outcomes of interventions; foundational social science knowledge and novel engagement, partnership and governance models that have enhanced stakeholder participation and community support.

GOAL AND SPECIFIC OBJECTIVES

	Achievement within project scope
Understand public perceptions of reef restoration and adaptation	
Track broad public sentiment using a biennial national survey	
Assess Traditional Owner, community and stakeholder perceptions	
Identify opportunities, risks and benefits to different groups	
Design and evaluate best practice, place-based engagement	
Scope and support the development of a regional multi-stakeholder platform	
Explore cross-sector partnerships for future scaling and co-benefits	
Co-design and co-develop biocultural assessment framework with TOs	
Facilitate two-way knowledge exchange and deliberation with communities	
Design and implement a collaborative monitoring pilot for coral recovery	
Evaluate and co-design RRAP engagement and adaptive management	
Establish a reef-wide Stakeholder Advisory Group	
Develop a framework to evaluate stakeholder and community engagement	
Assess the restoration policy system through a Reef Regulators Forum	
Identify effective pathways for reef restoration governance on the GBR	

CASE STUDY: KNOWLEDGE THROUGH PARTICIPATION

Reef restoration and adaptation is not solely a scientific and technical challenge; it also demands consideration of social, cultural, and economic feasibility to ensure interventions are widely accepted and can legitimately be adopted. Yet, prior to 2019, there was limited understanding of the human dimensions of reef restoration and adaptation and its implementation.

In response, RRAP has built a suite of new engagement platforms to generate new knowledge on best practice and underpin operational delivery. These initiatives create new spaces for stakeholders to be heard, informed, and involved, and they help build the foundations for shared stewardship of the intervention toolbox over time, reinforcing the need for collaborative processes that value trust and collective learning as essential to best practice.

Reef Regulators Forum: A bi-monthly platform bringing together key government agencies to align regulatory responses, share real-time updates, and explore implications of restoration science for the Reef. The forum has become a key mechanism for institutional coordination and cross-agency learning.

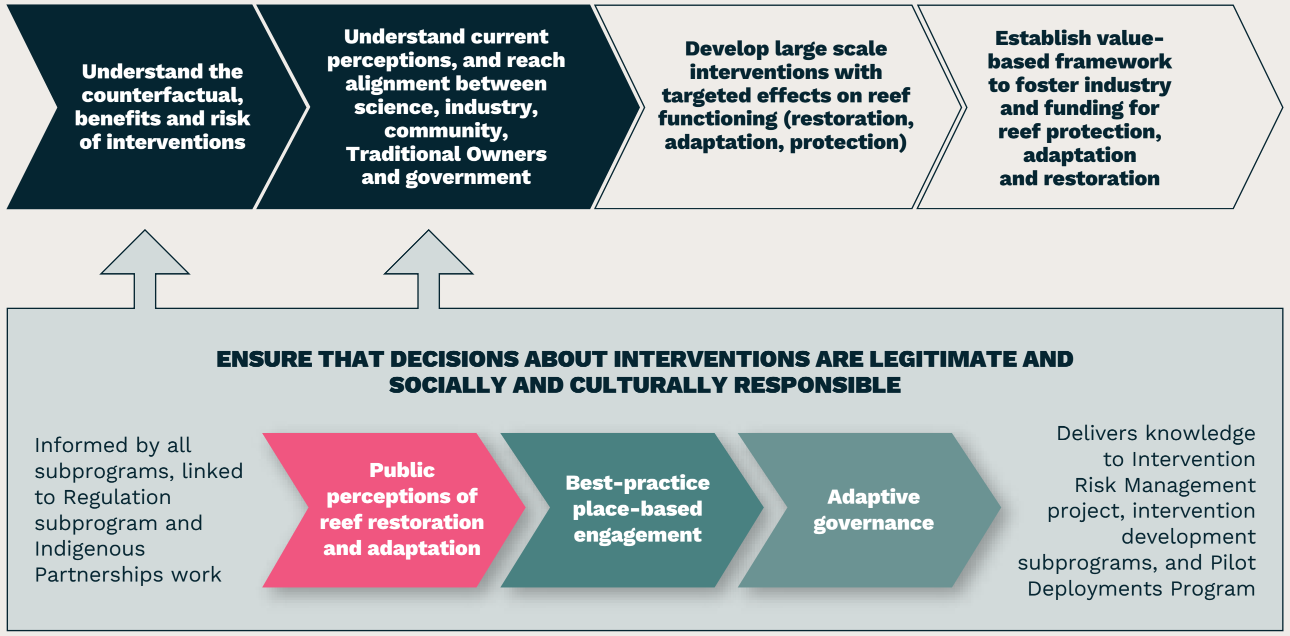
Community Panels: Panels were designed and run to engage the Reef community in Townsville and Cairns regions and provided structured opportunities for two-way dialogue to ensure that community values and perspectives informed RRAP research. These panels supported mutual learning, enabling participants to explore the risks, benefits, and uncertainties associated with emerging technologies.

Cairns-Port Douglas Reef Hub: The Reef Hub is an open collaborative network that connects people to share, learn, and pilot new collaborative approaches to care for reefs in the face of climate change. The Hub supported RRAP to connect to real people and real places and build capacity through the collaborative monitoring project.

Stakeholder Advisory Group: A forum including Indigenous Australians, restoration practitioners, marine industry, and community leaders to identify the ethical, cultural, and economic dimensions of proposed interventions. This group has offered critical external perspectives on the potential benefits and risks of RRAP interventions, and helped design how the program will engage stakeholders in future phases

Image: Members of RRAP's Stakeholder Advisory Group with members of RRAP's Translation to Deployment subprogram. Credit: Annah Piggot-McKellar, QUT.

At a Glance



Public perceptions of reef restoration and adaptation

Surveyed >5000 Australians and showed that most Australians believe climate change is negatively affecting the GBR, and they support measures to reduce threats and scale-up restoration actions.

Conducted 140 semi-structured interviews and identified six key domains of concern to Traditional Owners and stakeholders about reef restoration and adaptation: Indigenous Partnerships, Distributional Equity, Reef Outcomes, Community Engagement, Program Sustainability, and Unintended Consequences.

Analysed survey and interview responses to reveal that transparent and inclusive approaches to intervention research are critical to social acceptance. People's belief that environmental Impacts can be identified and tested influenced their support for interventions.

Applied knowledge and outputs from public perceptions research to the social and cultural risk assessment for the Pilot Deployments Program.

Best-practice place-based engagement

Scoped and supported the development of the Cairns Port Douglas Reef Hub with >50 active members as a multi-stakeholder platform for engagement

Found that stakeholders and community members envisage active roles in intervention research and deployment including educational, commercial, creative, capacity-building & information-sharing.

Facilitated deliberation between community members and scientists that enhanced trust and awareness and recognised diverse yet resolvable views on intervention benefits and risk.

Biocultural Framework co-designed as an Indigenous-owned decision support tool for Traditional Owner groups to assess risks and opportunities in intervention research and deployments

Identified that there is some unmet demand among restoration practitioners to have access to results from RRAP field studies and pilot deployments.

Adaptive governance

Identified governance pathways with clear roles, responsibilities, decision-making, and delivery mechanisms, to guide future RRAP interventions

Convened Regulators Forum to discuss policies, regulations and adaptation activities, thereby strengthening partnerships for intervention decision-making

Developed and applied a Monitoring, Evaluation and Learning Strategy to assess areas for improvement in engagement.

Built recommendations for best practice engagement and program governance that identifies social contextual factors affecting the acceptability of interventions for the GBR.

Convened a Stakeholder Advisory Group to guide strategic directions for engagement about reef interventions.

CASE STUDY: AUSTRALIAN PERSPECTIVES ON REEF INTERVENTIONS

At RRAP's inception, there was little comprehensive baseline data on Australian public attitudes toward large-scale interventions, nor on the factors shaping support, trust, and perceived risk. This limited the ability of policymakers and reef managers to anticipate community responses, design effective engagement strategies, and understand social licence for emerging approaches.

RRAP's biennial national surveys work to address this gap, trying to understand how Australians evaluate risks and benefits, the role of trust in governance and regulation, and how perceptions differ between the national population and communities living close to the GBR.

The results establish a robust social baseline, showing strong public recognition of the GBR's value and widespread support for action to protect it, alongside nuanced views about governance and intervention risk. While respondents expressed some uncertainty about trusting government, confidence in regulation and research remained high, and support increased where decision-making was seen as fair, inclusive, and responsive to community concerns.

Overall, the vast majority of Australians support or would approve novel approaches to sustaining the GBR, but there are clear differences in perceived value and risk across intervention types. Together, these findings provide critical evidence to guide future policy, regulatory decisions, and public engagement, enabling more informed and socially responsive management of the GBR.

SNAPSHOT OF 2024 BIENNIAL REEF INTERVENTIONS SURVEY RESULTS

69%
Are concerned or very concerned about GBR health

78%
Believe climate change is affecting health of the GBR

88%
Accept novel actions to help reefs adapt to climate change

82%
Trust science to provide solutions to help repair the Reef

UNDERSTAND PUBLIC PERCEPTIONS OF REEF RESTORATION AND ADAPTATION, AND OPPORTUNITIES TO DELIVER COMMUNITY AND STAKEHOLDER CO-BENEFITS

OBJECTIVE	ACHIEVEMENT
Assess public perceptions & sentiments toward reef restoration & adaptation intervention research	Revealed that the majority of Australians believe that climate change is negatively affecting the GBR, and they strongly support measures to reduce threats and upscale restoration actions (1, 2). People's belief that environmental impacts can be identified and tested was associated with their level of support for interventions. Perceptions that interventions are ethical and safe enhanced perceived feasibility and impact (3). The Australian public had complex emotional responses to different novel technological approaches to reef intervention. Technologies to protect the Reef tended to reduce negative emotions but without fostering much optimism, restorative interventions intensified both concerns and hope, and adaptive technologies provoked the most polarised reactions with some viewing them as risky, while others saw them as promising (4). Transparent and inclusive approaches to intervention research are critical to maintaining social acceptance.
Understand stakeholder perceptions of reef restoration and adaptation research	Demonstrated that most Reef community members agree that novel interventions are needed to address threats to coral reefs. However, they also believe in the importance of collective action at local and global levels, and in meaningful Traditional Owner and stakeholder involvement in the development and deployment of novel interventions. Reef community members share two common storylines about the future of the GBR (5). The first and dominant storyline is articulated as a probable future of precarity and loss but with hope for alternative possibilities wherein collective action and technologically assisted adaptation moderate loss. The second and less dominant storyline articulates a probable future of continued balance in the Reef wherein technologically assisted adaptation interferes with and disrupts that balance. Community and public support or interventions can be enhanced by forms of public engagement that allow co-creation of ethically grounded adaptation pathways (6).
Understand the distribution of opportunities, risks and benefits arising from intervention research and implementation.	Developed a conceptual framework for understanding social risk in relation to threats to individuals and communities, threats to First Peoples, threats to businesses or project implementation, possibilities for amplified social vulnerability, and risk perceptions. The six key domains of concern to Reef Traditional Owners, stakeholders, and members of the public are: Indigenous Partnerships, Distributional Equity, Reef Outcomes, Community Engagement, Program Sustainability, and Unintended Consequences (7).
Evaluate potential adverse outcomes of interventions.	Developed and applied social, cultural and economic impact assessment framework (8) to assess risks associated with the RRAP Pilot Deployments Program. The most frequently mentioned potential adverse outcomes were failure to achieve desired ecological outcomes, and to secure ongoing funding for restoration and adaptation research and implementation (7).
Identify opportunities to incorporate community rights, interests and capabilities in R&D activities, deployment plans and decision-making processes.	Demonstrated that engagement of community members in restoration and adaptation efforts has positive outcomes, leading to increased public support for meaningful action on climate change (9). The consultative risk assessment process developed by RRAP and currently being used in the RRAP Pilot Deployment Program, is an important route for incorporating community rights, interests and capabilities into intervention decision-making. The RRAP Modelling and Decision support suite also incorporates aspects of economic and social risks and benefits.

DESIGN AND EVALUATE BEST-PRACTICE, PLACE-BASED, ENGAGEMENT FOR DELIBERATION ON INTERVENTION RISKS, BENEFITS AND SCENARIOS.

OBJECTIVE	ACHIEVEMENT
Scope and support the development of a regional multi-stakeholder platform	Contributed to the scoping, design and mobilisation of the Cairns Port Douglas Reef Hub as a multi-stakeholder platform for place-based engagement in partnership with James Cook University and the Reef Trust Partnership's Community Partnership Program (10). The Hub operated successfully from 2019-2025 with >50 active members and provided an important interface for the program in Far North Queensland with local practitioners and researchers. It was the primary partner for the collaborative monitoring pilot.
Explore cross-sector partnerships for future scaling and co-benefits.	Identified that local stakeholders and community members envisage several roles they might play in intervention research and deployment in the future (11). These roles were not restricted to on-water activities but, instead, included educational, commercial, creative, capacity-building, information-sharing and other potential roles (12). Also applied new methods to engage regional stakeholders in a site selection process for pilot deployments of RRAP interventions (13). Identified that there is some unmet demand among restoration practitioners to have access to results from RRAP field studies and pilot deployments. Forward demand for diverse and meaningful participation is high and there is considerable opportunity to build and strengthen a constituency for scalable coral restoration and adaptation interventions.
Co-design and co-develop biocultural assessment framework with Reef Traditional Owners	Equipped Traditional Owners with culturally appropriate decision support tools to assess concerns with prospective use of interventions in their Sea Country (14). The Biocultural Framework (and associated guidelines (15)) have been co-designed and developed as an Indigenous-owned decision support tool (including recognising Indigenous Cultural and Intellectual

	Property (ICIP) of the Framework itself). The framework adopts a strengths-based approach to assessing opportunities for Reef Traditional Owner groups to partner in research and development, pilot deployment and future industry development.
Facilitate two-way knowledge exchange and deliberation with Community	Established and operated two regional community panels in the Townsville and Cairns regions that engaged >30 community members and RRAP scientists in deliberation about the science and its implications over a two-year period (16). Identified that providing opportunities for two-way dialogue increased transparency, joint-learning and largely confirmed support for RRAPs ambition and research. Facilitated deliberation between panel members and RRAP intervention scientists was found to enhance trust, awareness, and understanding in both groups of scientific intent and risks. Moreover, fostering deliberation recognised diverse yet resolvable views on risks and their management.
Design and implement a collaborative monitoring pilot for coral recovery	Co-designed and piloted a collaborative monitoring process for coral settlement devices with local stakeholders. Demonstrated that reef tourism operations and demonstration sites can enhance stakeholder and public understanding and acceptance of restoration initiatives (10). New skills and capabilities developed among partners from the training and monitoring activities and are now being applied in other projects. Concerns about the use of coral seeding devices were generally low and were significantly lower among Reef visitors who observed them at reef site(s). Reef visitors' observation of coral seeding devices at tourism sites did not affect their overall trip satisfaction, their perceptions of the Reef's beauty, or their level of concern about the future health of the Reef (17).

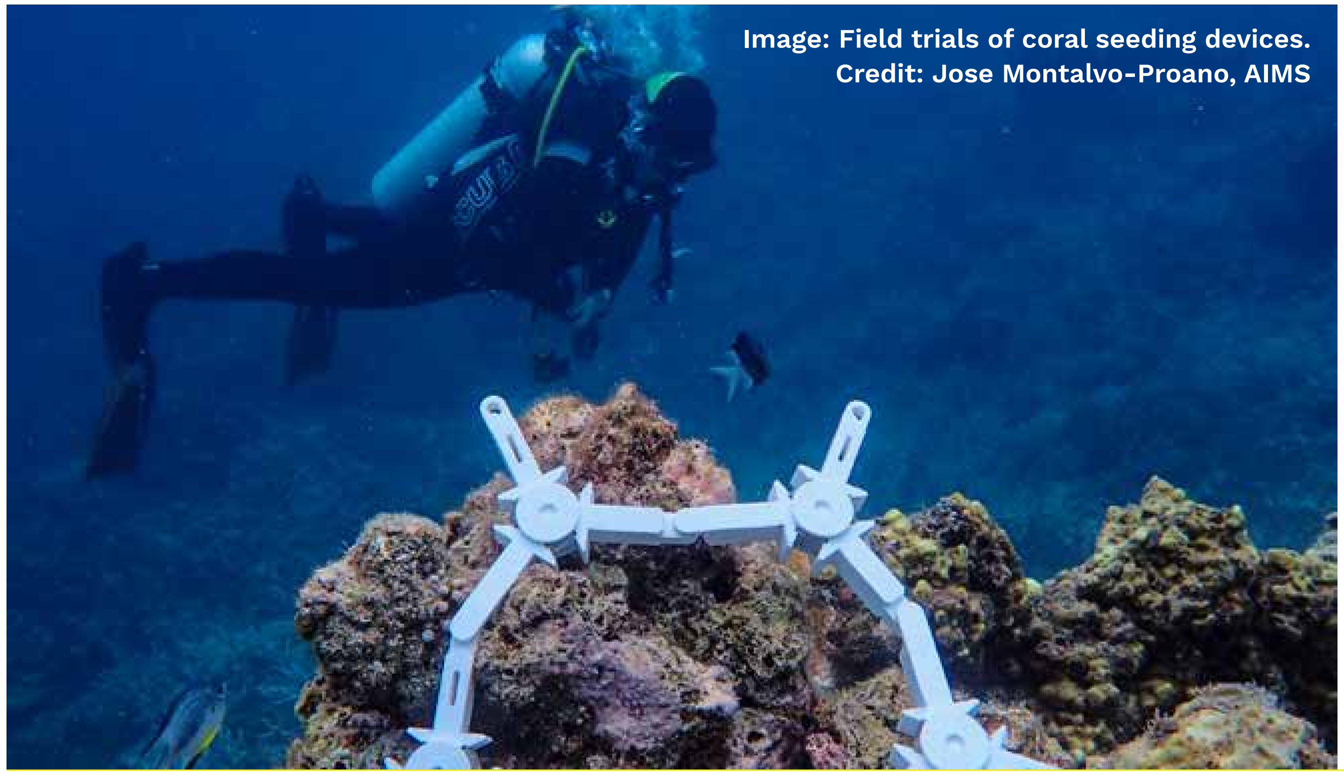


Image: Field trials of coral seeding devices.
Credit: Jose Montalvo-Proano, AIMS

ADAPTIVE GOVERNANCE AND LEARNING TO ENABLE EFFECTIVE DECISIONS AND OUTCOMES FOR THE REEF, ITS STAKEHOLDERS, AND TRADITIONAL OWNERS

OBJECTIVE	ACHIEVEMENT
Involve stakeholders and GBR Traditional Owners in the co-design of RRAP engagement research.	Established a reef-wide Stakeholder Advisory Group comprised of diverse membership from industry, Traditional Owners and the broader Reef community. The Group advised on strategic directions for engagement, and identified potential risks, opportunities, and benefits of RRAP engagement activities (12). Between 2022-2025, the group met 9 times and held two webinars. The Advisory Group's recommendations contributed to establishing the case for, and informed the development of, the RRAP Engagement Strategy (16).
Develop a framework to evaluate stakeholder and community engagement that supports learning and adaptive management	Designed and implemented evaluation frameworks to strengthen learning, adaptive management, decision-making, and stakeholder engagement. Developed and applied a Monitoring, Evaluation and Learning Strategy to assess the effectiveness of stakeholder and community engagement and identify areas for improvement (18). Provided recommendations on best-practice engagement and governance within RRAP, and independently corroborated the need for a cohesive RRAP Engagement Strategy and Communications Framework to identify social contextual factors likely to influence the acceptability of large-scale restoration activities on the GBR (9, 19).
Coordinate Stakeholder and Traditional Owner engagement activities across RRAP, and act as a point of contact for regulatory bodies	Identified potential governance pathways, including clarifying roles, responsibilities, decision-making processes, and delivery mechanisms to help guide further development and deployment of RRAP interventions in the future. Conducted regular Regulators' Forums to facilitate knowledge exchange between RRAP and the agencies involved in regulating activities within the GBR Marine Park, and between the agencies themselves (10). During 2024/25, five meetings were convened to discuss policies, regulations, and adaptation activities, thereby strengthening partnerships for intervention decision-making.
Identify effective pathways for reef restoration governance on the GBR	Delivered an options report on effective pathways for reef restoration governance on the GBR (20). Synthesised insights from Traditional Owners, reef stakeholders, and global case studies to illustrate how strong governance structures support ecosystem adaptation and resilience. Identified governance pathways with clear roles, responsibilities, decision-making, and delivery mechanisms, to guide future RRAP interventions and efforts to foster a healthy Reef. There remain many uncertainties around the application of existing policies, regulations and planning frameworks for large scale implementation of novel restoration and adaptation interventions. Results highlight that employing collaborative governance and learning-based approaches are recommended for large-scale ecological restoration and engineering programs. In addition, governance models should holistically frame community, stakeholder and public involvement in decision making linked to climate adaptation of complex social-ecological systems.

INDIGENOUS PARTNERSHIPS

RECOGNISE TRADITIONAL OWNERS AS RIGHTS-HOLDERS AND KNOWLEDGE-HOLDERS TO ENSURE THAT INTERVENTIONS ARE CULTURALLY LEGITIMATE

The Indigenous Partnerships work program ('IP') worked collaboratively with all RRAP subprograms to recognise the authority and cultural obligations of Traditional Owners (TOs) of GBR Sea Country, and to elevate the role of First Nations Australians in the design, delivery and evaluation of RRAP research and development. Importantly, the program positioned Traditional Owners as decision makers regarding RRAP activities that occurred in their Sea Country through a Free, Prior and Informed Consent (FPIC) process.

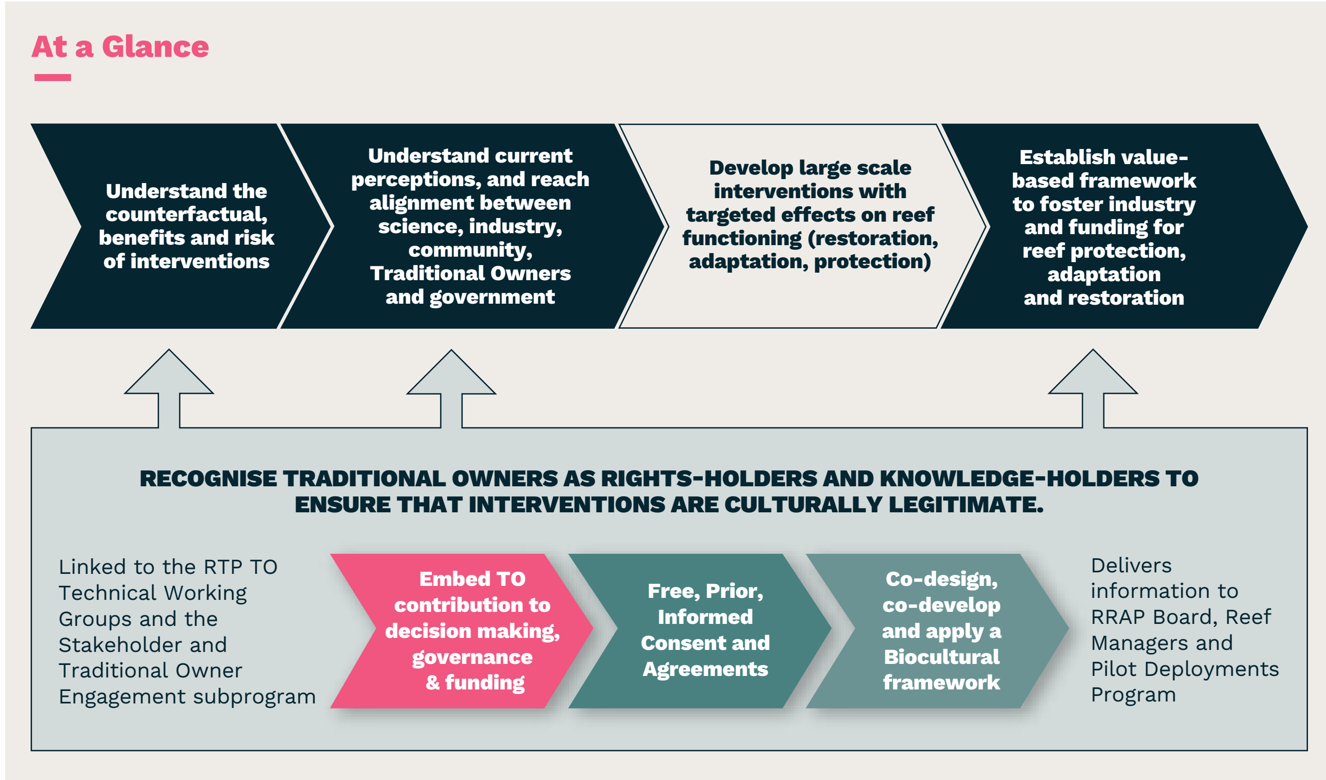
Between 2020 – 2025, IP focused on three main goals:

- Embed contributions of First Nations Australians to decision-making, governance and funding
- Ensure that Traditional Owners are informed about, consent to, and are employed to contribute to RRAP research and development activities in their Sea Country
- Co-design, co-develop, trial and refine a Biocultural Framework for Traditional Owners to use to evaluate the benefits and risks of environmental management actions.

Throughout Phase 1 of RRAP, IP worked closely with all RRAP subprograms to ensure that Free, Prior and Informed Consent (FPIC) was obtained from Traditional Owners before research and development was undertaken in their Sea Country. RRAP successfully embedded Traditional Owners across all levels of program governance and decision-making to ensure that intervention R&D, and future deployments at scale, can be done in the best possible way to help Country holistically.

GOAL AND SPECIFIC OBJECTIVES

Embed contributions of First Nations Australians to decision-making, governance and funding	**Achievement within scope of work**
Embed Traditional Owner roles at all levels of program governance	
Deliver two-way knowledge exchange with TO-led governance within the RTP	
Support contributions and participation by TOs in major RRAP events	
Establish a Traditional Owner working group to guide Pilot Deployments	
Ensure that Traditional Owners know about, and consent to, R&D in their Sea Country	
Test, refine and apply process for Free, Prior and Informed Consent	
Collaborate with RRAP intervention subprograms to produce factsheets	
Implement FPIC and knowledge exchange	
Co-design, co-develop, refine and test a Biocultural Framework	
Co-design and co-develop Biocultural Assessment Framework with TOs	
Trial the application of the Biocultural Framework in Sea Country	



Embed TO contribution to decision making, governance & funding

Reef Traditional Owners engaged as Independent Members of RRAP Steering Committee and a First Nations Member was appointed to the RRAP Board to assist with overseeing and operationalising the strategic direction of the Program.

Achieved two-way knowledge exchange between RRAP leadership and TO-led governance bodies with the Reef Trust Partnership. RRAP progress directly reported at each meeting of the RTP RRAS-COTS Traditional Owner Technical Working Group ensuring alignment of TO work in RRAP and other RTP-funded programs

Reef Traditional Owners contributed to all key RRAP events, including the 24 TO groups that presented at and/or participated in the Reef Resilience Symposium 2024, and TO's were employed in R&D and delivery as well as in training programs.

Established and convened 6 meetings of DREAMS to guide the design and implementation of the Pilot Deployments Program, and the directions of future (proposed) RRAP R&D.

Free, Prior, Informed Consent and Agreements

Collaborated with all RRAP subprograms to produce scientific knowledge products, presentations and project fact sheets that provided the information base for TO's to be fully informed about the work being proposed in their Sea Country.

Conducted multiple engagements with 24 groups of GBR Traditional Owners towards obtaining Free, Prior, Informed Consent. Consent was obtained for all activities (although it was sometimes conditional, or activities were adjusted in order to obtain consent).

Beyond FPIC, engagement with Traditional Owners provided a foundation for more equitable access to benefit-sharing for TOs from research, development, piloting and prospective future deployments at scale.

Created a fundamental shift in researcher perceptions of the Reef as a biocultural rather than purely biophysical seascape.

Reduced the pressure and load on TOs to engage with and educate researchers by replacing the potential multiplicity of repeated engagement with coordinated engagement through the AIMS Indigenous Partnerships team.

Co-design, co-develop and apply a Biocultural framework

Designed and conducted a literature review and collaborative workshop process with 15 Traditional Owner groups as the vehicle for identification, discussion and assessment of risks and opportunities of RRAP technologies

Co-designed and co-developed a resulting Biocultural Risk and Opportunity Assessment Framework with Traditional Owners to support decision-making about reef restoration and adaptation activities on Sea Country.

Tested and refined the Framework through case studies with Traditional Owner groups, including how to best support culturally grounded discussions, guidance on protecting Indigenous Cultural and Intellectual Property, connecting people to Country, and building long-term capability.

Developed and made available guidance materials for researchers to support meaningful, early and ongoing collaboration with Traditional Owners.

CASE STUDY – INDIGENOUS FUTURES PROJECT

BUILDING GENUINE PARTNERSHIPS AND GROWING CAPACITY IS FOUNDATIONAL TO REALISING TRADITIONAL OWNER ASPIRATIONS FOR CO-GOVERNANCE AND FAR GREATER INVOLVEMENT IN THE DAY-TO-DAY MANAGEMENT OF THE GREAT BARRIER REEF.

- Reef 2050 Traditional Owner Implementation Plan

Traditional Owners and Indigenous Rangers partner with RRAP researchers through the Indigenous Futures Project to expand the delivery of coral larval restoration interventions across the Great Barrier Reef. Co-designed with Traditional Owner governance groups, the IFP ensures activities are aligned with Traditional Owner aspirations, priorities and future opportunities. The project supports Traditional Owners to lead restoration activities on their own Sea Country and ensure they are among the first to access training in emerging reef restoration techniques and the operational skills needed to scale these approaches locally.

The IFP clearly demonstrates that Traditional Owner Ranger groups can successfully undertake and support the delivery of operational reef restoration interventions when provided with appropriate training, support and opportunities. The project also established accredited training pathways, developed training materials and built partnerships that support longer-term participation in the emerging reef restoration sector.

Aligned with the Reef 2050 Traditional Owner Implementation Plan, the three-year project commenced in 2023 and has achieved Indigenous-led capacity building and further developed the confidence and pathways required for Traditional Owner groups to participate in, lead and ultimately deliver emerging RRAP interventions and marine monitoring activities.

Image: Indigenous Futures Project activities on Heron Island.
Credit: Roelina Edmund, AIMS

SPAWNING ON HERON ISLAND

In 2024, Indigenous Rangers from six Traditional Owner groups joined Indigenous researchers, interns and trainees, alongside other RRAP scientists and support staff, on Heron Island during the annual mass coral spawning event. Participants built practical skills across multiple coral larval restoration approaches, including coral larval collection and rearing, land-based coral aquaculture systems, deployment of young corals on seeding devices, and long-term monitoring to assess restoration success.

EMBED CONTRIBUTIONS OF FIRST NATIONS AUSTRALIANS TO DECISION-MAKING, GOVERNANCE AND FUNDING

OBJECTIVE	ACHIEVEMENT
Embed Traditional Owner roles at all levels of program governance	Traditional Owners were embedded in RRAP governance at all levels, including key decision-making roles on the RRAP Board (one First Nations Board member), and in key advisory roles on the RRAP Steering Committee (two TO members). In addition, the RRAP Managing Entity contracted 2.5 to 3.5 FTE of staff time from the AIMS Indigenous Partnerships Team each year over the duration of RRAP Phase 1. These staff contributed to program governance and management in addition to leading FPIC development and implementation. Their role included knowledge brokering between researchers and Traditional Owners to ensure consent for projects was fully informed and opportunities to participate in projects were explored. All ad-hoc working groups established for specific functions over the duration of the program (e.g. Reef Resilience Symposium organising committee, RRAP Phase 2 Working Group) included First Nations representatives.
Deliver two-way knowledge exchange with TO-led governance within the RTP	Two-way knowledge exchange with TO-led governance bodies established under the RTP was achieved through multiple approaches. Staff from the AIMS Indigenous Partnerships Team who were embedded in the RRAP Managing Entity also hold important roles within the RRAS-COTS Traditional Owner Technical Working Group (TWG) which in turn was governed by the Traditional Owner Advisory Group. The TWG had governance oversight over the Deadly Restoration and Environmental Adaptation Murri Scientists (DREAMS) Group which helped to ensure alignment of strategic and tactical actions being undertaken by DREAMS with other TO-led initiatives. The Indigenous Partnerships team has developed a collaboration with the Biocultural Risks and Opportunities project within the Stakeholder and Traditional Owner Engagement subprogram. This collaboration grew as a direction from the RRAS Traditional Owner Technical Working Group, to incorporate Traditional Owner co-design in the project.
Support contributions and participation by TOs in major RRAP events	Over the duration of RRAP Phase 1, Traditional Owners contributed >887 paid workdays and >260 voluntary workdays towards the implementation of the R&D program across all of the intervention development subprograms. These contributions ranged from aquarium-based experiments for Coral Aquaculture and Deployment, contributing to larval reseeding work with Moving Corals, and assisting with drone surveys during in field work for Fogging and Marine Cloud Brightening. Mid-way through RRAP Phase 1, the program recognised the need to allocate additional funding to support TO participation in field and laboratory work. These funds supported additional capability-building for Ranger Groups in particular, including drone training prior to field work for Cooling and Shading, training in laboratory

	methods for Cryopreservation, and training in experimental methods and formal vocational qualifications in aquaculture. RRAP supported the attendance of Traditional Owners at the Reef Resilience Symposium in 2024. At this event, IP planned and ran a successful workshop on Co-Design and Indigenous Engagement with over 40 participants attending on the day. Traditional Owners delivered keynote address, facilitated and participated in a panel discussion, and spoke at the public forum for the symposium. More than 20 Indigenous organisations were represented at the event with over 50 Indigenous people participating across the 3 days, with many active in presenting research and asking questions during the presentations and discussion sessions.
Establish a Traditional Owner working group to guide Pilot Deployments	Through an expression of interest process, IP and a group of GBR Traditional Owners formed the Deadly Restoration and Environmental Adaptation Murri Scientists group (DREAMS) to assist with, and provide advice for, the planning and execution of the PDP and the next phase of the RRAP R&D program. The primary role and functions of the group was to: (i) assist with obtaining FPIC by advising on processes; (ii) create opportunities for co-design and training; (iii) be a consultation body for forward planning of new RRAP research and pathways for capability building; (iv) provide advice and collaboration on research design and methods, and opportunities for related involvement of Traditional Owners at all levels. DREAMS had their first 2-day workshop in June 2024 and convened on 5 additional occasions. Key discussion items have included site selection and Traditional Owner leadership and participation within the PDP, forward planning of RRAP R&D, major contributions to the PDP risk assessment of social and cultural values of the GBR in relation to intervention risk management in general, and risks associated with PDP and RRAP interventions specifically.

ENSURE THAT TRADITIONAL OWNERS KNOW ABOUT, AND CONSENT TO, RRAP RESEARCH AND DEVELOPMENT ACTIVITIES IN THEIR SEA COUNTRY

OBJECTIVE	ACHIEVEMENT
Test, refine and apply process for Free, Prior and Informed Consent	RRAP activities on Sea Country occurred only with the FPIC of respective Traditional Owners. Work in IP refined and applied a process for obtaining FPIC that recognises Traditional Owners as custodians of Land and Sea Country with decision-making rights and cultural governance authority. The process for FPIC involved the following steps: (i) IP team determined who's Sea Country RRAP research was proposed to take place; (ii) IP team contacted relevant Traditional Owners with cultural authority to organise a meeting with scientists and IP team members; (iii) IP team developed Fact Sheets in collaboration with scientists that

	outline the research project to inform Traditional Owners; (iv) IP team and scientists meet with Traditional Owners to discuss Factsheets and any other matters, including Traditional Owners outlining their aspirations for Sea Country; (v) In the early days a truth telling session was included to outline previous research that had been undertaken on Traditional Owners Sea Country to build a foundation for moving forward; (vi) Traditional Owners had a closed session (or met at a later date) to discuss Fact Sheets and any other questions they may have; (vii) Traditional Owners would bring IP team and scientists back into room (or reconvene another meeting) to provide an answer around consent (verbal or written) along with any conditions related to the consent; (viii) If consent was not granted then IP team would talk to scientists about contingency options and start the FPIC process over with other Traditional Owners; (viiii) If consent was granted IP Team would maintain contact with Traditional Owners providing updates as requested and assisting with meeting any conditions related to the FPIC; (x) IP team would assist around any proposed variations to an existing FPIC where required, including reconvening meetings with Traditional Owners. Over the duration of RRAP Phase 1, the FPIC process was led and implemented by the AIMS Indigenous Partnerships team, guided by the AIMS Indigenous Partnerships Policy, RRAP governance processes, and TO-led governance bodies established by the RTP. Moving forward, the RRAP partner organisations maintain an unwavering commitment to uphold knowledge equity, accountability, and transparency, ensuring Traditional Knowledge and Indigenous Cultural & Intellectual Property are respected equally alongside Western science.
Collaborate with RRAP intervention subprograms to produce factsheets	Developed a comprehensive set of intervention factsheets, and other scientific knowledge products, that were specifically designed for engagement with Traditional Owners and brokering knowledge about proposed RRAP research in Sea Country. These communication products were designed and produced in collaboration with all other RRAP subprograms, particularly the Intervention Development subprograms. Through the process of developing factsheets and presentations and meeting to discuss proposed research activities with Traditional Owners, RRAP scientists grew to have much greater cultural awareness and a deeper and longer-term view of how the reef is changing. Greater understanding of Traditional Ecological Knowledge also led to a major shift in RRAP scientists' perspectives to now view the Reef as a biocultural landscape where cultural values are intertwined with ecological values. The factsheets provided the foundation for consultation within the FPIC process. Factsheets about RRAP activities and interventions are available via the RRAP website.

Implement FPIC process and two-way knowledge exchange with Traditional Owners	Between 2020 and 2025, IP conducted >170 separate engagement activities with Traditional Owner groups associated with obtaining FPIC for more than 70 distinct RRAP field trips and research activities across all of the Intervention Development subprograms and the Ecological Intelligence for Reef Restoration cross-cutting subprogram. FPIC was obtained for all RRAP activities (although it was sometimes conditional upon TO participation, further discussion and/or time-bound until results were reported back). In some cases, the original research plan had to be adjusted (e.g. by limiting activities, changing activities or changing locations) in order to obtain consent. Not all Traditional Owner engagement went smoothly and, on various occasions, RRAP activities were paused or adjusted to step aside from any interference with governance and cultural authority matters emerging within and among TO groups. In some instances, TO groups requested a formal agreement be established instead of project-by-project FPIC discussions. In other instances, sites for proposed field work were in disputed zones between multiple TO groups and FPIC was obtained from all relevant groups and, in some cases, was granted on an interim basis pending further discussion. Competing priorities within TO groups occasionally delayed the FPIC process, most often in relation to obtaining 'updated' FPIC linked to proposed changes in the nature of the research. Finally, differences in field-trip planning, staffing and safety procedures among RRAP partners organisations occasionally impeded TO participation in RRAP field activities.

CO-DESIGN, CO-DEVELOP, TRIAL AND REFINE A BIOCULTURAL FRAMEWORK FOR TRADITIONAL OWNERS TO USE TO EVALUATE THE BENEFITS AND RISKS OF ENVIRONMENTAL MANAGEMENT ACTIONS.

OBJECTIVE	ACHIEVEMENT
Co-design and co-develop Biocultural Assessment Framework with TOs	Participants from 17 Traditional Owner groups contributed to the co-design, co-development and testing of the Biocultural Framework, including: Eastern Kuku Yalanji, Ngaro, Lama Lama, Wuthathi, Bromley Aboriginal Corporation RNTBC, Kuuku Ya'u, Gimuy Walubara Yidinji, Dingaal – Walmart, Nywaigi, Manbarra, Bailai, Taribelang Bunda, Gooreng Gooreng, Woppaburra, Darumbal, Wulgurukaba and Bindal (14). The overarching aim of the work was for the framework to be used by Traditional Owners of the Great Barrier Reef to assess the potential risks and opportunity pathways related to the potential future deployment of RRAP technologies on their Sea Country. The project was implemented via a comprehensive literature review that revealed that biocultural frameworks support Indigenous strengths-based narratives of care and responsibility for social-ecological systems undergoing change. The project team worked to deliver workshops that facilitated a process for Traditional Owners to better understand and document their concerns and scope a culturally appropriate tool that would build on that information to support decision making.
Trial the application of the Biocultural Framework in Sea Country	Tested and refined the Framework through case studies with Traditional Owner groups, including how to best support culturally grounded discussions, guidance on protecting Indigenous Cultural and Intellectual Property, connecting people to Country, and building long-term capability. The project team had discussions with three Traditional Owner groups (Manbarra, Darumbal and Lama Lama) as well as a regional corporation (Port Curtis Coral Coast Aboriginal Corporation - who represent Bailai, Gurang, Gooreng Gooreng and Taribelang Bunda peoples). The Lama Lama people worked with the project team to co-develop a case study. The case study was progressed via a workshop in Gimuy (Cairns) wherein the participants decided to consider the draft Biocultural Framework from the perspective of progressing an update to their research partnership protocol (14). Ongoing work is furthering the development and operationalisation of the BCF for additional reef management actions (Crown-of-thorns starfish control via the CCIP) adjacent to applications to RRAP R&D and pilot deployments. As deployments increase in scale in the future, further work with Traditional Owners is needed to build upon the Biocultural Framework to co-design and co-develop a mandatory compliance or risk-assessment gate.


Image: Indigenous Futures Project activities on Heron Island.
Credit: Roelina Edmund, AIMS

CASE STUDY: BUILDING STRONGER PARTNERSHIPS ON SEA COUNTRY

In 2019, Reef Traditional Owners identified a clear need for a tool to support informed decision-making about emerging reef restoration and adaptation activities happening on Sea Country.

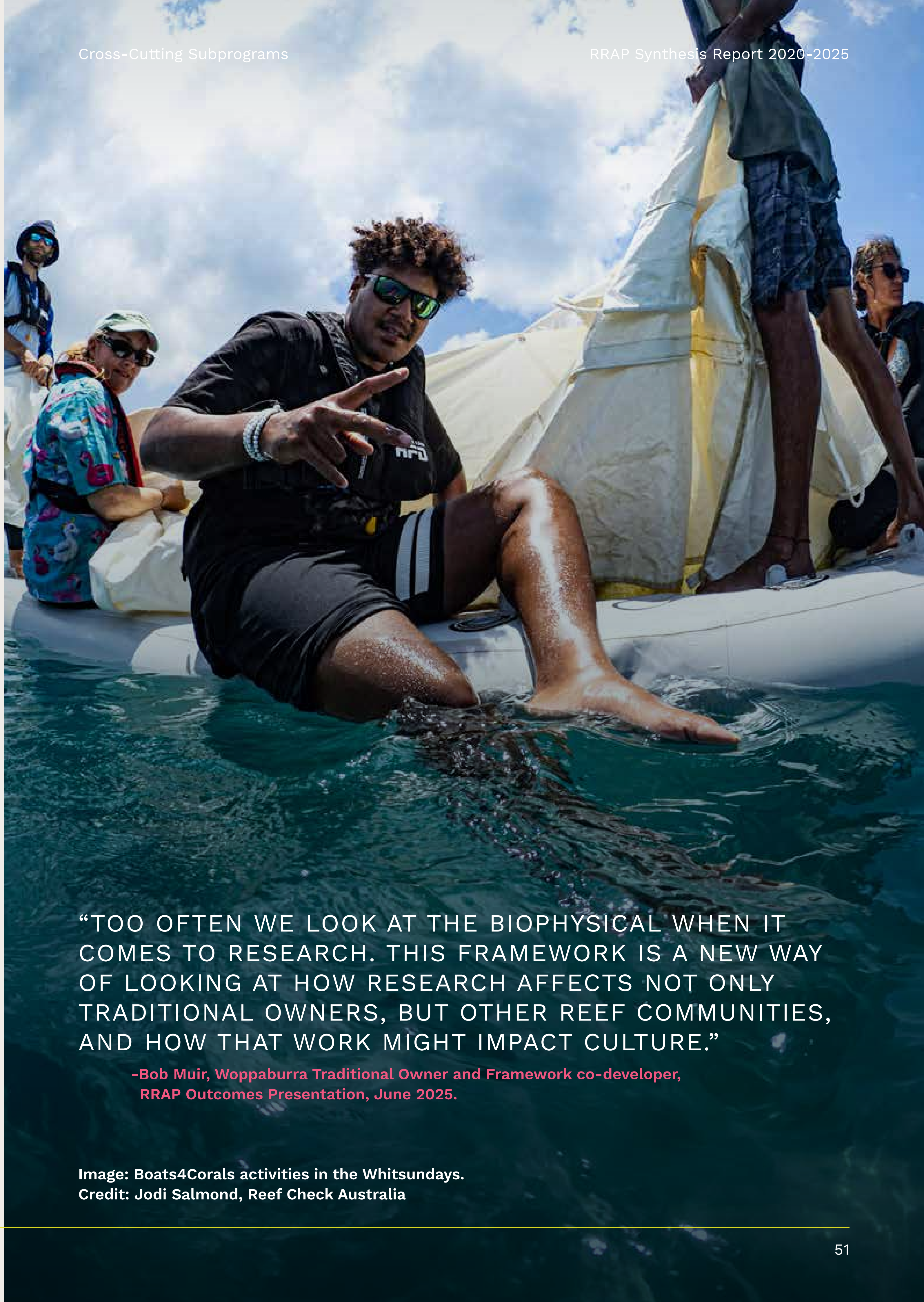
The Biocultural Risk and Opportunity Assessment Framework has emerged to address this need. It has been created by and for Reef Traditional Owners through collaborative workshops over a period of five years. The Framework provides protocol and principles to guide culturally grounded conversations within and between Traditional Owner groups.

A strength-based approach is central, recognising Traditional Owners not simply as risk managers for research projects, but as active partners who will shape positive futures for Land and Sea Country. This is reflected in the guided discussion themes, which include connecting people to Country, protecting Indigenous Cultural and Intellectual Property, and building long-term capacity.

The Framework has been designed so that it is transferable and adaptable to other research and development contexts. A pioneering pathway for stronger, culturally respectful partnerships on Country.

Image: Members of the Biocultural Framework project team, Konomie, 2023 (L-R: Bruce Taylor, Manuwuri Forester, Cath Moran, Kelli Schmitt, Libby Evans-Illidge, Bob Muir, Kirsten Maclean, not pictured: Carl Grant, Dion Devow, Peci Lyons).

Cross-Cutting Subprograms RRAP Synthesis Report 2020-2025



“TOO OFTEN WE LOOK AT THE BIOPHYSICAL WHEN IT COMES TO RESEARCH. THIS FRAMEWORK IS A NEW WAY OF LOOKING AT HOW RESEARCH AFFECTS NOT ONLY TRADITIONAL OWNERS, BUT OTHER REEF COMMUNITIES, AND HOW THAT WORK MIGHT IMPACT CULTURE.”

-Bob Muir, Woppaburra Traditional Owner and Framework co-developer, RRAP Outcomes Presentation, June 2025.

Image: Boats4Corals activities in the Whitsundays.
Credit: Jodi Salmond, Reef Check Australia

REGULATORY AND POLICY ENVIRONMENT

ENHANCE CAPACITY OF THE REGULATORY ENVIRONMENT TO EVALUATE, GUIDE, AND PERMIT INNOVATIVE REEF RESTORATION AND ADAPTATION INTERVENTIONS

The GBR Marine Park has been recognised as one of the world's best managed coral reef ecosystems, operated under The *Great Barrier Reef Marine Park Act* 1975 and its Regulations. In particular, the *Policy on Great Barrier Reef Interventions* outlines the regulatory framework for testing and implementing restoration and adaptation activities to build the resilience of the Reef in the face of climate change.

The Regulatory and Policy Environment subprogram ('REG') was established to research how regulatory frameworks could evolve to more effectively support innovative, science-based interventions while maintaining strong environmental and social safeguards. Deliberately focused on long-term system needs, REG considered how RRAP interventions, both in terms of research and implementation, could best integrate within the Marine Park framework while also complying with a complex array of other and at times overlapping regulations.

Between 2020 – 2025, REG focused on three main goals:

- **Map the regulatory environment and identify matters that could inhibit intervention** research and development and/or impede large-scale deployment in the future
- Investigate the **capacity of the existing regulatory environment** to address intervention research and development and large-scale deployment in the future
- **Develop guidelines to enhance the capacity** of the regulatory environment to address intervention research and development and large-scale deployment in the future

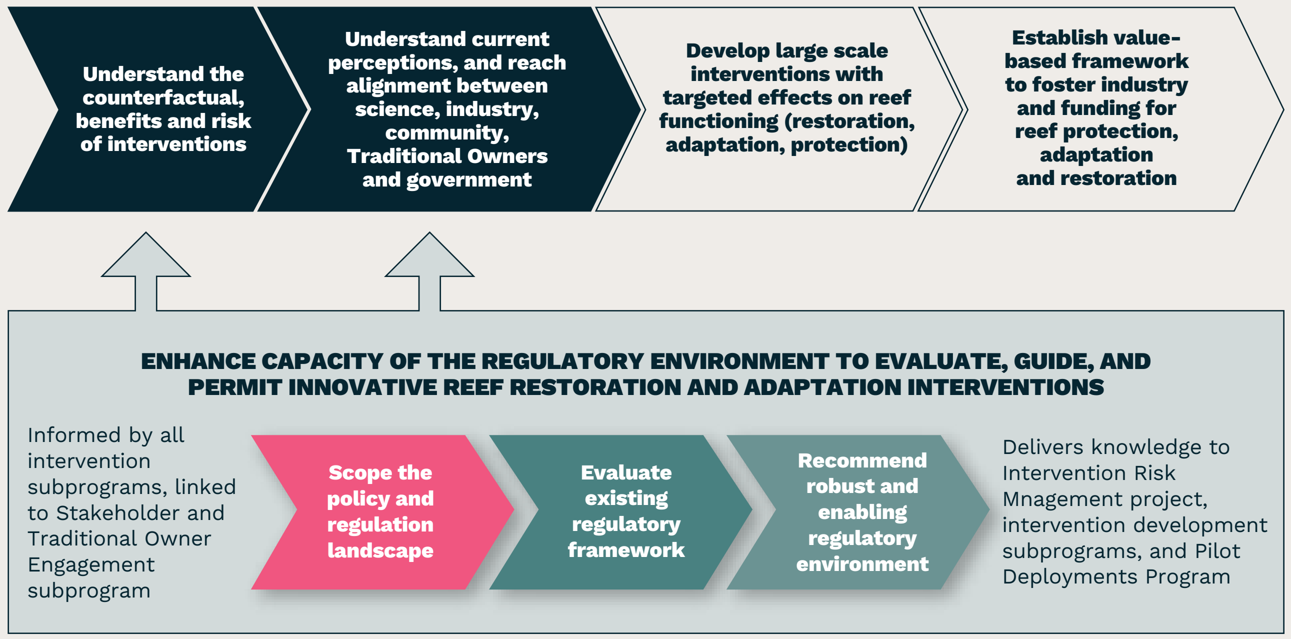
REG identified that to resolve potential gaps between scientific advances and regulatory adaptability, it will be important to: develop adaptive regulatory pathways; strengthen coordination and expertise; enhance stakeholder engagement to ensure timely, transparent, and socially aligned decision-making to support resilience and adaptation of the Great Barrier Reef.

GOAL AND SPECIFIC OBJECTIVES

	Achievement within project scope
Scope regulatory matters that could inhibit intervention research and deployment	
Review regulations for coral aquaculture, moving corals and fogging	
Identify regulations that hinder intervention R&D and deployment	
Evaluate capacity of the existing regulatory environment	
Assess policy approaches and tools for regulation of reef restoration	
Develop guidelines to enhance the capacity of the regulatory environment	
Evaluate regulatory and policy approaches and tools in other jurisdictions	
Develop and assess options for regulatory approaches and tools for the GBR	
Develop guidelines for regulatory and policy best practice for restoration	

RRAP Synthesis Report 2020-2025

At a Glance



Scope the policy and regulation landscape

Limited technical expertise specific to new methods and approaches within regulatory agencies hinders ability to assess and approve novel reef interventions.

Multiple overlapping jurisdictions create uncertainty and delays in approval processes.

Interpretation of existing regulations regarding large-scale deployment of reef interventions remains unclear, particularly concerning the balance between intervention benefits and potential environmental impacts.

Current frameworks do not provide clear assessment processes for the risks and benefits of innovative restoration approaches.

Evaluate existing regulatory framework

Current risk assessment systems face challenges with novel interventions combined with potentially novel ecosystem states.

Policies could more explicitly evaluate the positive impacts of restoration, adaptation, and ecological change-especially when change is the intended outcome.

Existing Heritage and Social Values policies offer entry points for assessing how interventions affect cultural and social values, but this is not yet fully developed.

Regulatory uncertainty persists due to evolving frameworks and ongoing reviews. Ambiguities around triggers under specific policies create uncertainty about future approval processes and permissible activities.

Recommend robust and enabling regulatory environment

Engage Traditional Owners, reef managers, and the broader community in co-designing regulatory approaches to ensure that governance decisions align with social and cultural values.

Streamlined processes for regulatory approvals will help facilitate timely decision-making.

Formalise risk-benefit assessment frameworks to ensure that novel interventions are evaluated against the counterfactual given likely climate scenarios.

Update existing regulatory guidelines to explicitly address the unique challenges of reef resto-ration and adaptation.

Monitor and adapt regulatory policies based on lessons learned from early-stage deployments of reef interventions.

SCOPE REGULATORY MATTERS THAT COULD INHIBIT INTERVENTION RESEARCH AND FUTURE DEPLOYMENTS

OBJECTIVE	ACHIEVEMENT
Devise plausible future deployment scenarios for RRAP interventions	Developed a set of plausible deployment scenarios for coral relocation and coral aquaculture along with cooling and shading that outlined future intervention activities as required for assessment of relevant policies and regulations (21).
Identify contextual regulatory issues associated with novel reef interventions	Highlighted capacity of regulators and the complex regulatory environment as key contextual factors. The introduction of novel reef interventions will likely necessitate changes in the assessment processes implemented by Regulators with some additional resource requirements (including personnel and training). The regulatory environment is complex and involves multiple different agencies and levels of government. Multiple regulatory requirements from distinct agencies with different environmental mandates apply to each intervention type. Established and coordinated a Regulators Forum to facilitate two-way knowledge exchange with Regulators.
Identify cross-cutting regulatory issues associated with novel reef interventions	Highlighted deployment scale, location and timing as important cross-cutting issues (22, 23). It is unclear how the scale of deployment affects regulatory approval processes. Activities that are acceptable at a small scale may not be approved at larger scales. Timeframes for essential R&D prior to deployment of interventions, particularly 'emergency response' deployments, might not align with approval timelines of regulatory agencies. The likelihood of approval for interventions varies among sites according to zoning plan applied to the GBR.
Identify policy-specific regulatory issues associated with novel reef interventions	Identified the following policy-specific matters that may be critical for obtaining regulatory approval for future large-scale deployment of reef interventions: • A species-specific coral harvest quota will be applied within the Queensland Coral Fishery, and QCF licences currently prohibit the release of coral back into the marine environment. • Approval for translocations of species within the GBR are only granted under a low-risk assessment. However, translocation risks increase with distance, quantity, and limited specimen containment. Exceptionally strong conservation reasons will be required for interventions that require long-distance translocation. • Protocols for movement of aquatic animals in Queensland include measures to prevent disease spread. This represents a significant regulatory and monitoring consideration for interventions involving aquaculture activities. • Current environmental protection and biodiversity legislation in Australia does not clearly distinguish between regulation of activities that have positive versus negative impacts on Matters of National Environmental Significance.

EVALUATE CAPACITY OF THE EXISTING REGULATORY ENVIRONMENT

OBJECTIVE	ACHIEVEMENT
Identify key regulatory approaches and tools that can address novel reef interventions in the GBR	Two key tools support the implementation of the *Policy on GBR Interventions and Guidelines for Application for Restoration/ Adaptation Projects to Improve Resilience of Habitats in the GBRMP*: the Risk Assessment – Permission System, and Environmental Impact Management – Permission System under the GBRMPA and DESI joint approach to risk assessment (24, 25). These risk assessment policies are, in turn, informed by the Traditional Owner Heritage Assessment Policy and Social Values Policy as well as the EPBC Act. The risk assessment is also informed by the overarching Zoning Plan for the GBR Marine Park.
Evaluate limitations of the existing regulatory environment in application to novel interventions	Across the set of relevant legislation, International conventions, regulations, policies, plans, position statements and strategies, the following areas of uncertainty emerge in relation to regulation of reef interventions: • Existing policies support reef interventions but need clearer guidance. The Interventions Policy and Restoration/Adaptation Guidelines provide a tiered risk framework, yet require more detail on how benefits, counterfactuals, and systematic evaluation should be applied (25). • High uncertainty, limited expertise, and reliance on pre-existing policies make it difficult to assess innovative restoration and adaptation projects effectively, particularly as climate change can give rise to novel ecosystems. • Opportunities exist to improve benefit assessment and integrate ecological intent. Policies could more explicitly evaluate the positive impacts of restoration, adaptation, and ecological change—especially when change is the intended outcome (e.g., assisted gene flow, assisted evolution). • Existing Heritage and Social Values policies offer entry points for assessing how interventions affect Traditional Owners but these should be further developed. • Ambiguities around triggers under the EPBC Act and the Sea Dumping Act, plus potential revisions to zoning and risk frameworks, create uncertainty about future approval processes and permissible activities (19).

Develop recommendations to improve the capacity of existing policy and regulatory approaches and tools to enable restoration and adaptation interventions	In the context of the limitations and areas of uncertainty listed above, recommended actions include (26): • Update risk assessment frameworks to consider net benefit activities holistically or establish a separate framework that is specific to restoration and adaptation interventions. • Develop guidance as to how assessment of benefits from restoration and adaptation actions should be contrasted with the counterfactual within regulatory approval processes. • Provide guidance about the potential effects of restoration and adaptation interventions on Traditional Owner and social values, as well as how these effects should be considered in the approvals process. • Clarify how and the circumstances under which restoration and adaptation interventions should be assessed under the EPBC Act. • Regularly update policy and regulatory approaches to facilitate currency with rapidly evolving restoration and adaptation science.

DEVELOP GUIDELINES TO ENHANCE THE CAPACITY OF THE REGULATORY ENVIRONMENT

OBJECTIVE	ACHIEVEMENT
Review the literature to identify recommendations directly relevant to novel reef interventions	Effective governance of novel reef interventions requires a dynamic approach that is responsive to environmental changes, meaningfully engages diverse stakeholders, and incorporates clear, actionable strategies (25): • Decision making approaches must be flexible to adapt to changing conditions and rapid development of restoration and adaptation science. • Governance must be inclusive, collaborative and co-designed through engagement with Traditional Owners and a wide range of stakeholders. • Current policies may need to be updated, or new ones introduced, to manage the challenges associated with deployment of novel reef interventions at the scale required to combat climate change impacts. • Clear guidance on translating governance recommendations into practice is essential and there is a need for actionable measures that can be incorporated into policy.

Design options for regulatory and policy approaches and tools applicable to emerging technologies including reef restoration and adaptation	Applicable approaches and tools for regulation of these technologies include: (i) halting the development and adoption of innovation when risks are considered too significant; (ii) allowing the technology to be developed and adopted on a limited scale while closely monitoring its impacts to guide development of an appropriate regulatory response; (iii) setting guidelines for how the technology should be developed and used to ensure it is safe and beneficial; and (iv) piloting innovative approaches to regulation, such as sandboxes for technology trials, integrated governance, and/or performance-based co-regulation. In the context of reef restoration and adaptation, policy/regulatory change should occur through the following strategies (21): • Conversion: reinterpret existing rules are reinterpreted to serve new purpose while formal structures remain unchanged. • Displacement: phase out previous regulations and introduce new regulations introduced that better address emerging innovations. • Layering: add new elements to existing regulatory framework without removal/replacement of existing regulations.
Formulate guidelines for regulatory best practice (governance principles) for novel reef interventions	Governance principles for novel reef interventions should: • Embed inclusive participation of all relevant parties, including Rights Holders, in decision-making. • Be flexible, responsive, and adaptive to evolving knowledge of the environment, and of the risks and benefits of novel interventions. • Embed proactive forward-planning in the face of uncertainty, such as horizon scanning and scenario planning, to future-proof governance. • Encourage testing and evaluation of new interventions under controlled conditions to inform comprehensive and nuanced assessment of risks and benefits. • Leverage collaboration across different agencies to address the complexities of development, deployment and monitoring of novel reef interventions and to enhance monitoring, evaluation and learning about intervention governance. The operationalisation of these governance principles hinges on the availability of human, financial, and technical resources. Teams must be adequately staffed and resourced. This may involve hiring new employees with technical skills related to the interventions, and skills in areas such as stakeholder and rightsholder engagement, risk assessment, and future and system thinking. Organisations involved in end-to-end delivery of novel interventions will be required to anticipate and respond to future changes including testing and evaluating new approaches to management and policy.

Review the literature on risk governance of emerging technologies	Review of the literature on risk governance of emerging technologies revealed: • A call to adopt a risk-weighted system based on set criteria and the inclusion of adaptable, future risk scenarios or strategic foresight to enhance risk comprehension and planning. Environmental decision-making should move away from traditional concepts of 'natural' and 'pristine' systems to acknowledge the ongoing impact of humans in creating novel ecosystems. • A prevailing discourse that advocates for some merging of government and industry regulation to better navigate uncertainties during technological development. Governance should be flexible, responsive, adaptive and anticipatory (27). In addition to best practice governance principles (i.e., transparency, accountability, participation, integrity, and capacity), review of the literature identified several common approaches to risk governance of emerging technologies, including: • Decision making should be inclusive, collaborative and deliberative involving public and stakeholder participation and engagement. • Risks should be anticipated and addressed proactively, including evaluating trade-offs, such as those between sustainability risks and global warming mitigation efforts, to balance risks and benefits effectively. • Diverse expertise and data should be brought to be in risk governance, including integrating economic, social, and environmental considerations with technical and governance insights. • Potential role for state and international cooperation to manage risks that have cross-border implications.

Image credit: Gary Cranitch, Queensland Museum

INTERVENTION RISK MANAGEMENT

UNDERSTAND AND EVALUATE INTERVENTION RISKS AND PROVIDE GUIDANCE AND ADVICE ON RISK ASSESSMENT AND MANAGEMENT

The Intervention Risk Management project ('RISK') designed, tested and implemented a world-leading process for robust evaluation of ecological, social, cultural and heritage risks associated with the deployment of interventions.

Between 2022 – 2025, RISK focused on three main goals:

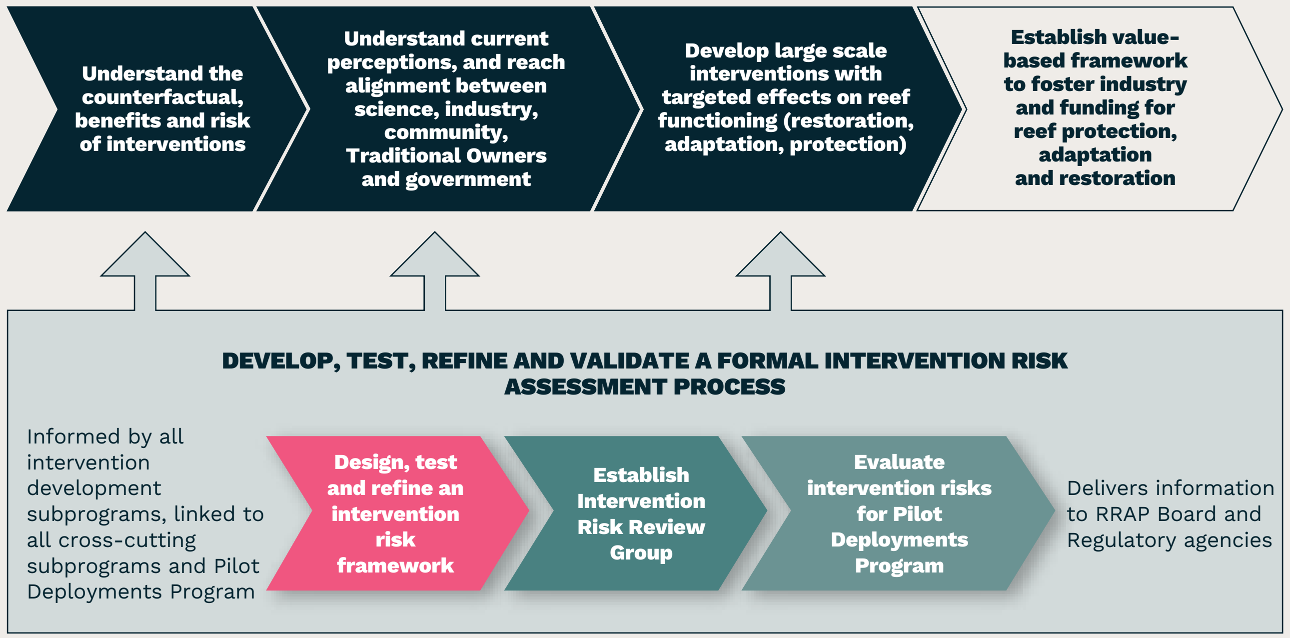
- **Design, test and refine a framework** to identify specific risk pathways for RRAP interventions and that incorporates best practices for expert elicitation
- Create **an independent Intervention Risk Review Group (IRRG)** to provide guidance, advice and review of intervention risk assessment and management.
- **Implement intervention risk framework with iterative IRRG review** to appraise risks associated with Conservation Aquaculture and Slick Collection and Release methods prior to pilot deployments on the Reef.

The Intervention Risk project established and applied a robust, transparent framework to evaluate the ecological and social risks of reef interventions, supported by an independent Intervention Risk Review Group (IRRG) providing iterative oversight and review. This work was highly collaborative, integrating expertise from across RRAP intervention and cross-cutting programs to ensure a comprehensive and connected approach to risk assessment. This work has enabled systematic identification and characterisation of risks for RRAP-type interventions, strengthened the evidence base for decision-making, and provided assurance to regulators and stakeholders that risks are being rigorously assessed and managed. Building on this strong foundation, the intervention risk framework and IRRG process are well placed to continue to support decisions on the Pilot Deployments Program and future interventions, while improving the understanding of intervention risks and evolving methods to address increasingly novel and complex options.

GOAL AND SPECIFIC OBJECTIVES

	Achievement within project scope
Design, test and refine an intervention risk framework	
Workflow for objectives and values framing aligned to end-user needs	
Workflow for risk identification applicable for different dimensions of risk	
Develop approach for causal mapping of risk pathways	
Structured design for expert elicitation of risk following best practices	
Create an independent Intervention Risk Review Group (IRRG)	
Establish a sub-committee of the RRAP Board to provide guidance & advice	
Convene the IRRG to provide independent input, oversight and risk review	
Implement intervention risk framework for the Pilot Deployments Program	
Implement intervention risk framework for Conservation Aquaculture	
Implement intervention risk framework for Slick Collection and Release	
Implement risk framework for social, cultural and heritage dimensions	
Apply intervention risk framework to other intervention types	

At a Glance



Design, test and refine an intervention risk framework

Advanced intervention risk science and built a fit-for-purpose framework for novel reef interventions.

Created robust, transparent and adaptable methods to assess ecological, social, economic, cultural and heritage risks.

Established a broader risk assessment process comprising assessment methods, application to specific intervention proposals, and a quality management system for consistency, assurance and continuous improvement.

Developed staged workflows for intervention proposal review, objectives and values framing, risk identification, causal pathway mapping, risk analysis, and risk characterisation with risk management advice.

Embedded risk processes into program decision-making, produced regulator-facing outputs, and provided feedback into intervention planning.

Establish Intervention Risk Review Group (IRRG)

Established an independent, interdisciplinary Intervention Risk Review Group with an independent Chair and national and international experts.

Supported a stepwise review process that enabled independent guidance, oversight and assurance for RRAP governance and regulators.

Convened 9 multi-day workshops, 36 online meetings and 22 focused working group sessions, providing multiple touchpoints across method development and application to specific interventions.

Provided the information, assessment outputs and structured opportunities needed for independent review while upholding IRRG's independence.

The IRRG process strengthened confidence that intervention risks were assessed with rigour, integrity and transparency.

Evaluate intervention risks for Pilot Deployments Program

Applied the full framework, with iterative IRRG review, to Conservation Aquaculture and Slick Collection and Release.

Combined expert elicitation, causal pathway mapping, literature review, RRAP research and monitoring data.

Found low overall ecological risk across all ecological value groups and intervention methods at pilot deployment scale.

Extended assessment to social and cultural dimensions, integrating Traditional Owner perspectives, First Nations knowledge systems and FPIC principles.

Applied the framework to more novel options, including heat-evolved symbionts, and aspects of assisted gene flow, fogging and Marine Cloud Brightening, to guide future research and design.

DESIGN, TEST AND REFINE A RISK MANAGEMENT FRAMEWORK

OBJECTIVE	ACHIEVEMENT
Establish an Intervention Risk function, and identify and review the available information and research activities for assessing intervention risks	The gap that the Intervention Risk function addressed was the lack of maturity in people's understanding of the potential risks of intervening in coral reef systems. RISK has advanced intervention risk science, developed world-leading assessment processes, and improved the understanding of intervention risks. Decisions relating to intervention deployment on the Great Barrier Reef are critical in nature and multi-layered, requiring careful consideration and evaluation. Decision-makers must consider the potential outcomes of interventions holistically across the ecological, social, economic, cultural and heritage values they manage (as relevant to the intervention being assessed). Progress towards deployment of large-scale interventions on the GBR requires building the understanding of the risks versus the benefits, against the backdrop of the impact of climate change on the Reef. As a foundational capability, this decision-making landscape required improved approaches to intervention risk assessment, hence this was a key focus and achievement of the RISK project during this phase of RRAP. In 2022–2023, RISK established processes for integration of relevant knowledge across RRAP, and consolidated knowledge and identified gaps. This included cataloguing work-to-date across and beyond RRAP R&D, and upcoming research activities, relevant to understanding and evaluating intervention risks. Also, mechanisms were scoped and agreed for obtaining independent input (from outside of RRAP) to provide assurance to regulators and other key stakeholders—see creation of the Intervention Risk Review Group (IRRG) under Goal 2.
Scope and define the design requirements for a fit-for-purpose Intervention Risk Framework	RRAP-type interventions may be technically bold, publicly visible, ethically complex and difficult to assess through conventional environmental risk processes. These projects may involve deep uncertainty, limited precedent, contested values, potential cross-system effects, and decisions that must be made before all evidence is complete. Due to the novel nature of RRAP-type interventions, and the complexity of the social-ecological system and biocultural landscape in which they may be deployed, a fit-for-purpose approach to risk assessment was found to be essential. In developing the Intervention Risk Assessment approach and methods (287), the following key design requirements were identified and adopted: • Robust - The methods are robust and transparent, and applicable to circumstances where data and information may be limited. • Comprehensive - The approach and methods are broad and inclusive and consider and evaluate potential risks across multiple dimensions of Great Barrier Reef values, including ecological, social, economic, cultural and heritage dimensions. • Agile - The approach and methods are flexible and adaptable. The methods can be applied to multiple RRAP intervention types, at different stages of development, and with different levels of data availability and analysis needs, with the capacity to incorporate new data and information as it arises. • Relevant – The context and framing of the assessment has a line of sight to regulatory frameworks, while maintaining a holistic view and considering diverse perspectives. The methods ensure spatial and temporal relevance of the outputs to potential future conditions of the Reef and allow comparison with the "no new interventions" reference case. • Informative - The approach and methods are informative for the continued development and planning of RRAP interventions – they identify and generate understandings of the factors and conditions that can influence the severity and likelihood of the risks, and they examine and inform risk management and mitigation options. • Supports decision-making - The approach can be conducted in a timely manner and outputs are informative and meet the needs of regulators.
Develop, test and refine a formal risk assessment method and process for novel interventions	Successfully built a framework to specifically identify and assess the potential risks of proposed reef interventions and how they would be implemented on the reef. This includes ecological, social, economic, cultural and heritage dimensions. The process is grounded in the latest science, and incorporates broad knowledge, experience and evidence. Integrates insights and knowledge from across RRAP's portfolio, from engagement and partnership to science and engineering. The *Intervention Risk Assessment methods* provide guidance for robust and consistent risk assessment of different types of coral reef interventions, from early-stage investigations through to large-scale deployment plans. These methods sit within a broader *risk assessment process* that consists of three key components: (1) the methods used for intervention risk assessments, (2) the application of these methods to assess specific intervention proposals, including the roles and responsibilities of contributors, and (3) the Quality Management System that provides consistency, continuous improvement and quality assurance of both method development and application. An independent *Risk Review process* was also established as an initiative of RRAP and is described under Goal 2 below.

Create the component methods for the stages, ensuring needs of Regulators and other decision-makers are met	Designed methods for Intervention Risk Assessment. In simple terms, it starts with reviewing the intervention proposal to be assessed, and then has five core stages: **0. Understanding the intervention proposal:** Review of the intervention plans, including location, scale, technologies used, and contextual conditions. **1. Objectives and values framing:** Identification of the GBR management objectives and Great Barrier Reef (and any broader) Values potentially affected by the proposed intervention. **2. Risk identification:** Systematic identification of possible risks and outcomes, using best practice procedures, literature reviews, engagement with Traditional Owners and stakeholders, and research outputs. **3. Risk pathway mapping:** Development of causal maps to trace the mechanisms by which intervention activities could lead to consequences for GBR values. **4. Risk analysis:** Assessment of the likelihood and severity of potential consequences, followed by further analysis. A variety of methods can be used for the risk analysis, including expert elicitation. **5. Risk characterisation and risk management advice:** The understanding gained about the risks of proposed intervention(s) in the previous steps is brought together to characterise the potential risks to GBR values. An independent group (IRRG) provides external oversight and quality assurance throughout the process and conducts formal reviews to verify findings. An operational understanding of the Reef Authority's reef interventions policies and regulatory processes, along with those of other regulators, informed the development of RRAP's Intervention Risk Assessment approach and methods. Regulators, Traditional Owners and other decision-makers were provided with opportunities for input to the Intervention Risk Framework development, and given visibility of its applications. This occurred via meetings and briefings, the RRAP Regulators Forum, workshops with the DREAMS team, and risk workshops.
Document the component methods for each stage, and the overall approach, to Intervention Risk Assessment	Created comprehensive documentation of the methods used to assess intervention risks (287). This provides a guide for Assessment teams undertaking evaluations, and serves as a reference for regulators, Traditional Owners, and other stakeholders engaged in decision-making. The approach integrates existing best practices in environmental risk management, operationalises environmental, social, governance and ethical considerations, and includes specific requirements for reef intervention contexts. The approach is adaptable to different types and scales of interventions and incorporates both qualitative and quantitative data. Where applicable, structured expert judgment methods are applied to ensure defensibility and transparency.
Test and refine method for application to diverse dimensions of risk including ecological, social, economic, cultural and heritage.	Tested and refined the methods to ensure they are robust and practical for assessing potential risks to Great Barrier Reef values; the approach and methods have been independently verified by the IRRG. The IRRG concluded that the RRAP Intervention Risk Assessment process, if applied as intended by people with appropriate expertise, is fit for the purpose of assessing the risks associated with proposed reef interventions. Collaboratively extended the methods to also consider intervention risks to attributes identified in the Strong Peoples – Strong Country framework developed by Reef Traditional Owners.
Embed intervention risk processes within program and GBR decision-making landscape	RISK has supported a broader responsible progression capability that has been embedded within the RRAP program, helping decision-makers anticipate and manage intervention risk issues earlier. It created a practical way to connect intervention risk science and assessment with evidence planning, transparent risk assessment, independent review, regulator-facing outputs and public-facing engagement needs. Without such a structured and trustworthy intervention risk capability, projects may face four risks. First, inaccurate characterisation of interventions as safe or harmful, or a lack of risk information. Second, promising interventions may stall because uncertainty is not translated into tractable research, monitoring, safeguard and decision needs. Third, projects may progress inconsistently, with risk, ethics, engagement and regulatory issues handled too late or too unevenly across the portfolio. Fourth, RRAP and reef managers may face avoidable legitimacy risk if high-profile interventions are perceived to be moving faster than the evidence, scrutiny or engagement needed to support responsible decisions. The risk assessments aim to be a trustworthy source of information for regulators, Traditional Owners, stakeholders and other interested groups on the potential risks of interventions. The process allows for scrutiny in near-real time by regulators and generates feedback for intervention teams. This has enhanced the understanding of potential risks and guided the ongoing development and deployment planning of interventions. The process identifies factors influencing risk and highlights areas where risk mitigation, monitoring, or further research may be needed. Although designed specifically for RRAP and the Great Barrier Reef context, this risk assessment framework is applicable to reef interventions in other regions. It provides a model for evaluating novel restoration and adaptation technologies in complex, high-value ecosystems under uncertainty.

ESTABLISH INTERVENTION RISK REVIEW GROUP (IRRG) TO PROVIDE INDEPENDENT GUIDANCE AND REVIEW OF INTERVENTION RISK ASSESSMENT AND MANAGEMENT

OBJECTIVE	ACHIEVEMENT
Appoint a sub-committee of the RRAP Board to provide independent and interdisciplinary guidance and advice	Successfully created a panel of 13 members with an Independent Chair and comprising international and national subject matter experts who are external to RRAP. The group is called the Intervention Risk Review Group (IRRG), and their key role is to consider matters related to, and provide guidance and advice on, the assessment and management of Intervention Risk. This independent, inter-disciplinary expert group was established as an initiative of RRAP in consultation with regulators, and has been operating since late 2022. The IRRG provides advice to RRAP governance on the management of intervention risk and is designed to also provide assurance to regulators. The IRRG applies two levels of quality assurance. The first relates to the methods used by RRAP to identify and evaluate risks and outcomes. The second relates to the application of those methods to specific interventions (or combinations of them that form a proposed deployment). The IRRG achieves this quality assurance through a series of touchpoints where IRRG reviews outputs from RRAP as the risk assessment is conducted. This proactive approach to quality assurance, with multiple touchpoints, allows IRRG to review RRAP's methods and outputs in a stepwise progression through the assessment. In addition, the approach of multiple touchpoints allows RRAP to integrate advice (e.g., in future deployment proposals) and adjust R&D to ensure the necessary knowledge about the efficacy of interventions is generated. These processes have been carefully managed to maintain the independence of the IRRG process.
Regularly convene the IRRG to provide independent input, oversight and review functions	IRRG held 9 multi-day workshops and 36 online IRRG meetings between November 2022 and June 2025. In addition, since the start of 2023 RRAP and IRRG held 22 small working group meetings and focus groups on subjects including: intervention risk assessment /risk review methods; use of symbionts; modelling; Pilot Deployment plans; species selection; genetics; engagement; social and cultural dimensions. The IRRG had visibility of each stage of the Intervention Risk Assessments conducted by RRAP and they reviewed the detailed findings of assessment reports. The IRRG considered whether each assessment process met agreed standards and was implemented with integrity and transparency. The quality assurance aspects of their role included discussing and reviewing draft outputs and the near final version of assessment reports, observing processes including expert elicitation discussions, and providing advice on the rigour and completeness of each risk assessment. The focus of the risk review work has been on the Pilot Deployments Program, and some additional intervention options (e.g., use of heat evolved symbionts, cooling and shading interventions) being investigated by RRAP. The overall outcome of IRRG's work has been to offer to regulators and the public assurance that the assessments of the interventions have been carried out well, the risks have been properly characterised and described, and that the regulators have the risk information they need to make informed decisions about whether to proceed with the interventions.

IMPLEMENT INTERVENTION RISK FRAMEWORK TO APPRAISE RISKS ASSOCIATED WITH RRAP-TYPE INTERVENTIONS AND THE PILOT DEPLOYMENTS PROGRAM

OBJECTIVE	ACHIEVEMENT
Implement full intervention risk framework, with iterative IRRG review, for Conservation Aquaculture and Slick Collection and Release (ecological dimensions)	The RRAP Intervention Risk Assessment for the Pilot Deployments Program (288) constituted a major advance in evaluating the ecological risks of scaling up coral restoration interventions on the Great Barrier Reef. A comprehensive approach was applied, combining expert elicitation, causal risk pathway mapping, literature review, and empirical data from RRAP research and monitoring, with IRRG review ensuring scientific rigour, transparency and credibility. The assessment focused on Slick Collection and Release and Conservation Aquaculture interventions. Potential risks were assessed across key ecological value groups, including corals (target and non-target), plankton and microbial communities (including algal symbionts), coral reef ecosystems, and other reef-associated organisms such as fish, turtles, and marine mammals. Risks were analysed across five sub-themes: coral population resilience, ecosystem resilience, disease and pests, algal symbionts, and impacts to reef structure and non-target organisms. Factors influencing the likelihood, severity and overall risk were systematically identified and considered. Across all value groups and intervention methods, findings indicated a Low overall ecological risk. This applied to all identified risk pathways, including potential reductions in genetic diversity, disease transmission, disruption to symbiosis, and physical disturbance, with strong agreement among experts. Key drivers of this low-risk profile included the relatively small scale of deployments, the use of locally sourced native corals and symbionts, high natural connectivity among reef populations, and the short duration of handling and culture phases. Existing mitigation measures were found sufficient. These include careful site and broodstock selection, genetic management, biosecurity protocols, deployment design and intensity controls,

	and ongoing monitoring. While knowledge gaps remain, these are not considered limiting for current decision-making and priority gaps are being addressed through ongoing research. Overall, the Pilot Deployments activities pose low risk to environmental and biodiversity values and were assessed as consistent with Great Barrier Reef management objectives, supporting continued progress through carefully managed testing and development of reef interventions.
Implement full intervention risk framework, with iterative IRRG review, for Pilot Deployments Program (social and cultural dimensions)	The social dimensions risk assessment advances a robust, evidence-based understanding of the social risks associated with reef intervention at pilot scale. It extends the framework to incorporate social and economic values, providing a structured and repeatable approach across eight interconnected value domains. A key outcome has been the development of a comprehensive conceptual model of social risk pathways. Through causal pathway mapping and interdisciplinary analysis, the work has clarified how intervention activities may influence social values via recurring mechanisms related to program design and governance, experiences on Country, and how outcomes are perceived and understood. This has significantly improved the conceptual understanding of how ecological interventions interact with social values, including indirect and perception-driven impacts, and the interdependencies between values such as access, wellbeing, equity and empowerment. The work integrates diverse perspectives, including Traditional Owner participation and First Nations knowledge systems, incorporating cultural values, biocultural relationships, and principles such as Free, Prior and Informed Consent (FPIC). This ensured that social risk pathways reflect cultural authority, connection to Sea Country, and the importance of equitable participation and recognition. It also provides practical risk management advice for current and future intervention programs, including guidance on governance, engagement, communication, capacity building and equitable distribution of opportunities, while identifying priorities for monitoring, research and adaptive management. Collectively, the intervention risk framework establishes a strong foundation for integrating social considerations into reef intervention design and decision-making, supporting the development of interventions that are not only ecologically sound, but socially acceptable, inclusive and sustainable.
Apply intervention risk framework, with iterative IRRG review, to assisted adaptation intervention option involving the use of heat-evolved symbionts	The framework has also been applied to assisted adaptation options involving heat-evolved symbionts, demonstrating capability to assess more novel interventions. This work evaluated their potential use (subject to approvals and FPIC) within Conservation Aquaculture under the Pilot Deployments Program, applying the ecological risk assessment iteratively with IRRG review. This improved understanding of risks and mitigation considerations, informed program design and research priorities, and strengthened confidence in its application going forward.
Apply intervention risk framework, with iterative IRRG review, to other intervention types	The framework has further been applied across a broader suite of emerging intervention types under RRAP, including Assisted Gene Flow of corals and symbionts. Through development of causal maps and risk pathways, this work articulates how these interventions may interact with Great Barrier Reef values, highlighting key mechanisms, uncertainties and areas of sensitivity for future investigation. It has also supported early-stage consideration of interventions such as fogging pilot deployments and Marine Cloud Brightening, with the assessment applied at conceptual stages to explore potential pathways, identify knowledge gaps, and inform design, experiments and research priorities. IRRG involvement has supported consistency while allowing adaptation across intervention types and stages of maturity. Full assessments have not been completed. Together, these applications are building a more consistent understanding of risks across the RRAP intervention portfolio while supporting the progressive development of assessment methods for increasingly novel and complex reef intervention options.


Image: Brightly colored *Acropora* corals. Credit: Gary Cranitch, Queensland Museum

ECOLOGICAL INTELLIGENCE FOR REEF RESTORATION

OPTIMISE INTERVENTIONS BY UNDERSTANDING NATURAL REEF RECOVERY

The Ecological Intelligence for Reef Restoration R&D subprogram ('EcoRRAP') developed and implemented critical new monitoring technologies to deliver new knowledge of coral ecology and evolution that is essential for the success of reef restoration.

Between 2020 – 2025, EcoRRAP focused on three main goals:

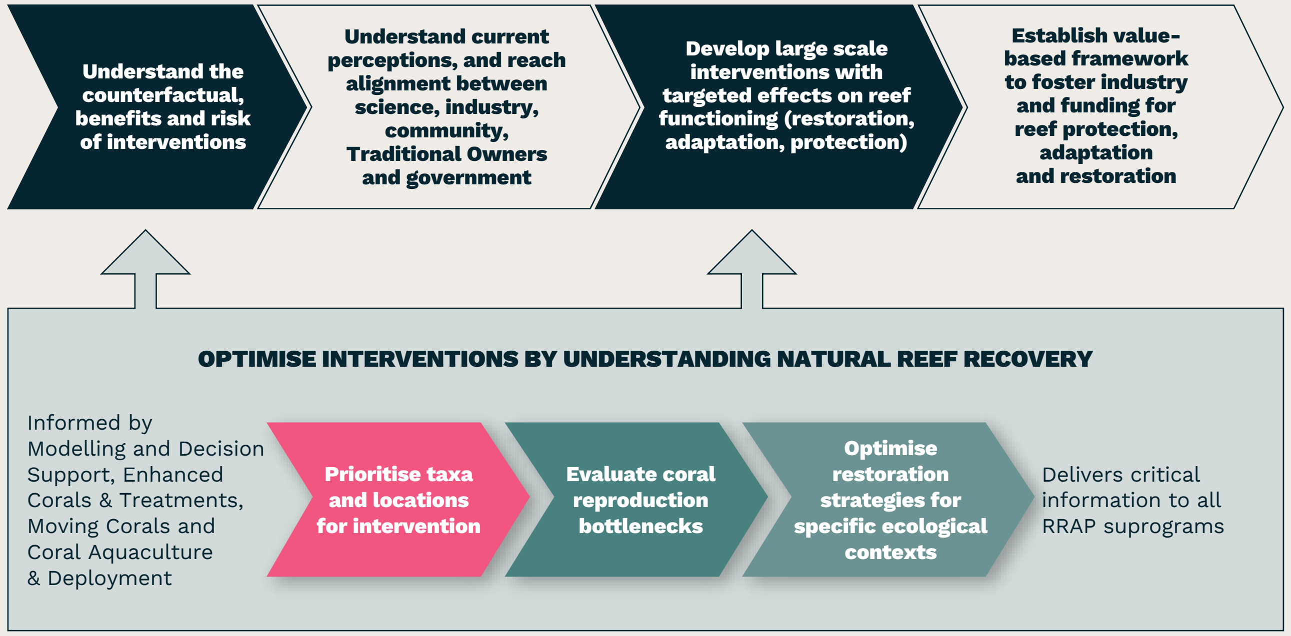
- **Prioritise taxa and locations for interventions** by quantifying coral vital rates, reef recovery, and natural adaptation at a network of sites
- **Evaluate coral reproduction bottlenecks** through assessment of larval dispersal and post-settlement survival, and coral densities required for successful reproduction
- **Optimise restoration strategies** accounting for site-specific reef dynamics, and quantifying drivers of variation in coral heat tolerance, vital rates and reef recovery potential across and along the GBR

Throughout Phase 1 of RRAP, **EcoRRAP** worked closely with the Modelling & Decision Support subprogram, the Intervention Risk Management project, and with the six Intervention Development subprograms, to ensure that intervention development and deployment was underpinned by robust and comprehensive ecological and biological data. Key outcomes from the program included: unprecedented datasets quantifying how coral vital rates vary along and across the GBR, among reef habitats and with depth; high-resolution physiochemical observations that match the spatial footprint and temporal range of the coral demography datasets; essential ecological and population genetic data for calibrating coral larval dispersal and connectivity; novel field-based experiments to determine how coral reproduction depends on the density and spatial distribution of colonies on the reef; and world-first multispecies data quantifying functional relationship between coral growth and temperature.

GOAL AND SPECIFIC OBJECTIVES

	Achievement within project scope
Prioritise taxa and locations for intervention	
Establish permanent sites on reef clusters (Reference Reefs)	
Generate high resolution physicochemical and ecological time series data	
Generate and curate data for parameterising decision support models	
Evaluate coral reproduction bottlenecks	
Quantify larval supply and settlement and validate connectivity models	
Site-specific guidelines for size, density and species of corals to deploy	
Identify locations that are likely to require ongoing deployment for recovery	
Identify threshold coral density where interventions are required	
Optimize restoration strategies for specific ecological contexts	
Understand how natural adaptation influences efficacy of interventions	
Develop guidelines for setting ecologically relevant restoration targets	
Quantify how temperature affects growth of coral species along the GBR	
Assess effects of bleaching on coral growth and heat tolerance	
Identify genomic loci that influence heat tolerance	
Understand how adaptive variants disperse among reefs over time	

At a Glance



Prioritise taxa and locations for intervention

Monitoring sites established along 1600 km of the Great Barrier Reef, spanning across inshore to offshore, and covering >104,000 m² of reef.

Developed and published novel methodologies to monitor coral reefs at unprecedented spatial and temporal scales.

Produced and disseminated coral biology & ecology datasets with unprecedented spatial and taxonomic resolution for the GBR from 2021 - 2025, including vital rates for over 25,000 coral colonies and through two marine heatwave events.

Integration of datasets with GBR ecosystem and population dynamics models.

Evaluate coral reproduction bottlenecks

Developed and applied new methods for quantifying coral larval supply and settlement that inform reef site selection to maximise intervention efficacy.

Identified specific improvements required for hydrodynamic models to accurately predict larval supply and settlement.

Revealed taxon-specific environ-mental drivers of recruitment.

Resolved coral colony density and proximity to other colonies of the same species that is required to maximise fertilisation success.

Optimise restoration strategies for specific ecological contexts

Developed and analysed new models of climate change adaptation which show that selective breeding interventions can enhance heat tolerance of coral populations.

Revealed taxon specific drivers of coral growth and survival across the length and breadth of the GBR.

Created novel datasets with unprecedented resolution of how temperature affects growth and population recovery potential of corals on the GBR.

Identified genomic signals of coral population adaptation to local reef environments.

Uncovered patterns of coral genetic diversity that reflect larval dispersal capacity and identified cryptic species.

FOUNDATIONAL DATA TO PRIORITISE TAXA AND LOCATIONS FOR INTERVENTION

OBJECTIVE	ACHIEVEMENT
Establish permanent sites on reef clusters across and along the GBR	104 permanent sites were established across 19 reefs from the Capricorn Bunkers to Masig Island in Torres Strait, spanning a distance of ~1,600km and including nearshore and offshore reefs. At each reef, survey plots were established in each of four habitats and at two depths with a total area ~104,000 m^2 (28).
Collect high-resolution biological and ecological time series data.	Reefs were surveyed over five years which included marine heatwave and mass bleaching events in 2022 and 2024 (29). At each reef, environmental conditions, genetic diversity, population vital rates (for >25,000 coral colonies), coral community composition and structure, and fish diversity, biomass and behaviour (corallivory and herbivory, (30–32)), were collected and compiled (33, 34).
Collect high-resolution physico-chemical environmental time series data	Oceanographic loggers recording temperature, salinity, light, and currents have been deployed continuously at monitoring sites since 2021. Topographic (depth, slope, surface area, surface rugosity, fractal dimensions) data across multiple spatial resolutions and extents have also been collected and curated (35–37).
Provide the biological baseline data required to evaluate the effectiveness of RRAP interventions	Data from the surveys across EcoRRAP reference reefs are publicly accessible, including 3D models of survey plots and large area maps of sites together with datasets documenting size, growth and survival of coral colonies and other variables including coral cover (38, 39). Data revealed that cryptic coral species are common and can differ in heat tolerance (40) and that coral symbionts can track latitude and inshore-offshore reef positions most closely than their coral hosts (41). Discovered that dispersal ranges widely among GBR corals, highlighting the vulnerability of brooding species (42).
Supply EcoRRAP data for improving model parametrisation at different ecological levels (from colony rates to population rates).	EcoRRAP data are now routinely used in GBR ecosystem and population models that assess where and when restoration is needed, and which type of intervention would be most beneficial. Some key examples include; 1. **C~scape:** Data on annual growth and survival from almost 10,000 coral colonies were used to build population dynamics models for six coral types. These models also assess habitat and environmental variables to inform site selection for restoration. 2. **CoralBlox:** EcoRRAP data is used to inform model parameterisation and calibration in a coral ecosystem model that compares restoration outcomes under diverse management scenarios. 3. **Ecological Heuristics:** EcoRRAP data have been combined with literature data to guide reef site selection to maximise the survivorship and growth of out-planted corals. 4. **eReefs and Relocatable Coastal Model (RECOM):** Oceanographic data have been used to improve hindcasts made by these models for the GBR and the Torres Strait. 5. **Selection of broodstock for coral aquaculture:** Information on cryptic species informs broodstock selection for coral aquaculture. 6. **Biodiversity Credit Accounting framework:** Structural complexity, benthic and fish data, informed the selection of metrics for a new Reef Condition Index.

EVALUATE CORAL REPRODUCTION BOTTLENECKS

OBJECTIVE	ACHIEVEMENT
Provide empirical rates of larval supply and relationship with settlement	Larval supply ranged from very few to >3 larvae m^{-3} in the Capricorn-Bunker region (43) and up to 10 larvae m^{-3} in the Palm Islands (44). There was a significant relationship between the number of larvae arriving and how many successfully settled on the reef. In addition, new methods were developed to successfully identify and quantify coral larvae from plankton tow samples using molecular techniques (45), and to automate continuous sampling of the water column to capture variation in larval supply over time (46).
Identify where and when enhancement of larval supply is warranted	High-resolution modelling will be required to identify sites where intervention to enhance larval settlement will be most beneficial each year (47). For the Capricorn-Bunker reefs in the southern GBR, model results indicate that parts of the northern edge of Heron Reef and the south-west edge of Wistari Reef consistently receive lower larval supply. However, larval supply and settlement varied among years (43).
Validate connectivity modelling to inform restoration strategies	Coral dispersal was measured and modelled in the inshore Palm Islands and the offshore Capricorn Bunker reefs (43, 44). Hydrodynamic model predictions correlated well with measurements of sea level and currents on the reef except at sites near channels and small passages (43). However, modelled larval supply and settlement did not reliably match supply and settlement measured on the reef at the scale important for restoration (10’s to 100’s m).

Provide guidance on the size, density and species of coral juveniles that are likely to survive in different reef environments	Success of interventions will require choosing the right coral species and size to match local conditions (48). Juvenile corals > 10 mm diameter have a better chance of survival across most reef environments, with survival increasing with size at most study locations (37, 49). Water temperature also plays a key role, with *Acropora* surviving better in cooler southern reefs, while other species, like massive *Porites* and submassive Merulindae, doing better on the warmer northern reefs (50).
Determine the criteria of site selection for macro- and micro-habitat restoration	Cooler offshore sites favoured *Acropora* recruitment, while *Porites* thrived in warmer offshore areas (48). Survival was not strongly affected by temperature overall, but responses varied by species and depended on colony size and bleaching status (37). Predation on outplanted juvenile size coral fragments was lower in areas with higher existing coral cover but bleaching of small coral fragments increased with size.
Identify sites that match criteria for restoration and recovery and where reefs would remain dependent on restored corals	Coral recruitment and survival patterns varied widely across different reef areas and coral types. Some reef sites, like the Capricorn-Bunker and Offshore Central reefs, had high recruitment and relatively high net coral gains but they also had high coral mortality, particularly for sensitive species (51). Such reefs would likely remain dependent on ongoing interventions to maintain healthy populations. Other reefs, like the Offshore Northern cluster had lower coral mortality and some strong net coral gains and are more likely to require a single year of intervention (48).
Characterise the critical densities of corals needed for effective local reproduction	Results for three corals species across two locations reveal that fertilisation worked best when colonies were within half a meter of each other and that fertilisation rates were nearly zero between colonies that were 15 and 20m apart (52). The distance to the nearest reproductive neighbour was a better predictor of fertilisation success than colony density although wind and currents also play a big role (53).
Identify the minimum target coral density that stimulates faster natural recovery	Coral populations need to exceed 13 to 50 colonies per 100 square meters to ensure reliable cross-fertilisation of gametes annually (54). Restoration efforts should aim to re-establish coral populations within this density range, with colonies placed close enough to ensure successful fertilisation (45). Restoration practitioners should also consider colony size when determining outplant density.
Provide criteria of when coral density is too low or sufficiently high for site selection.	Sites with at least 50 colonies per 100 square meters offer a much better chance for natural recovery (39), particularly if most colonies are within 4–10 meters of each other. Sites with fewer than 13 adult colonies per 100 square meters are too sparse because fertilisation success is limited (54), especially if colonies are spaced more than 10–15 meters apart. Deployments should aim to cluster corals in groups with a maximum spacing of five metres between colonies.

OPTIMIZE RESTORATION STRATEGIES FOR SPECIFIC ECOLOGICAL CONTEXTS

OBJECTIVE	ACHIEVEMENT
Gauge how ongoing natural ecological adaptation affects the effectiveness of interventions	Significant progress has been made toward understanding coral adaptation to temperature change. While substantial uncertainty remains, RRAP models now predict how selection for heat tolerance influences population dynamics and coral community trajectories under climate change. Results estimate that heat tolerance of coral populations could increase by 2.5 - 6 DHWs over the next 75 years. RRAP models also show that if assisted evolution interventions can generate sufficient increases in heat tolerance of deployed corals this can significantly enhance the heat tolerance of coral populations on the reef.
Assess effects of coral community composition on reef recovery, biodiversity and ecosystem functions	Using large-area-imaging and artificial intelligence on large areas of reef (>25,344m^2), analyses confirm that reefs in the GBR and the Torres Strait have diverse and variable community composition and structure, and this influences reef recovery potential (55). Community composition and structure varied from north to south, from inshore to offshore and among habitats and reefs. Further research is needed to reveal whether there is an optimal benthic community structure to promote reef recovery and maintain biodiversity and ecosystem functions (56).
Quantify variability in vital rates of key species across environments, and how different species contribute to reef recovery	Across and along the GBR and Torres Strait, coral growth and survival varied markedly among taxa and were strongly size-dependent (49). For all coral taxa between 2021-2022, small (~5 cm diameter) colonies exhibited ~85% annual survival compared to ~93% for medium (10–20 cm) and ~96% for large (>80 cm) colonies . Smaller colonies showed faster relative growth compared to larger colonies. Taxa with slower growth (i.e. massive *Porites, Goniastrea, Platygyra*) had higher survival (97–99%) than fast-growing branching taxa (e.g. 89-92% for tabular and corymbose *Acropora*), consistent with well-established life-history trade-offs (57). While growth and survival were consistent across environmental gradients for most taxa, some taxa (*Acropora* and *Pocillopora*) were affected by turbidity, temperature, or current velocity. In contrast, recruitment was driven primarily by environmental gradients. Current velocity, sedimentation, and depth negatively affected recruitment, with offshore, clear-water reefs exhibiting three-fold higher densities than inshore turbid reefs (58).
Appraise trade-offs between community resistance and ecosystem functions, and determine ecologically relevant restoration targets	Comprehensive data are now available to identify which vital rates limit coral population maintenance and recovery potential, and how this varies across and along the GBR (51, 59). For *Acropora* (a taxon important for recovery) recruitment was higher offshore, particularly on reef backs and flanks, whereas inshore reefs, and especially reef fronts, appear recruitment limited. However, *Acropora* had higher survival inshore versus offshore and on reef backs versus fronts. In contrast, colony growth was

	higher inshore versus offshore across all size classes and it was higher in the Northern GBR compared with the Southern GBR. Collectively these data identify regions, reefs and habitats where coral populations naturally recover either through persistence and growth of remnant colonies or through recruitment (57). Such information is critical to determine which interventions should be implemented in which locations to accelerate reef recovery where it is most needed (59).
Identify the key predictors for reef recovery potential across different reef environments	RRAP data now enable interventions to be tailored to complement the dominant recovery process in each environment. However, rates of reef recovery depend on post-disturbance size structure, subsequent recruitment dynamics, and species composition (37). During the 2022 bleaching event on the GBR, the effect of depth on colony-level bleaching severity was taxon- dependent, and the effect of wave velocity differed between inshore and offshore reefs. In general, bleaching lowered coral survival and growth, with larger colonies better able to survive and grow during heat stress compared to smaller colonies (49). Environmental effects on growth and survival were secondary to the effect of size and bleaching severity.
Resolve the relationship between environmental conditions and historical maximum coral cover.	Novel analyses of 32 years of data from the GBR now demonstrate how environmental factors (hard substrate, temperature and water clarity) constrain the maximum coral cover ‘upper limit’ that a benthic community can sustain (29, 36). Overall, upper limits were much lower than is commonly assumed and they varied across and along the GBR (median of 33% coral cover, and only 17% of locations exceeded 50% coral cover). Upper limits increased with hard substrate availability and also increased towards the southern reefs compared with central and northern regions. These analyses are critical for prioritising sites for interventions as sites with similar coral cover can actually be in very different stages of recovery depending on the site-specific upper limit and coral composition (33).
Quantity how chronic and acute temperature changes affect coral growth	Using a large temperature-growth experiment conducted over three years in aquarium facility, RRAP has delivered a step-change in understanding how temperature effects growth for five coral taxa. For all species, growth is slow at low temperatures, increases gradually with rising temperature, reaches an optimum where growth is maximised, and then quickly declines as temperatures continue to rise toward a clear thermal maximum at which growth is no longer possible. This study also determined how acute heat and cold stress affects subsequent growth of surviving coral colonies. Results show 50-150% decreases in growth for all species which lasted at least six months following exposure to both high (30°C and 31°C) and low (19°C and 21°C) temperatures (60).

Assess how growth temperature curves vary between taxa and across the GBR	There were distinct differences in growth-temperature relationships for different species (60). While all coral taxa exhibited a reduction in thermal optimum from north to south, the shape of the temperature-growth curves varied between taxa. One branching coral taxon, *Pocillopora verrucosa* consistently exhibited the highest—or second highest—thermal optimum across all reefs, making this species a promising candidate for assisted evolution initiatives. Overall, chronic temperature increases under climate change will have different effects on coral growth depending on species and region, and changes in growth rate may limit population recovery after disturbance events (61). When incorporated into models of coral community dynamics, among-species differences in how temperature affects growth can lead to changes in coral community composition over time under some climate change scenarios.
Resolve the relationship between local historic temperature patterns and local growth temperature curves	Growth temperature curves–and particularly thermal optima–showed a strong positive relationship with local (reef-level) historic summer temperatures. This pattern was further supported by the high consistency in thermal optima among individual colonies of the same taxon from a given reef. Together, these results provide strong evidence of local thermal adaptation of growth across all coral taxa studied (61).
Identify how historical thermal exposure relates to local thermal optima and thermal maxima for coral colonies and populations	For corals on the GBR, the optimal temperature for growth is more closely aligned with local summer temperatures than the thermal maximum at which growth is no longer possible. While the far southern reefs exhibited a lower critical maximum temperature, reefs across the remainder of the thermal gradient showed similar values. These patterns suggest that, over evolutionary timescales, natural selection has resulted in corals having a thermal optimum that is finely tuned to the local thermal environment, and that tuning the thermal optima has had a greater effect on population fitness than adjusting the thermal maximum to match the highest temperatures experienced occasionally on the reef.
Determine how coral colony growth shifts across populations and communities following bleaching in different regions	Corals from the warmer northern reef exhibited significantly greater growth reductions after cold stress, whereas corals from the cooler southern reef showed greater reductions following heat stress. Therefore, proposed interventions involving transplantation of heat-tolerant corals from northern to southern reefs on the GBR must account for potential growth suppression in winter when assessing risks and benefits of such interventions. Additional work quantifying latent effects of marine heatwaves showed that colony size and bleaching severity were the most important drivers of reduction in growth and survival probabilities during the year following the mild mass bleaching event, with only marginal effects from environmental conditions (49).

Evaluate how bleaching responses of coral colonies and populations scale with temperature optima	The shape of the relationship between temperature and coral growth was not a reliable predictor of species' tolerance to marine heatwaves based on field observations of coral bleaching (62). This is likely because different metabolic pathways control colony growth compared with the pathways that are involved in the breakdown of the symbiosis between the coral host and algal symbiont during marine heatwaves.
Assess how rapidly the optimal temperature for coral colony and population growth shifts due to bleaching events	Based on the poor correlation between heat tolerance and growth versus temperature relationships, our results suggest that marine heatwaves are unlikely to cause a rapid shift in the optimal temperature for coral growth. It remains unclear whether and how the shape of the relationship between growth and temperature will shift under climate change.
Quantify how heat tolerance differs among coral species and aligns with coral traits	Comprehensive data now quantify how coral growth depends on temperature for multiple coral taxa and demonstrate that among-taxon variability in these relationships is linked to morphological and life-history traits (37, 49). For example, the heat-sensitive tabular coral *Acropora hyacinthus* has slower growth in summer but maintains growth at 80% of its maximum growth for >70% of the year at most locations. In contrast, the heat-tolerant branching coral *Pocillopora verrucosa* grows slowly in winter and only grew above 80% of its maximum growth for 45-65% of the year to maximise growth in summer (61, 62).
Estimate the distribution of naturally occurring adaptive genetic diversity, especially linked to heat tolerance, for GBR corals	Across the GBR, populations of the brooding coral *Stylophora pistillata* are genetically distinct at each reef and there are low levels of genetic mixing between reefs (63). Consistent with this low mixing, *S. pistillata* populations have genetic differences related to heat adaptation that are mostly unique to each region. In contrast, genetic diversity linked with temperature adaptation is geographically widespread in a spawning species that has higher larval dispersal (*Pocillopora verrucosa*) (42). Revealed that there is extensive 'hidden' coral biodiversity on the GBR, with 'cryptic' genetic clustering of corals within species and species-complexes that often segregate by environment (40).
Identify genomic loci that are candidates for thermal tolerance	Results from genomic analyses (based on genotype-by-environment associations) show that *Stylophora pistillata* corals are adapting to temperature changes within individual reefs. While most of the genetic markers involved in adaptation differed between reefs, 29 of these genetic adaptations appeared repeatedly in different populations (62).
Determine whether the geography of natural adaptive variation is consistent among coral species	Analysis of over 800 colonies of the coral *Acropora hyacinthus* revealed that genetic mixing between closely related species (hybridisation) shares adaptive variation among taxa in the Capricorn Bunker region (64). However, hybridisation was much less common in the northern reefs. Results also showed that certain genetic signals of adaptation were consistent among different species in the south, suggesting that hybridisation may enable these populations to co-adapt to changing conditions (62).
Assess whether reef-level adaptive genetic diversity is predicted by environmental or geographical attributes	Comprehensive surveys of genomic diversity for four GBR coral species showed that genetic diversity did not differ among reefs or regions for two species and one species complex. However, for the *Acropora hyacinthus* complex (which consisted of 4 district groups) average genetic diversity differed among regions. These data indicate species and regions where coral populations are more likely to adapt to environmental change (62).
Evaluate spatial and time scales over which natural gene flow is sufficient to spread adaptive variants	The scale of larval dispersal determines how adaptive genetic variants spread throughout the GBR. Data for seven coral species (*Stylophora pistillata, Pocillopora verrucosa, P. damicornis, Acropora spathulata, A. millepora, A. kenti* and *Pachyseris speciosa*) revealed that the 'neighbourhood' of genetically similar corals was relatively small for most species, just tens to hundreds of meters (62). However, for spawning species with higher dispersal potential, gene flow extended across entire reefs, likely spreading genetic variants more widely.

Image: *Spirobranchus* worm.
Credit: Gary Cranitch, Queensland Museum

CASE STUDY: PUBLICLY AVAILABLE DATASETS

RRAP is a public good initiative committed to sharing knowledge and insights for the benefit of the wider scientific community. Alongside peer-reviewed publications, RRAP datasets are curated and hosted within established repositories that are maintained by partners and affiliated research initiatives. Datasets aim to apply recognised standards and identifiers, ensuring information remains accessible and reusable over the life of the Program and beyond.

Dissemination of RRAP datasets has been further supported through presentations and discussions at national and international conferences, workshops, and scientific meetings. The mission has been to raise awareness of emerging insights, encourage reuse by the research community, and foster new collaborations across institutions and disciplines.

Publication

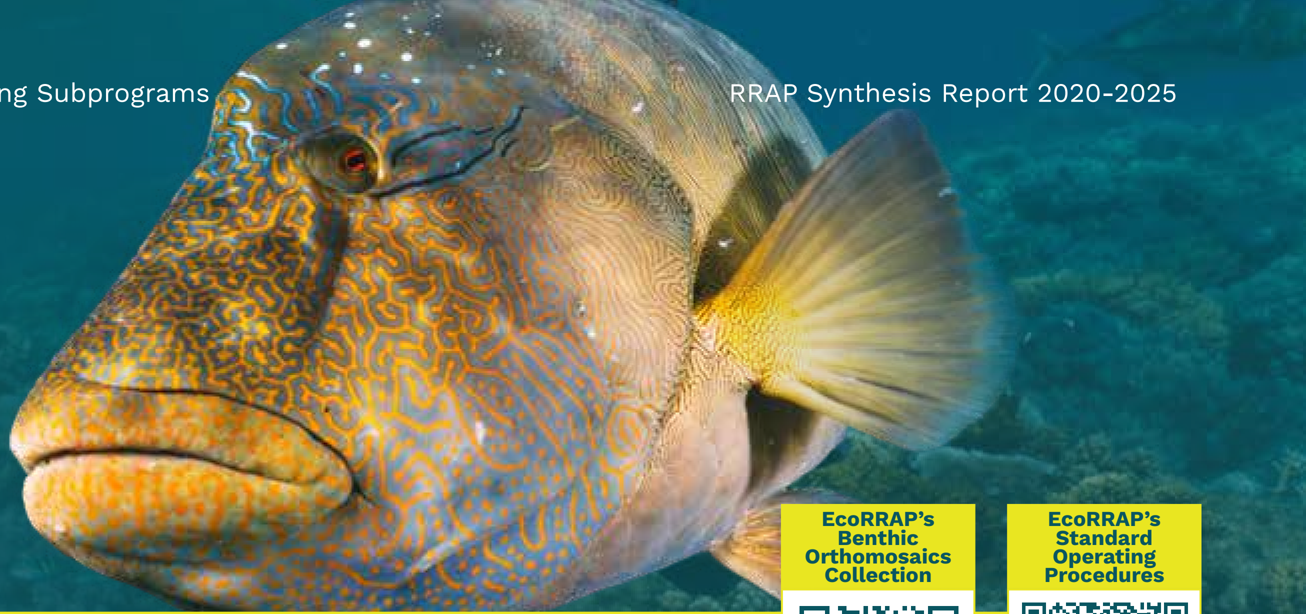
DIGITAL DATA HUB FOR DECISION DESIGNERS

RRAP's Modelling and Decision Support subprogram aims to enable reef managers to make quality decisions about the potential implementation of interventions on the Great Barrier Reef.

The M&DS Information System has been a central to this process. It acts as a digital hub to easily collate data and complex information from multiple sources. It then makes that information available to users, including data synthesis and summaries. The IS has secure storage and embeds clear records of the data sources and workflows.

This capability has improved continuity across project phases and has enabled the team to build directly on previous modelling work rather than restarting analyses.

Image: Reef with scaling reference tools used to produce 3D maps of reef.
Credit: AIMS



EcoRRAP's Benthic Orthomosaics Collection

EcoRRAP's Standard Operating Procedures

INTELLIGENCE FOR INTERVENTION

RRAP's Ecological Intelligence Subprogram aims to maximise the success of restoration interventions by advising on the 'what', 'where', and 'when' of interventions, and by filling crucial gaps in ecological knowledge of the Great Barrier Reef.

EcoRRAP designed and implemented a field-program in the Great Barrier Reef and Torres Strait. Site instrumentation and monitoring have generated an enormous baseline of empirical data, asking and answering - what should reef recovery and growth look like? What drives it? Where is it most successful and why?

These datasets include high-resolution spatial records of reef condition over time, obtained through underwater photogrammetry, known as benthic orthomosaics. Information can be used for ecological analysis, model parameterisation, and comparative studies, and have been embedded in RRAP's M&DS systems to assess the benefits and risks of intervention in a particular time and place on the Reef.

EcoRRAP's data collection methods have also been published as a suite of Standard Operating Procedures, offering new solutions for reef managers or restoration practitioners to monitor natural recovery and the impacts of an intervention.

Image: EcoRRAP Project Lead Renata Ferrari (AIMS) holding scaling reference tool.
Credit: I McLeod

MODELLING AND DECISION SUPPORT

ENABLE DECISION-MAKERS TO REACH HIGH-QUALITY DECISIONS THAT GUIDE INVESTMENT AND ACTION IN REEF RESTORATION AND ADAPTATION.

The Modelling and Decision Support R&D subprogram ('M&DS') functioned as an independent decision-support enterprise that was appointed to guide cross-institutional modelling capability development and application.

Between 2020 – 2025, M&DS focused on three main goals:

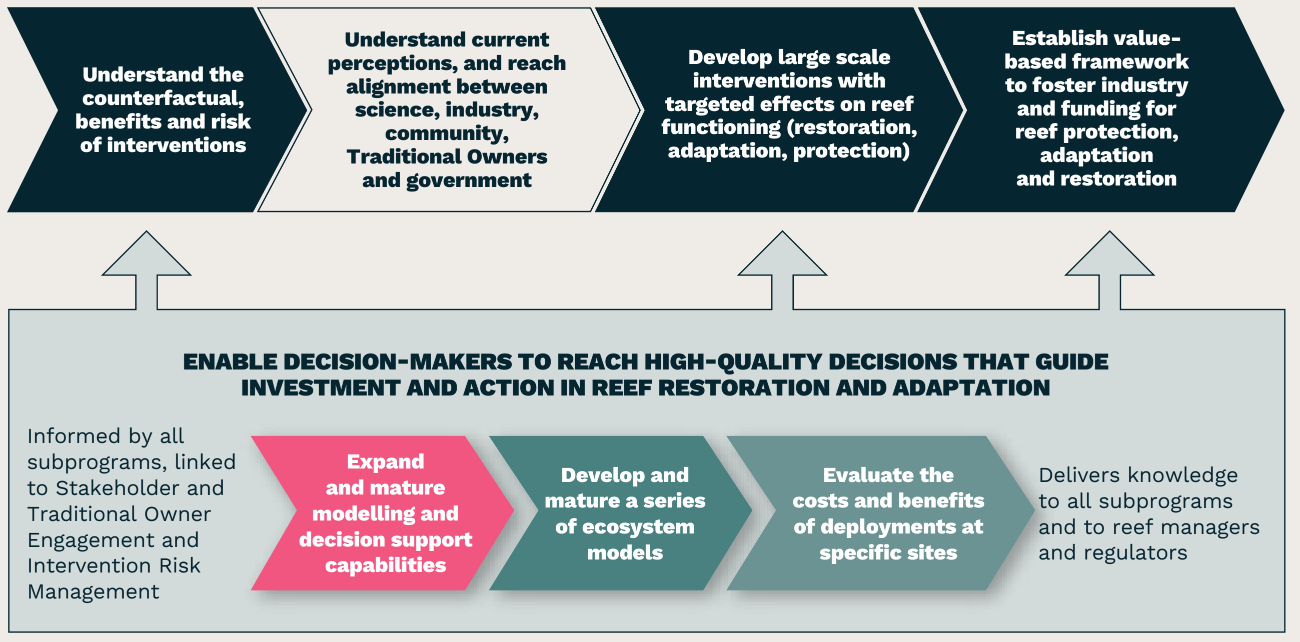
- **Develop and mature a series of ecosystem models** to characterise the range of likely future ecological states of the GBR under different climate change and intervention scenarios
- **Expand and mature modelling and decision support capabilities** that optimise net benefits of intervention research and development for the GBR.
- Evaluate the **costs and benefits of deployments at specific sites within reefs,** with consideration of coral vital rates and site environmental conditions

Throughout Phase 1 of RRAP, M&DS operationalised and applied new capability for making and communicating quality decisions regarding use of RRAP interventions for resilience-based management of the GBR. The integration of Trust, Knowledge, and Partnership principles underpinned delivery of credible support for high quality decision-making. Work within M&DS has ensured that physical, ecological, value and risk modelling of the Reef, and interventions, are consistent, defensible, informative for decision-making, and will endure beyond the life of the Program. The systematic approach to capability maturation, stakeholder engagement, and programmatic integration positions M&DS to support the transition from pilot-scale interventions to large-scale reef restoration and adaptation operations, contributing to the resilience-based management of the Great Barrier Reef under climate change.

GOAL AND SPECIFIC OBJECTIVES

	Achievement within project scope
Expand and mature modelling and decision support capabilities	
Test and refine pathways to decision-making about deployments	
Develop and operationalise RRAP Decision Support tools	
Develop and implement an integrated RRAP Information System	
Develop and mature a series of ecosystem models for evaluating RRAP interventions	
Enhance ReefMod capability to incorporate heat stress and predict bleaching	
Extend ReefMod to estimate reef carbonate budgets	
Improve reef connectivity estimates using CoCoNet and eReefs	
Create and integrate a model of genetic adaptation in corals	
Develop a user interface for scenario testing (RRAP Restoration Explorer)	
Evaluate costs and benefits of deployments at specific sites within reefs	
Develop a new model to estimate within-reef variation in coral dynamics	
Compare how demography versus environment affects intervention success	
Partition uncertainty between processes to assess intervention benefits/risks	
Develop and apply a spatially-explicit coral model at the within-reef scale	

At a Glance



Design, test and refine risk management framework

Demonstrated that interventions can potentially deliver robust outcomes against multiple objectives under uncertainty and constraints.

Supported informed strategic and tactical intervention decision-making and management planning.

Decision-support tool designed to help reef managers, modellers and decision-makers address the challenges of adapting to climate change in coral reefs.

Comprehensive Information System that integrates previously siloed datasets and systems to deliver science-based insights.

Develop and mature a series of ecosystem models

Improved capability to forecast reef conditions and values under different climate change scenarios and 'no-intervention' (counterfactual) scenario.

Ecological models matured to now accurately hindcast, and predict future impacts of,mass bleaching on the GBR with depth-and taxon-specific responses.

Downscaled projections of climate change based on the latest climate models to provide more accurate estimates of severity and impacts of future heat stress events.

Incorporated genetic adaptation of corals to heat stress into ecological models to produce more robust projections of future coral resilience and adaptive capacity under climate change.

Evaluate the costs and benefits of deployments at specific sites

Developed, tested and refined a new coral population dynamics model that resolves dynamics at the spatial scale of a typical RRAP intervention deployment site.

Formulated models to generate predictions that capture biological, ecological and environmental variability and uncertainty.

Showed that variability in coral population dynamics decreased in warmer climate futures as most trajectories were compressed towards low coral cover.

New capability to simulate the outcomes and efficacy of RRAP cooling and shading interventions, assisted evolution, and larval reseeding and coral seeding interventions, including scenarios with deployment of one or multiple interventions simultaneously.

EXPAND AND MATURE MODELLING AND DECISION SUPPORT CAPABILITIES

OBJECTIVE	ACHIEVEMENT
Enable the appropriate people to make and communicate quality decisions for development and deployment of interventions to optimise net benefits to the GBR.	Since inception, successfully delivered 14 separate Modelling and Decision Support studies across a range of critical research questions. Each study generated actionable knowledge and leveraged existing datasets, models, processes and systems together with new knowledge generated by RRAP. Studies included: • What is the ecological outlook for the GBR under possible climate futures? • What do we learn from counterfactual modelling at site-scale versus reef-scale versus region-scale versus GBR-scale? • Which reefs and reef clusters meet desired attributes for intervention? • Which reefs have common characteristics to inform understanding of intervention value at scale? • How do reefs within a cluster interact and what are the implications for reef selection for deployment? • What are the impacts of site-scale deployment considerations on intervention efficacy and value? • How do different levels of coral enhancement influence outcomes? • What is the impact of enhanced coral deployment on native corals?
Test and refine the pathway to decision-making across RRAP in relation to location selection for RRAP Pilot Deployments Program	Ensured that the right combination of people, processes, information, and technology were in place to support confident, timely decisions and identify any gaps requiring further refinement (65, 66). Success of the capability was evident in the site selection process for the Pilot Deployments Program. The structured process reduced a combinatorially vast space (thousands of potential sites, dozens of criteria, diverse stakeholder views) to a defensible preferred list of 53 candidate reefs. The process involved iterative discussions over roughly 12 months and incorporated a satellite/ReefGuide longlist, a Cairns stakeholder workshop (29 participants, 460 comments across 85 reefs), and a technical workshop with 21 specialists.
Ensure programmatic integration across RRAP and other aligned programs	Developed the M&DS suite as a nested, multi-scale framework: ReefMod (67) and CoCoNet (68) provide regional projections; C~scape (69) translates these to reef-cluster scales; CoralBlox (70) resolves sub-reef ecological processes relevant to intervention design; ADRIA wraps CoralBlox in a decision-support shell for rapid scenario comparison and can also run the ecosystem models for more comprehensive analyses; and ReefGuide provides spatial screening for candidate sites. The Information System centralises data management and model integration across the suite. Aligned the ecological and intervention-specific knowledge emerging from RRAP subprograms with the development and testing of the M&DS suite. Integrated development of the M&DS suite across RRAP, the COTS Control Innovation Program, Reef 2050 Plan Reef Integrated Monitoring and Reporting Program (RIMReP) and the Reef Authority (71). Through this integration effort, RRAP aimed to share current knowledge and capabilities in data management, modelling and decision support across the Reef Trust Partnership Programs, and to identify opportunities for further alignment and integration. A series of workshops held between May and October 2023 facilitated rich knowledge exchange, strengthened connections, and identified clear actions for continued collaboration.
Develop and implement a Communications Plan to ensure effective collaboration across partners and participant entities	Embedded the RRAP M&DS guiding principles (below) to demonstrate the value of collaborative dialogue for producing robust, policy-relevant research. • Trust: Deliver insights that are credible, defensible, and trusted by stakeholders and the scientific community. • Knowledge: Work with decision-makers to generate and communicate evidence-based insights for reef management. • Partnership: Co-develop and apply fit-for-purpose tools to support long-term reef restoration decisions. RRAP M&DS provided comprehensive briefings to the IRRG through structured sessions to ensure that IRRG members understood M&DS capabilities and could make informed decisions about modelling approaches for reef interventions. RRAP M&DS also led a comprehensive stakeholder engagement process centred on understanding and reporting climate risks to the GBR and implications for Australia. This process exemplified collaborative dialogue, resulting in significant improvements to the report, including: • More explicit articulation of model assumptions, limitations, and their potential implications for projections. • Clearer presentation of the range of possible outcomes and the factors influencing projection reliability, including improved integration of uncertainty. • Clearer comparison of model predictions against observational data and more nuanced interpretation of results. • Enhanced discussion of regional variations and management implications. • More detailed explanation of coral adaptation modelling. • Enhanced discussion of the functional relationship between heat stress and coral mortality in the models.

Systematically increase the breadth and maturity of modelling and decision support capability within RRAP.	Over the duration of RRAP Phase 1, the M&DS capability evolved from meeting the specific knowledge needs of RRAP to delivering broader GBR decision support and providing traceable, and accessible knowledge via the RRAP Information System. This was achieved by integrating previously siloed datasets and systems to deliver science-driven insights in relation to: • Reef Counterfactuals: Forecast reef conditions and values under different climate change scenarios and conventional management approaches. • Reef Interventions: Evaluate whether and how interventions can deliver robust outcomes against multiple objectives under uncertainty and constraints. • Reef Characterisation and Selection: Support informed strategic and tactical intervention decision-making and management planning. Established working groups to drive critical programs of work that relied upon the coordination and collaboration across R&D teams, including: (i) Operational Delivery Improvement, (ii) Decision Support Systems, (iii) Model Evaluation and Validation and (iv) Publications. Working groups focused on the integration of capabilities, validating models and enhancing operational processes, capturing and documenting standard ways of working, ensuring quality consistency and more efficient delivery. Developed a Technology Strategy to set and define the maturity levels and technical governance required to ensure M&DS studies and outputs directly aligned with RRAP's objectives, resource constraints and timelines. Subsequently, an Operational Delivery Improvement group led the implementation of the Strategy, including developing a data management plan and maturity assessment framework.
Complete and release decision support platform to enable rapid assessment of multiple intervention scenarios	Successfully created ADRIA (Adaptive Dynamic Reef Intervention Algorithms), a decision-support tool designed to help reef managers, modellers and decision-makers address the challenges of adapting to climate change in coral reefs (72). This tool wraps CoralBlox in a decision-support shell and can also run the ecosystem models for fuller analyses. Overall, ADRIA allows evaluation of different conservation solutions in complex settings where multiple objectives need to be considered, and helps investors identify which options represent the highest likelihood of providing returns on investment (73). ADRIA uses a set of dynamic Multi-Criteria Decision Analyses which simulates a reef decision maker to identify candidate locations for intervention deployment which consider ecological, economic and social benefits (74, 75). The platform translates outputs from ecological models to three metrics for ecosystem-service provision (Reef Condition Index, Reef Tourism Index, and a Reef Fishing index) that are used to inform economic models (73). ADRIA has been effectively integrated with other models in the RRAP M&DS suite (e.g., ReefMod), facilitating numerous explorations of management intervention scenarios (76).

Develop and implement an Information System to streamline integration of RRAP datasets and model simulation results,	Developed, tested and applied an Information System that draws together coherent specifications that meet the needs of the M&DS suite, the RRAP program, stakeholders and end-users to integrate knowledge, systems and processes (77). The information system successfully facilitated user and study team engagement (78).
Expand capability of eReefs and CoCoNet for improving ecosystem connectivity and adaptation estimates.	The CoCoNet model provides regional reef-connectivity projections alongside ReefMod, with eReefs delivering particle tracks. The parameterisation and functionality of CoCoNet for incorporating extensive data inputs in near real-time, integration with eReefs, monitoring ecosystem dynamics and simulating effects of RRAP interventions has been substantially improved. The eReefs component delivered particle tracks for the entire GBR (using the GBR1 model) and individual reefs (using nested RECOM models, e.g. (79)). Improved ecosystem connectivity estimates (80, 81), and incorporating natural adaptative capability, provide a clearer picture of what is happening across the entire GBR ecosystem and more accurate predictions of future responses to scalable interventions.

IMPROVE FUNCTIONALITY OF ECOLOGICAL MODELS FOR EVALUATING RRAP INTERVENTIONS

OBJECTIVE	ACHIEVEMENT
Improve ReefMod parameterisation and functionality, including: improvement of bleaching models; hindcast reconstruction of coral cover trends; and downscaled projections of heat stress.	The parameterisation and functionality of the ReefMod model has been substantially improved. First, ReefMod now provides better projections of the impacts of coral bleaching, including directly linkages to empirical data and incorporation of depth- and colony-dependent responses (76). Previously in the model, all coral colonies at a site had the same heat tolerance but ReefMod now incorporates among-colony variation in heat tolerance to provide more accurate reproduction of the observed relative coral cover changes after bleaching on the GBR using AIMS LTMP and MMP datasets (67). Second, RRAP M&DS has consolidated the ability of ReefMod to reconstruct past trends of GBR coral cover by revising the hindcast (2008-2024) using updated environmental data for bleaching and cyclones and coral connectivity (GBR1 which increases the resolution of larval dispersal to 1 km compared to 4 km previously). With these improvements, the latest hindcast of coral cover trajectories closely aligns with observed trends in GBR-wide coral cover from 2008 to 2024 . Third, projections of climate change based on the latest climate models (CMIP6) have been downscaled to 10 km resolution which provides better estimation of the severity and impacts of future heat stress events . Additional technical work was completed to reduce the influence of warm-biased models in the final ensemble of GBR warming model projections. Results indicate that keeping global warming below 2°C would allow coral recovery in the second half of the century as

	temperatures stabilise. Under the most likely pathway (SSP2-4.5, ~2.7°C), the GBR is on a high-risk trajectory: there is a 95% likelihood that average coral cover will not exceed ~6.7% by 2050 across the more likely scenarios, and under SSP2-4.5 coral cover is projected to decline to ~5% by 2100. Higher-warming pathways (SSP3-7.0, ~3.6C; SSP5-8.5, ~4.4C) produce universally dire outcomes across all model runs (82).
Extend ReefMod to include an important reef value: carbonate budgets	Successfully incorporated bioerosion by parrotfishes into operation within ReefMod to enable estimation of reef carbonate budgets. Quantified relationships between parrotfish foraging and bioerosion over depth and showed that bite rates of 5 parrotfish species did not change with depth. However, bioerosion models parameterized using bite rate data from the northern GBR overestimated bioerosion by ~50% on the southern GBR, highlighting the importance of using region- or site-specific bite rate data (83). In addition, applied a computed tomography-scanning approach to measure the density of the reef substratum over depth and showed that, with every 1 m increase in depth, the density of any dead substrata decreased by 2.5%. However, for reef carbonate budgets to be more precisely estimated for the GBR, additional research is required to determine latitudinal parrotfish bite rates and site-specific substratum density.
Create and integrate a model of genetic adaptation in corals	Refined the model of coral adaptation to warming in ReefMod to produce more robust projections of future coral resilience and adaptive capacity under climate change (82, 84). The evolutionary model has been simplified to a single trait (survival) to simulate the dynamics of coral survival under acute heat stress. Analyses of the new model show that limiting global warming to no more than +2°C above pre-industrial levels is critical for maintaining coral populations at levels necessary to sustain viable reef ecosystems on the GBR (82, 85). In parallel, developed and applied an eco-evolutionary genetic simulation of a single reef experiencing projected climate change under various theoretical assisted evolution interventions (coral fragmentation, selective breeding, assisted gene flow, and gene editing). Initial results suggest that interventions such as gene editing, selective breeding, and assisted gene flow would greatly enhance the reef relative to the counterfactual. Gene editing has the most beneficial effect, while selective breeding and AGF have positive effects without compromising genetic diversity.
Build the RRAP Restoration Explorer	Successfully created and trialled a 'fast' version of ReefMod that is embedded in a user interface to considerably increase our simulation capacity while promoting interoperability with other decision-support tools (e.g. ADRIA). Used the model to simulate the effects of deployment of RRAP interventions (assuming start date in 2030) throughout the century (86). Analyses showed that increasing the area of restoration could result in higher benefits in coral cover, ranging from 5-10% depending on the number of corals deployed. Furthermore, there was up to 4-fold increase in coral cover benefit when the out-planted corals had +5 DHW greater heat tolerance, compared to non-enhanced coral out-plants (76). This +5 DHW enhancement represents an upper-bound modelling scenario; demonstrated enhancement at this level has so far been achieved only under nursery and laboratory conditions, whereas realistic enhancement from currently deployable local-to-local restoration is of order ~1 DHW. Created user-friendly interfaces that do not require any coding skill and that allow reef practitioners to set-up, run and visualise specific scenarios of interventions across the GBR. Conducted workshops with reef practitioners to demonstrate the capabilities of the software and associated web-based interface.
Improve model credibility in simulating inshore reef dynamics	Not yet completed for ReefMod due to reprioritization of effort toward eco-evolutionary models of coral adaptation.
Integrate the effects of ocean acidification and coral reproduction via brooding	Not yet completed for ReefMod due to reprioritization of effort toward eco-evolutionary models of coral adaptation.
Updated parameterization of thermal traits (coral growth, mortality, fecundity)	Not yet completed for ReefMod due to reprioritization of effort toward eco-evolutionary models of coral adaptation.

DETERMINE THE COSTS AND BENEFITS OF DEPLOYMENTS AT SPECIFIC SITES WITHIN REEFS, WITH CONSIDERATION OF CORAL VITAL RATES AND SITE ENVIRONMENTAL CONDITIONS

OBJECTIVE	ACHIEVEMENT
Develop an Integrated Population Model (C~scape) that can incorporate empirical data delivered by RRAP quantifying coral vital rates and fine scale physical and environmental data.	Developed, tested, refined and applied a new ecological model that represents ecological mechanisms at a 'site' level consistent with the spatial scale at which interventions are deployed and intervention benefits will first be detected. C~scape uses a series of spatial layers to divide each reef into a set of ecologically relevant patches that represent all the available substrate for corals to inhabit. Each 'site' has distinct depth, wave exposure and proportion of suitable substrate and sites are connected through a new and high-resolution connectivity model (81). The ecological engine of C~scape is a site-specific Integral Projection Models that predict the number of corals of each size for each of six coral types from one year to the next based on environmental conditions (69). C~scape also explicitly models dynamics of population thermal tolerance as a function of natural selection on heat tolerance. This new model already incorporates the latest coral demographic data for the six coral types monitored by EcoRRAP, including temperature-growth relationships and coral

	dispersal ranges based on population genetic analyses. In summary, coral population dynamics are based on site-specific coral colony growth and mortality rates which are determined from: the temperature experienced each day of the year; site wave exposure, depth and region of the GBR; the disturbance regime at the site; and the amount of coral recruits of each coral type coming from other sites within the cluster and/or reefs around the cluster via linkage to the regional-scale ReefMod model.
Develop C~scape to capture uncertainty in coral growth, survival and fecundity and propagate this through to population level outcomes	A Bayesian framework for the growth, survival and fecundity of corals allows predictions of population growth that capture the uncertainty within each of these vital rates. This uncertainty is then propagated across the sea scape generated by the model, and emergent trends in the simulated coral communities are captured. Results showed that within-reef variability in coral population dynamics was maintained under the most optimistic climate change scenarios but decreased across multiple spatial scales in warmer climate futures as most trajectories tended to be compressed towards low coral cover by mid-century (87).
Identify sensitivities in the coral life cycle where increasing the abundance of a demographic stage leads to the greatest change in the overall population growth.	Evaluated the sensitivity of coral population growth to demographic processes in different environments. Simulated a theoretical reef that has four sites with different depths and wave exposure and then analysed C~scape on that theoretical reef using coral demographic data from different GBR regions. Results showed that differences in growth and survival across regions could cause substantially faster recovery of coral cover in the northern GBR and in shallow sites. Differences in vital rates had a stronger effect in interaction with wave exposure in the central and southern GBR compared with the north. Finally, findings suggest that fewer baby corals would need to be deployed in the northern GBR compared to the central or southern region to achieve similar intervention benefits.
Improve the capacity of the model to capture fine-scale connectivity.	Iteratively improved the site characterisation of C~scape to align with the resolution of the available within-reef connectivity layers. The most recent site clustering pipeline provides a distribution of site sizes that is ideal to maximise its compatibility with the available connectivity. Furthermore, the resulting site size frequency distribution is very similar to the planned targeted size of sites for deployment of enhanced corals during the Pilot Deployments Program.

Expand the capacity to include intra-reef site variables in the model which can influence population growth and the success of interventions.	As described above, C~scape was developed to represent ecological dynamics at sites based on local conditions and vital rates (69). Sites are assigned a specific geomorphic type, wave exposure, depth and amount of suitable coral habitat. By characterising sites in this way, it is then possible to generate site specific population projections based on the variation in vital rates with environment. Ultimately, this approach enables C~scape to explore the dynamics generated by the interaction between demography, connectivity, simulated interventions, and disturbance regimes (37).
Compare the relative importance of demography, intra-reef variability, temporal dynamics, and connectivity in their influence on intervention success.	C~scape can identify environmental conditions and demographic patterns that determine intervention efficacy. For instance, the model outputs the expected size and cumulative survivorship that deployed corals are expected to have after five years as a function of their taxa and the region where they are deployed. Simulating the properties for corals deployed in different habitats within reefs can, therefore, identify the habitats and deployment tactics that yield the most surviving large corals after 5 years. Analyses of the model indicate that interventions might need double the number of corals in the south compared to the north to generate a similar targeted number of reproductive adults. This modelling capability is critical for optimizing deployment strategies and tactics.
Build capability to partition uncertainty between demographic processes and site characteristics to assess projected intervention benefits and risks	C~scape has been purpose-built to uptake the demographic data generated by the EcoRRAP program and to capture the site-level spatial scale needed for informing site selection for interventions. C~scape can reproduce observed historical coral-cover trajectories at scale, and project future dynamics to 2100 across Shared Socioeconomic Pathways (SSPs) informed Global Climate Models. Model analyses reveal that variability in demographic processes drives different community dynamics across the GBR, and across sites within clusters. This demographic variability creates emergent community dynamics like differences in the onset of decreases in among-site variability in coral recovery trajectories as climate change progresses (88).

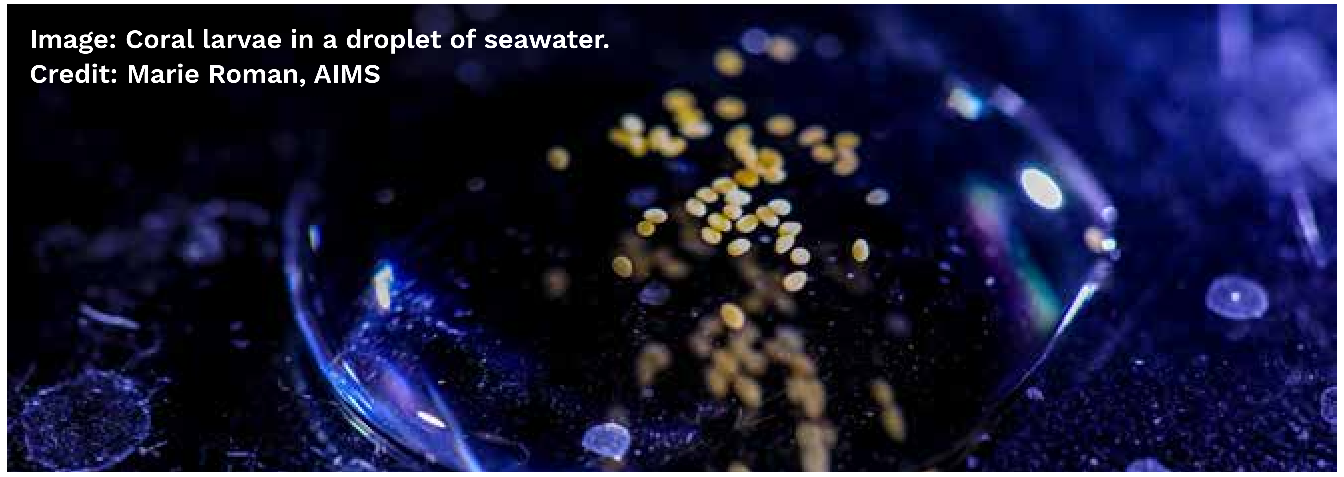


Image: Coral larvae in a droplet of seawater.
Credit: Marie Roman, AIMS

RRAP's marine cloud brightening (MCB) and fogging efforts highlight the vital role of modelling when no empirical precedent exists. Prior to RRAP inception, no observational data or modelling platforms existed for assessing the feasibility of the methods on the GBR. New atmospheric models were needed to predict the potential of these interventions.

Over five years, the pioneering 'Virtual Atmospheric Laboratory' has now:

- Validated the basic physical premise of MCB
- Assessed environmental risks, and shown that even extreme cooling and shading scenarios have no concerning impact on local weather patterns.
- Indicated potential localised cooling effects that could help mitigate bleaching during heatwaves.
- Provided new insights into atmospheric conditions over the Great Barrier Reef, and their influence on the reef ecosystem and mass bleaching events particularly during marine heatwaves.

Without these models, safe and effective planning for cooling and shading intervention would not be possible.

Image: Fogging plume being generated during cooling and shading trials on the Great Barrier Reef.
Credit: SCU

CASE STUDY – NEW MODELLING TOOLS TO IMPROVE DECISION-MAKING

Delivering effective at-scale restoration requires the ability to make informed decisions about uncertain futures. Modelling becomes not just helpful but essential when measuring the potential impact of restoration on a vast and complex ecosystem like the Great Barrier Reef.

RRAP's goal was to develop models that could help to explore future scenarios under interventions, simulate outcomes and weigh trade-offs, long before large-scale field trials took place.

Now, a new suite of advanced or progressed modelling tools include:

- Simulating long-term ecological outcomes on the GBR scale, without intervention (counterfactual)
- Evaluating Crown-of-thorns starfish outbreaks and management strategies alongside additional intervention
- High-resolution spatial modelling for site-specific planning.

Counterfactual projections have indicated widespread coral cover decline under likely climate scenarios, underscoring the critical need for restoration interventions alongside an urgent reduction in global greenhouse gas emissions.

Crucially, the models have also been integrated into a new decision-support platform. ADRIA is emerging a tool to help to determine which interventions are needed, where they should be deployed, and what combinations are most likely to help maintain a resilient Great Barrier Reef.

TRANSLATION TO DEPLOYMENT

ENSURE THE TECHNOLOGY, LOGISTICS AND SUPPLY CHAINS ARE IN PLACE TO ALLOW TRANSITION FROM INTERVENTIONS R&D TO DEPLOYMENTS AT SCALE

The Translation to Deployment R&D subprogram ('T2D') worked to ensure that the prerequisites for future deployments of RRAP interventions are in place well in advance, focussing initially on the industry capabilities, human capacity, methodological knowledge, logistics and costing information required for the Pilot Deployments Program.

Between 2020 – 2025, T2D focused on three main goals:

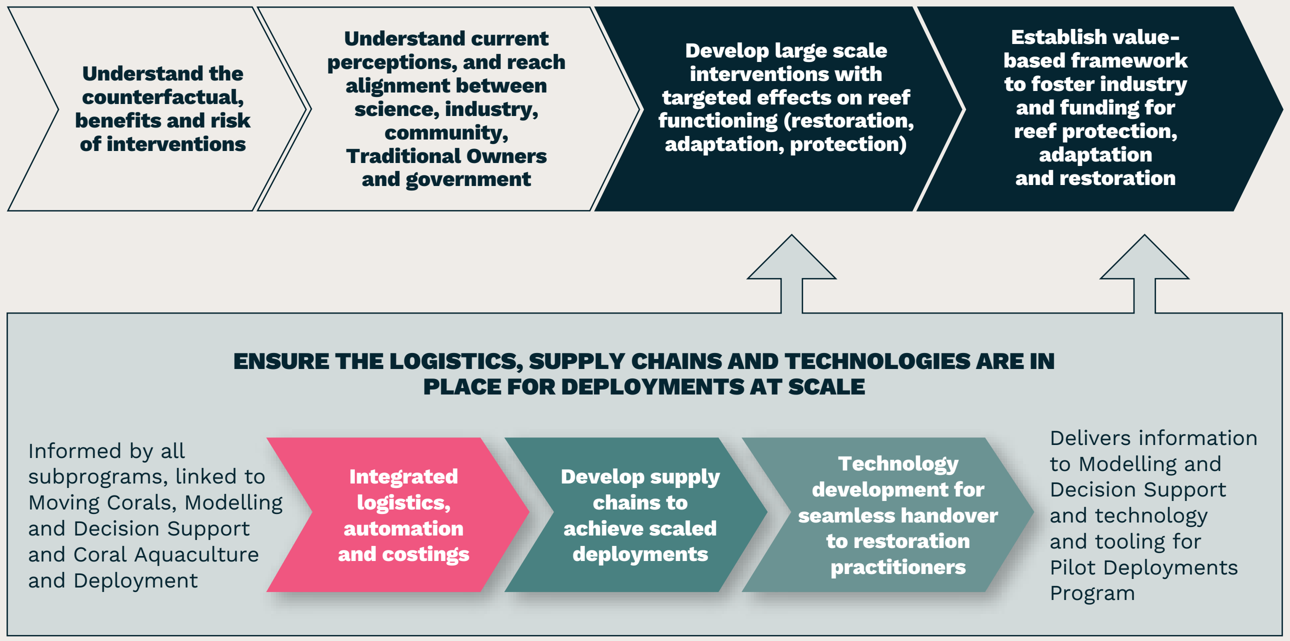
- Deliver **integrated logistics, automation and intervention costings** across the research and development program
- **Establish deployment supply chains** (organisations, intervention method knowledge, logistics and costing) for interventions at scale
- **Targeted technology development** including automation for coral aquaculture production and a reef deployment guidance system

Throughout Phase 1 of RRAP, T2D facilitated and developed critical enabling activities necessary for transitioning priority interventions into viable, large-scale reef management actions. Key outcomes included detailed and dynamically updated intervention cost modelling which incorporated all aspects of capital expenditure, labour and operational costs. In addition, T2D worked closely with the RRAP Pilot Deployments Program to map critical paths for achieving scaled deployments of RRAP interventions at two locations on the GBR. Finally, T2D worked closely with the intervention development subprograms to develop automated and autonomous research prototypes that greatly increased coral production and deployment capacity and reduced costs.

GOAL AND SPECIFIC OBJECTIVES

	Achievement within project scope
Integrated logistics, automation and intervention costings	
Logistics and cost modelling for coral seeding and larval reseeding	
Implementation plan for the first tranche of large-scale deployments	
Develop a roadmap for automation to reduce intervention costs	
Establish deployment supply chains for RRAP interventions at scale	
Map critical path to deploy RRAP interventions at large scale	Pilot Deployments Program
Research prototype development for seamless handover to restoration practitioners	
Coral Spawn and Larvae Imaging Camera System (CSLICS)	
Coral Growout Robotic Assessment System (CGRAS)	
Jig Cutter and Press	
Deployment Guidance System	Pilot Deployments Program

At a Glance



Integrated logistics, automation and costings

A logistics simulation model was developed as a configurable dynamic model in Python for simulating and visualising intervention campaigns.

Identified automation opportunities to significantly increase coral production. These developments required similar hardware and software frameworks which were leveraged across subprograms to speed development.

Develop supply chainsto achieve scaled deployments

Mapped the critical outputs and inputs, timelines, dependencies, decision points and stage gates for each of the interventions used in the Pilot Deployments Program Conservation Aquaculture and Slick Collection and Release.

Developed the concept plan, and secured funding, for the RRAP Pilot Deployments Program which commenced in 2025. Work on supply chains for scaled deploy-ments is ongoing within the Pilot Deployments Program.

Technology development for seamless handover to restoration practitioners

Automated continuous monitoring of coral larval culture density. The Coral Spawn and Larvae Imaging Camera System (CSLICS) can provide tank density estimates every 15 seconds, a 20-fold efficiency gain compared to manual counts.

Developed the Coral Growout Robotic Assessment System (CGRAS), a semi-automated platform for counting and assessing coral recruits. CGRAS reduces labour from >2 h to ~12 min per tile for a ~12-fold efficiency increase.

Built and tested the 'Deployment Guidance System'. This system comprises of a modular, on-boat vessel guidance system and device dispenser to achieve high-throughput, safe and efficient on-water deployments with robotics and Artificial Intelligence (AI).

DELIVER INTEGRATED LOGISTICS AND AUTOMATION ACROSS THE R&D PROGRAM

OBJECTIVE	ACHIEVEMENT
Develop and apply models, algorithms and workflow processes to provide logistics modelling and optimisation for a GBR reef restoration industry.	Developed and continuously refined integrated process, logistics, and cost models across multiple RRAP interventions, including conservation aquaculture, slick collection and release, and cooling and shading (89). A configurable, dynamic logistics simulation model was built in Python to simulate and visualise intervention campaigns and assess operational requirements under different deployment scenarios. Detailed logistics and cost models were continually maintained and updated in close collaboration with RRAP subprogram leads and project teams to reflect evolving intervention designs. Automated workflows were developed to support extensive scenario analysis and Monte Carlo simulation, enabling assessment of the impacts of uncertainty. The modelling team also worked closely with the Modelling and Decision Support subprogram to integrate cost and logistics models with ecological and spatial models of the reef. Collectively, these modelling capabilities supported evidence based planning, optimisation of deployment strategies, and cost effective research and operational decision making across the program (90–92).
Develop an implementation plan for the first tranche of major intervention trials	Developed the concept plan (93), and secured funding, for the RRAP Pilot Deployments Program which commenced in 2025.
Identify opportunities and develop a roadmap for use of automation to enhance efficiency and capability of reef restoration interventions	Identified many automation opportunities that could significantly increase coral production and improve logistics. In the first instance, there was a shared need to use imaging and machine learning to: count coral settlers, recruits and algae in work being conducted by CAD and ECT; count coral eggs in CRYO; count coral larvae, settlers and recruits and identify substrate characteristics in MC; and finally, to count coral settlers and assess rubble characteristics in RS. Furthermore, assessing the growth and health of coral spat was identified as a mission-critical automation technology development for CAD. Such counting algorithms were not available for operational use in aquaculture prior to RRAP, but they require similar hardware and software frameworks which were leveraged across subprograms to speed method development and testing.
Design and engineering iterations	There were numerous design and engineering iterations across the suite of the technologies being developed within T2D. Most of these changes occurred due to adjustment of the coral aquaculture process as there are numerous challenges associated with attempts to automate a process that is constantly evolving. However, changes were mostly variations at a technical level that caused only minor delays to progress.

DEVELOP SUPPLY CHAINS TO ACHIEVE SCALED DEPLOYMENTS

OBJECTIVE	ACHIEVEMENT
Map critical path to achieve RRAP deployments, including technical as well as funding, regulatory, community capacity building and social licence goals.	Mapped the critical outputs and inputs, timelines, dependencies, decision points and stage gates for each of the interventions used in the Pilot Deployments Program (slick collection and release and conservation aquaculture). As reef restoration initiatives move toward large scale deployments, it is critical to maintain oversight of the up-to-date cost and logistics models for the planned intervention strategy and tactics. RRAP T2D conducted constant scenario analyses to support decision making and research planning for the other RRAP subprogram and, since 2024, for the PDP. Other aspects of logistics modelling with a more long-term view, considered the optimal locations of multiple coral aquaculture facilities under different deployment scenarios, and computational optimisation for routing of motherships supporting a fleet of small vessels during deployment optimisation (94). In addition, T2D formulated a model to determine the optimal location and sizing of coral aquaculture industry facilities that would be required for scaled deployments given the known time-dependent survival rate of coral spat (95). Assessed growth time in a facility in terms of its impact on survival (post-deployment) considering growth quantity requirements and growth facility production constraints. We explore the sensitivity of optimal facility number, location, and sizing to changes in the geographic distribution of demand and cost parameters computationally. Results show that the relationship between growth time and survival is critical to optimising operational decisions for grown resources.

TECHNOLOGY DEVELOPMENT FOR SEAMLESS HANDOVER TO RESTORATION PRACTITIONERS

OBJECTIVE	ACHIEVEMENT
Develop Machine vision and software-systems for counting and tracking coral larvae through the rearing phase of coral aquaculture process.	A scalable system for automated, continuous monitoring of coral larval culture density was developed across multiple tanks (96). This networked system of cameras is called the Coral Spawn and Larvae Imaging Camera System (CSLICS), which involves using computer vision and machine learning algorithms on images of coral spawn and larvae captured by top- and side-mounted cameras over 500L coral culture tanks. Several prototypes were iteratively developed and tested in the National Sea Simulator during the GBR summer coral spawning events in 2022, 2023 2024 and 2025. The performance of the machine learning algorithms was validated against replicated manual counts for each deployed system and coral species.

	The CSLICS can provide tank density estimates every 15 seconds, a ~20-fold efficiency gain compared to performing manual larval density counts and has been used for 10 species to date. In addition, developed a desktop version of the CSLICS, with the capability of estimating the developmental stage during early coral embryonic development and fertilisation success in samples collected from stocked larval culture tanks. The new algorithms can distinguish between different coral larval developmental stages (i.e., eggs, first cleavage, 2-cell stage, 4-8-cell stage and >16-cell embryos) resulting in a ~7 fold reduction in operation time and with additional benefits of improved consistency and automated data storage and tracking.
Develop robotic, machine vision and software systems for counting, mapping and tracking coral recruits on concrete settlement tiles throughout grow-out phase of coral aquaculture process.	Developed the Coral Growout Robotic Assessment System (CGRAS), a semi-automated platform for imaging coral settlement tiles and automatically counting and assessing recruit health (89). The system combines robotic image capture with machine learning–based analysis to identify coral recruits and juveniles across multiple species, achieving approximately 95% agreement with expert counts. A hardware prototype has been successfully validated by the sub-project team, demonstrating reliable performance under operational conditions. CGRAS substantially reduces the labour required for tile assessment—from approximately 140 minutes to around 12 minutes per tile (approximately 12-fold efficiency improvement)—by streamlining cleaning, handling, imaging, and counting processes. This enables more consistent, high-frequency monitoring of coral growth, which is critical for improving yields during aquaculture. The system is now being adapted for integration with automated device assembly machinery, supporting end-to-end scalability of coral production workflows. By enabling rapid, standardised assessment across large numbers of tiles, CGRAS addresses a key bottleneck in coral grow-out and provides the data foundation required for optimising cultivation strategies at scale.
Mechanical augmentation of processes involved in cutting settlement tiles and assembling deployment devices.	Developed and trialled a novel 'Jig Cutter'. Testing revealed that the initial cookie cutter concept, which attempted to cut a 28×28 cm concrete tile in a single action required excessive force, rendering the method impractical (89). As a result, the Jig Cutter was developed using a "bend and snap" technique, which required significantly less force and produced cleaner, more consistent breaks. In addition, a prototype 'Jig Press' was developed to press fit three coral tabs into each coral device. Introduction of both jigs improved tile and device process time, thus improving viability of scaling up baby coral deployment operations.
A vessel guidance system (set up for small vessel) to control path of boat and guide coral deployments with artificial intelligence (AI) capability	Meticulous planning of intervention tactics is essential to optimise ecological outcomes and maximise cost efficiency (97). To tackle this challenge for large scale deployments via coral seeding and larval reseeding, RRAP invested in the development of a 'Deployment Guidance System'. This system comprises an on-boat vessel guidance system and device dispenser to achieve safe and effective on-water deployment. It is also equipped with ReefScan (underwater camera) and an in-house AI system for suitable substrate detection to support on-vessel deployment decisions (98–100). The Deployment Guidance System is designed to support practical, on-water operations by helping crews make timely and informed decisions during coral deployment. The AI component analyses underwater imagery to identify suitable areas of reef, reducing the reliance on constant input from expert marine scientists (101). It operates directly on equipment onboard the vessel, providing real-time feedback (around 5.5 frames per second) without the need for external connectivity. Trials across multiple Great Barrier Reef sites show that the system achieves 77.8% agreement with expert judgement, and 89.1% accuracy in classifying smaller image regions, while improving the speed and consistency of deployment activities. In addition, the development of a shared, annotated dataset of reef imagery supports ongoing improvement and broader collaboration across the RRAP program (102–104).

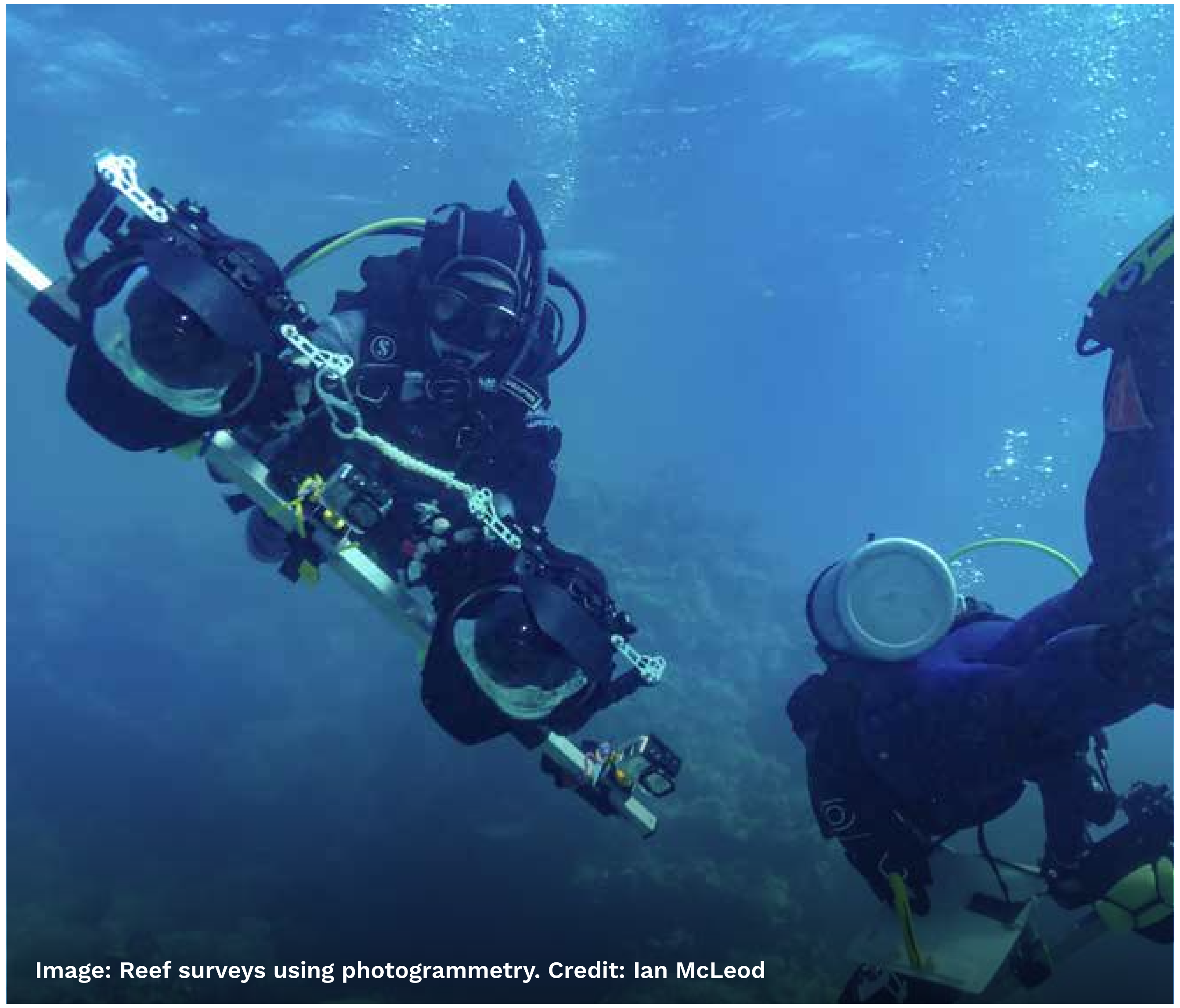


Image: Reef surveys using photogrammetry. Credit: Ian McLeod

CASE STUDY - SCALING CORAL PROPAGATION IN AQUACULTURE

Scaling up coral propagation for restoration isn't just a scientific challenge; it's also a practical one. Reef managers and practitioners need aquaculture tools that reduce costs, save time and make large scale intervention deployments more logistically feasible.

Enter CSLICS (Coral Spawn and Larvae Imaging Camera System), a scalable network of cameras that uses machine learning to automate spawn and larvae counting and monitoring.

Traditionally, monitoring coral fertilisation and survival in restoration aquaculture is labour-intensive and time-consuming. Each rearing tank requires 20–30 minutes of manual sampling per hour, making large-scale operations logistically unfeasible, consuming hundreds of labour hours daily. Manual methods also risk damaging fragile coral larvae and can't deliver the precision needed for accurate counts or early detection of cultural crashes.

CSLICS was designed to deliver real-time counts, reduce manual handling, provide early warnings of tank crashes, quantify fertilisation success, and store data in a centralised database, all within around 1 minute per sample. This not only improves quality control but significantly cuts operational costs of larval rearing.

CSLICS

OPERATING TIMES REDUCED FROM 30 MINUTES TO **1 MINUTE**

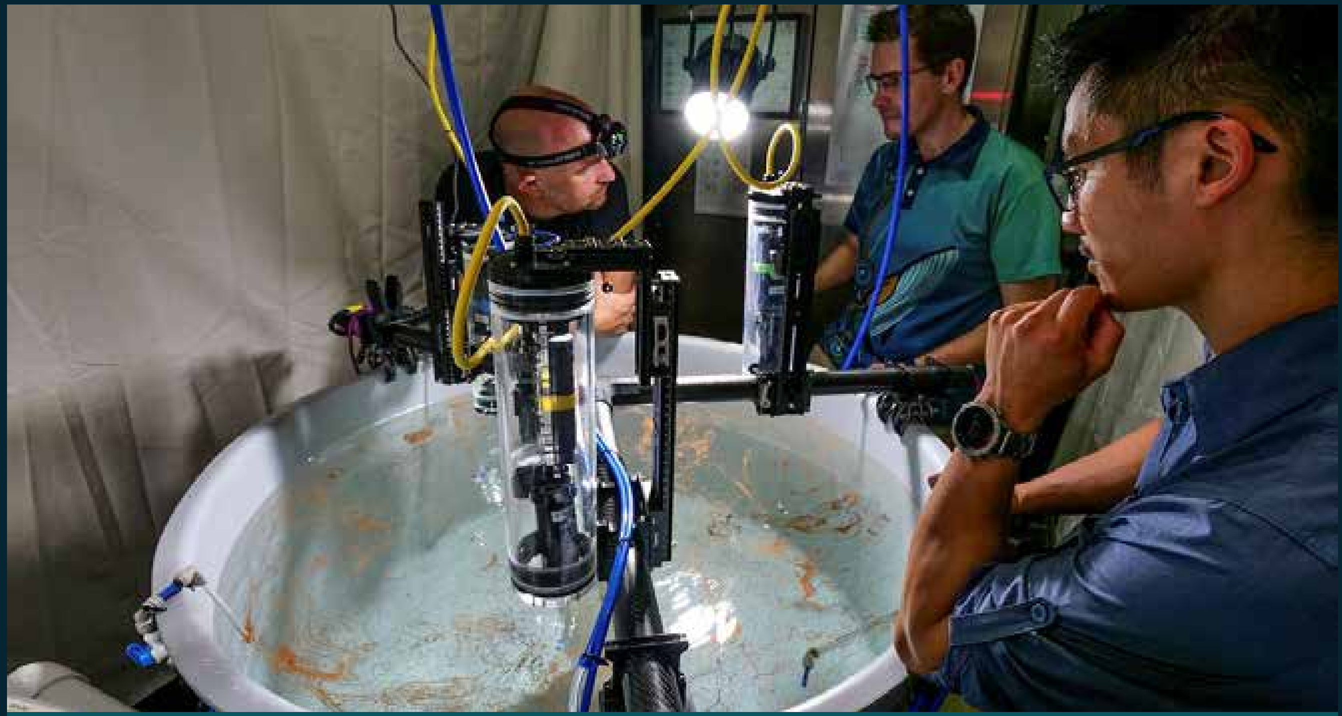
Another major survival and growth bottleneck occurs in the coral grow-out phase, when settled larvae develop into coral recruits. Manual assessment and inventory of each settlement tile can take up to two hours, making it impractical for large-scale operations.

One solution evolved under RRAP is CGRAS (Coral Grow-out Robotic Assessment System). This robotic system uses a camera-equipped arm to scan coral settlement tiles, with onboard software detecting recruits, assessing health. CGRAS has reduced tile processing time to around just 10 minutes, enabling weekly health assessments at scale.

CGRAS

OPERATING TIMES REDUCED FROM 120 MINUTES TO **10 MINUTES**

Together, CSLICS and CGRAS have transformed coral propagation under RRAP by automating critical bottlenecks, paving the way for large scale deployment via coral aquaculture.



Andrea Severati and Christopher Brunner (AIMS) from the Coral Aquaculture and Deployment team, and Dorain Tsai (QUT) from the Translation to Deployment team inspect coral larvae under CSLICS monitoring system. Credit: Marie Roman, AIMS

Dorian Tsai (QUT) from the Translation to Deployment team inspects the CGRAS robot as it monitors coral spat. Credit: Marie Roman, AIMS

RRAP Synthesis Report 2020-2025

INTERVENTION DEVELOPMENT SUBPROGRAMS

Image Credit: Gary Cranitch, Queensland Museum

COOLING AND SHADING

LIMIT SOLAR RADIATION TO DECREASE HEAT STRESS AND BLEACHING

The RRAP Cooling and Shading R&D subprogram ('C&S') successfully developed world-first cooling and shading technologies that have the potential to protect corals from bleaching.

During 2020 – 2025, C&S focused on three main goals:

- **Design, fabricate and test new technologies for solar radiation management** including infrastructure, instrumentation and methodologies for testing seawater atomising systems
- **Establish whether marine cloud brightening and fogging** using sea salt spray **could mitigate coral bleaching** under natural atmospheric conditions
- **Develop a framework for operationalising** cooling and shading technologies by linking cloud dynamics, meteorology, ocean temperature and coral stress indicators

Throughout Phase 1 of RRAP, C&S made excellent progress toward the subprogram goals and objectives. Fogging is now technically feasible and marine cloud brightening has been advanced beyond the laboratory to outdoor field testing. Both have been show to have the potential to be ecologically effective. However, before scaled deployments are considered, larger and longer field trials of cloud brightening are required, and new capability for rapid response deployment of fogging during doldrum conditions is needed. Moreover, further improvements to nozzle spray technology are needed to improve the economic viability and scalability of these interventions. Additional intervention risk assessment work is ongoing, and the evolution of social licence and pathway to regulatory approval are needed for both fogging and marine cloud brightening.

GOAL AND SPECIFIC OBJECTIVES	Achievement within project scope
Design, fabricate and test new technologies for solar radiation management	
Develop field-deployable seawater atomisation systems for marine cloud brightening	
Procure and manage specialised research and engineering infrastructure	
Establish and optimise seawater atomisation nozzles	
Iteratively upscale prototype system towards operational feasibility	
Develop field-deployable seawater atomisation systems for fogging	
Design, construct and test seawater fogging system	
Optimise technologies through multi-year field trials	
Establish whether cloud brightening and/or fogging can mitigate coral bleaching	
Design, procure and utilise bespoke multi-platform instrumentation	
Quantify cloud responses to controlled sea spray injections over the GBR	
Assess feasibility of using seawater fogging to shade and cool reefs	
Determine potential for cooling and shading to reduce heat stress	
Develop a framework for operationalising proposed cooling technologies	
Quantify GBR cloud occurrence, formation and brightness	
Assess exchange of gases and aerosols between ocean and atmosphere	
Develop and evaluate numerical models of ocean-atmosphere dynamics	

At a Glance

Understand the counterfactual, benefits and risk of interventions

Understand current perceptions, and reach alignment between science, industry, community, Traditional Owners and government

Develop large scale interventions with targeted effects on reef functioning (restoration, adaptation, protection)

Establish value-based framework to foster industry and funding for reef protection, adaptation and restoration

LIMIT SOLAR RADIATION TO DECREASE HEAT STRESS AND BLEACHING

Informed by Regulation and Stakeholder and TO Engagement, linked to Ecological Intelligence and Enhanced Corals and Treatments and Indigenous partnerships

New technologies for fogging and marine cloud brightening

Proof-of-concept for ecological efficacy

Framework for operational deployment

Delivers information to Modelling and Decision Support and Intervention Risk Management

New technologies for fogging and marine cloud brightening

Identified effervescent spray nozzles as the most field ready technology for cloud brightening, and impact-pin nozzles as the best technology for fogging.

Iteratively improved cloud brightening technology and plant, delivering three orders of magnitude increase in sea spray production and an order of magnitude increase in energy efficiency.

Successfully tested marine cloud brightening system in the marine environment, generating a sea spray plume that was detectable 12 km downwind from the source.

Iteratively improved fogging technology and plant, increasing shading up to ~30%, and area shaded up to 23 ha, depending on wind and humidity.

Determined that a minimum production of 10^{14} fog droplets s^{-1} is needed for meaningful shading of up to 15%.

Proof-of-concept for ecological efficacy

Identified that aerosol injections have potential to brighten clouds over the GGR, though further study is needed to understand their long-term effectiveness.

Developed and analysed models that provide world-first evidence that sea temperatures could be ~1°C lower on the GBR where cloud brightening is deployed.

Showed that shading for four hours per day can decrease coral bleaching and lower mortality of bleached corals.

Demonstrated that benefits of shading due to fogging diminished under prolonged heat stress, with results being highly variable among coral species.

Identified mobile vessel-based fogging as the recommended strategy to optimise efficiency and efficacy of fogging deployment under varying weather conditions.

Framework for operational deployment

Cutting-edge atmospheric monitoring aircraft to measure effects of small-scale and rapidly reversible cloud brightening trials.

First ever direct quantification of aerosol composition over the GBR over summer, including during a marine heatwave.

Embedded First Nations participation to jointly design and deliver research, field data collection and cultural consultation.

Identified highly dynamic weather patterns and large-scale climate variability as ongoing challenges for reliably predicting outcomes of shading interventions.

Revealed that regional marine cloud brightening can be achieved without impacts on clouds beyond north-eastern Australia, and without significant impacts on rainfall.

CASE STUDY: CONCEPT TO CAPABILITY

For over 30 years, marine cloud brightening (MCB) existed largely as theory, with no real-world examples or outdoor testing. In the last five years, RRAP's Cooling and Shading team have transformed the MCB concept into field-ready research infrastructure, advancing from theoretical modelling to land-based testing and, subsequently, marine field trials.

The program has been deliberately iterative: designing experiments, simulating effects, assessing risks, trialling technology, monitoring outcomes and refining methods. New infrastructure and tools include:

- ARIEL (Aerosol, Radiation and their Interactions Experimental Laboratory): a custom-built containerised marine cloud brightening plant that generates sea spray with the right properties to be lofted to cloud bases and change how much heat reaches the sea surface.
- An airborne research platform: one of Australia's first purpose-built aircraft for aerosol–cloud interaction studies, fully outfitted with meteorological, aerosol and cloud microphysics instruments to understand how MCB could work over the GBR.
- Developed cutting edge drone capabilities for atmospheric sampling operating from vessels at sea

In its first campaign over the GBR, the aircraft collected data of cloud formation and aerosol interactions, which ultimately proved consistent with MCB theory. It marks the first time for this field of research that aerosol–cloud interactions have been measured over the GBR and the first outdoor MCB experiment globally, helping turn theory into actionable knowledge.

By building the capability and infrastructure, the team ultimately hope to support managers and communities to understand and weigh the intervention benefits, risks and trade-offs.

Image: (L-R) Brian Adam, Brendan Kelaher , Daniel Harrison, Diana Hernandez-Jaramillo, Alejandro Tagliafico from Southern Cross University with drones used in cooling and shading field trials. Credit: SCU

Image: A light aircraft was fitted with monitoring equipment to form part of the Marine Cloud Brightening team's airborne research platform. Credit: Daniel Harrison, SCU

DEVELOP A FIELD-DEPLOYABLE SEAWATER ATOMISATION SYSTEM FOR CLOUD BRIGHTENING

OBJECTIVE	ACHIEVEMENT
Procure and manage highly specialised research and engineering infrastructure and bespoke instrumentation platforms	Acquired, calibrated and deployed extensive research and engineering infrastructure required for research and development of Cooling and Shading interventions (105, 106), including: • World-first fogging system with 20-fold output increase since prototype. • Data systems and methodologies for high-resolution aerosol measurement. • World-first prototype marine cloud brightening systems including nozzle arrays, compressors, and control skids. • Integrated hardware and software components for nozzle arrays, compressors, manifolds, and droplet dispersion systems with real time monitoring and logging systems. • Developed crewed and uncrewed aircraft designed specifically to support cloud brightening and fogging experiments
Establish a facility for testing candidate technology types and nozzle variants.	Constructed a dedicated nozzle testing facility with two wind tunnels that can generate wind speeds between 1 - 10 m s^{-1}. The facility enables the accurate measurement of sea spray aerosol droplet production rates and particle size distributions of both background conditions and downwind of the nozzle under test (107, 108). The plant is equipped with industrial grade monitoring equipment to display and log operating parameters and outputs for a wide range of nozzle types.
Deliver an integrated field program for development and testing of cooling and shading systems	Expanded the operational and knowledge boundaries of field-based marine, atmospheric and cloud microphysical research via an integrated multi-year field program (109). Research and development involved multiple research vessels, drone operations, aircraft operations, and atmospheric research teams located at research stations all operating in concert. Field campaigns included yearly on-reef engineering trials and experimentation for fogging and MCB systems during summer (2021 – 2025) and off-reef testing of prototype hardware and instrumentation during winter.
Optimise nozzles through laboratory experimentation, testing new designs, and modelling	Systematically tested multiple nozzle designs and identified that while sea spray particle sizes are consistent across most effervescent type nozzles, the nozzle design and operating conditions have a large effect on the number of particles produced and energy requirements (110). Results also show that spraying at higher salinity successfully increases the number of particles produced within the required particle size range. Effervescent spray atomisation was the best performing and most appropriate for outdoor use of the technologies examined to date, other technologies have potential in the longer term but need further research and development. Effervescent technology was improved over time through nozzle scale up, engineering improvements, and optimisation of flow, pressure, and other operating parameters. A further increase in particle production rate by around one order of magnitude is desirable to minimise energy requirements prior to pilot deployment.
Develop electro spray method for aerosol production through R&D in micromachining to achieve scale	Significantly progressed research into the electrospray method for producing sea spray droplets within the desired size range (110). Consistently achieved the required ‘cone-jet’ mode using a 3.5% saline solution without the need for surfactants. Preliminary results indicate a significant reduction in power requirements for sea spray production could be achieved using smaller nozzle diameters and electrode separation. Considerable further research and development are required to assess feasibility of this alternative nozzle technology for marine cloud brightening applications however electrospray is considered a serious contender for implementation scale cloud brightening.
Sequentially evaluate alternative spray generation options using the nozzle testing facility	Evaluated alternative aerosol spraying technologies to increase sea salt aerosol production rates using a smaller plant and lower energy use (108, 110). • Flash boiling nozzles - trials revealed maximal output efficiency per unit energy occurred at very low nozzle flows such that many nozzles would be needed for an upscaled system. However, the power required to produce particles at the desired rate was similar to the effervescent nozzle system. Although energy requirements per droplet are on par with the current effervescent system, the size distribution of flash boiling nozzles may be superior to effervescent. • Rayleigh jet nozzles - results show that this method could potentially deliver aerosols at the required rate and size, with high monodispersity and a significantly lower power use. However, the method requires ultrafiltration of water that may not be feasible for continuous deployments at sea. • Ultrasonic nozzles - Early trials showed these nozzles could not meet required targets so development was discontinued. • Electrospray nozzles and continued development of effervescent technology are discussed above.
Model nozzle atomisation process using computational fluid dynamics	Applied computational fluid dynamics models to inform the development and testing of nozzles for production of sea spray (110). Overcame limitations of standard fluid dynamics models by developing a novel ‘Explicit Volume Diffusion’ model that resolves particle movements over grid and sub-grid scales within the nozzles themselves. The new model is coupled with a particle tracking approach to accurately predict nozzle spray performance.

Construct and test higher production rate seawater atomisation technology	Iteratively improved seawater atomisation technology and associated plant over time, delivering greater than an order of magnitude increase in sea salt aerosol production over the course of the project (109). The original prototype consisted of 100 nozzles in a manifold configuration supplied by a single air compressor. Subsequently the system was expanded to 320 nozzles in a tower configuration supplied by three air compressors. Ultimately, a second unit was integrated for a total of 640 nozzles supplied by six air compressors and two high pressure seawater pumps.
Evaluate various prototype hardware configurations for producing salt spray under field conditions	Advanced the readiness of marine cloud brightening technology for initial small-scale and rapidly reversible outdoor experiments. The first prototype sprayer provided proof-of-concept for field-based atomisation of seawater, producing an estimated 2.7×10^{14} droplets per second with diameter around 40 nm. Iterative engineering enhancements over time increased production rate close to 4-fold to ~ 10^{15} s^{-1}, generating a sea spray plume detectable more than 12 km downwind of the source (110).
Apply computational fluid dynamics modelling to support development of spraying prototypes	Successfully applied computational fluid dynamics modelling, in conjunction with experimental measurements, to refine the design and operating parameters for sea water atomisation nozzles. Due to the complexity of the flow within a nozzle, experimental measurements by themselves are insufficient for optimising design and operation (111, 112).

DEVELOP A FIELD-DEPLOYABLE SEAWATER ATOMISATION SYSTEM FOR FOGGING

OBJECTIVE	ACHIEVEMENT
Review technology to identify the most promising nozzle candidate/s for fogging prototype	Surveyed existing technologies that had potential to produce seawater droplets within the size range required for fogging. Identified impact pin nozzles and acoustic nozzles as the most promising candidate technologies. Testing revealed that impact pin nozzles produced orders of magnitude larger droplet production rates compared with acoustic nozzles (113).
Determine whether any existing system can achieve the desired production rate with practical energy use.	A staged evaluation of available freshwater fogging configurations was undertaken to assess their suitability for marine deployment and to better understand spray output characteristics under both sea- and land-based conditions (113). Initial trials used a re-designed off-the-shelf system combining an Ozmist sprayer with a MeeFogTM impact-pin nozzles. Findings from these trials informed the design and development of a customised MeeFog plant system by RRAP engineers in collaboration with Mee Industries (USA). Subsequent refinements to this system improved operational flexibility and end-user functionality while maintaining practical energy requirements.
Construct the seawater fogging system including designing and constructing proof-of-concept nozzles, prototype and final full scale seawater fogging system.	Iterative development of the seawater fogging system resolved numerous engineering challenges, including scalability, energy efficiency and operational robustness. Engineering upgrades lead to the following major advances (113): • Increase in average level of shading from 16% to 27% with maximum up to 40% • Increase in area shaded from ~1 ha to ~23 ha depending on wind speed • Reduction in energy consumption by 10% • Improved capacity from ~4 to over 8 hours of operation per day. • Development of fully portable self-contained higher efficiency fogging units that can be deployed from small vessels.
Confirm that the fog nozzle technology can achieve the desired production of droplets with reasonable energy consumption.	Successfully developed a fogging system that could generate around 10^{14} – 10^{15} droplets per second. Initial trials on land refined the system operating procedure and the sensor array required for plume monitoring. Subsequent trials demonstrated the system could be reliably deployed at sea, producing stable fog plumes with promising levels of shading under calm, high humidity conditions (114). Following nozzle upgrades, the portable self-contained fogging systems can each produce around 2×10^{14} droplets per second using around 11 L diesel fuel per hour.
Model light scattering to estimate the required droplet concentration to achieve the desired shading	Radiative transfer modelling was used to simulate light scattering by fog droplets. Results showed that under favourable conditions (1 m s^{-1} wind, 70% humidity) a mid-range production of fog droplets at a rate of 10^{14} to 10^{15} s^{-1} can generate at least 15% shading across 2.7 km^2 (270 ha), or 30% shading across 1.9 km^2 (1.9 ha). A minimum production rate of 10^{14} droplets per second is needed to achieve meaningful time-averaged shading of up to 15%. Higher production rates are recommended to achieve 30% shading and to counteract dilution of the fog plume by shifts in wind direction. Low relative humidity, suboptimal alignment between the fog plume and the position of the sun in the sky, or stronger winds, can also decrease the level of shade achieved (113).
Evaluate model predictions for fogging using the suite of shading, cooling and fog plume metrics	Field trials confirmed the model predictions that atomising seawater can generate low-lying fog that reduces solar radiation to potentially mitigate coral bleaching. Fogging with larger droplets provided more consistent shading, particularly under low humidity conditions. However, wind speeds above 3 m s^{-1} diluted the fog and decreased shading by up to 50%. The fogging machinery and plume can benefit operationally from real-time monitoring to respond to changes in wind and humidity to maintain the shading effect over target areas. This work identified that a larger number of smaller fogging units spread across the prevailing breeze is the most promising operational configuration.

Estimate the required droplet emission rate under different fogging scenarios	Modelling studies show that aerosol size with respect to ambient relative humidity, volume of water to be pumped, and wind speed are key factors that determine whether the fogging plume is sufficiently thick to shade UV and visible light to the target level. A flow rate of at least 7.5 $L\ s^{-1}$ is required to produce 30% shading one km downwind of the sprayer. Combining the desired aerosol size of particles ~0.3 µm with this flow rate corresponds to production of ~8 x 10^{15} particles s^{-1} (113). Higher production rates are recommended to counteract variability in shading caused by shifts in wind direction.

ESTABLISH WHETHER ADDITION OF SEA SALT AEROSOLS CAN ALTER CLOUD BRIGHTNESS AND/OR GENERATE STABLE FOG OVER THE REEF

OBJECTIVE	ACHIEVEMENT
Design, implement and test cloud-monitoring instrumentation for aircraft	Developed a bespoke airborne sensor platform optimised for marine cloud brightening research (105). Successfully deployed the aircraft during four field campaigns to measure cloud microphysics, aerosol size distributions and meteorological conditions. Upgraded the aircraft to improve safety and efficiency with enhanced avionics, and increased data reliability by installing a second cloud droplet probe. Designed and integrated software and hardware for real-time data analysis to optimise data collection during the evolving atmospheric conditions in-flight (106, 115).
Model and measure dispersion of sea salt aerosol plume to inform sampling and deployment tactics	Provided the first empirical evidence of dispersion of artificially generated sea salt aerosols for marine cloud brightening (110). Drone-based measurements showed that, close to the source, the plume reached ~150 m altitude. Further from the source (1 - 10 km downwind), the aircraft detected the plume at cloud base heights. Moving the sprayer to align with prevailing winds was effective for concentrating aerosols beneath clouds (116, 117). Under these conditions, artificially generated aerosols exceeded background marine aerosol levels and maintained a distinct vertical profile consistent with model predictions(118).
Implement satellite remote sensing analysis in support of field trials	Cross-validated new methods for satellite remote measurement of cloud condensation nuclei against shipborne measurements over the GBR. Results show that, over the entire GBR, background CCN concentrations range from 50 to 200 cm^{-3}, which is within the range where addition of aerosols affects how reflective the clouds are. These new methods and data are essential for understanding efficacy of marine cloud brightening (110).
Implement surface based LiDAR measurement of aerosol, plume, and cloud properties	Surface-based LiDAR measurements of the plume and background conditions were conducted during field campaigns within the Townsville, Whitsundays, and Capricorn Bunker regions of the GBR. Results consistently showed the plume was uplifted
	into the targeted region at cloud bases (106, 116). Additionally, a LiDAR ceilometer was temporarily installed at the One Tree Island Research Station for monitoring background meteorology, aerosol, and cloud properties. Data from this monitoring will be linked to particle concentration measurements to estimate the background aerosol climatology over the southern GBR. These data are essential for evaluating potential risks and efficacy of marine cloud brightening trials in the future.
Characterise plume dynamics and dispersion under varying atmospheric conditions	Conducted world-first in situ characterisation of aerosol dispersion from vessel-based effervescent nozzle system (106, 119). Demonstrated that, contrary to expectations, evaporative cooling does not suppress aerosol dispersal (116). This is likely due to the very small droplet sizes created by the nozzle system (107). Results showed consistent spread of the plume to cloud base heights, with aerosol dispersion also influenced by wind speed and atmospheric conditions.
Upscale aircraft and vessel-based measurement and sampling techniques for data collection across altitude and over large areas.	Iteratively improved sampling strategies to increase scale from limited sampling of aerosol plume close to the source up to measurement of meteorology and aerosol-cloud interaction studies beneath and within clouds (115, 120, 121). Established a research aircraft as a cutting-edge tool for atmospheric research that is essential for monitoring the performance of small-scale cloud brightening field trials (105, 122). Coordinated sampling and data integration from surface ships, drones, and aircraft to characterise aerosol-cloud interactions in different atmospheric layers. Designed and calibrated sensor and analysis platforms that would be required to evaluate localised and larger-scale responses to potential marine cloud brightening interventions.
Conduct multiple vessel – multiple aircraft atmospheric perturbation experiment to assess efficacy of large-scale cooling and shading	Deployed vessels for spraying and sampling sea salt aerosols during small-scale marine cloud brightening field trials (110). During each campaign, sea salt aerosols were released from a primary spray vessel while a secondary sampling vessel along with crewed and uncrewed aircraft tracked the resulting plume and cloud response. This integrated approach enabled simultaneous in situ and remote sensing observations of aerosol dispersion, cloud albedo changes, and any changes in light and heat reaching the ocean surface. These data provide critical insight into cloud responses to aerosol injections, the influence of background meteorology, and potential secondary effects on cloud lifetime and precipitation. In general, results show that seeded clouds contain a much larger number of droplets for the same total cloud water content and confirm the ability of the current MCB equipment to generate the predicted brightening responses in low cloud over the GBR.
Assess the influence of meteorological and cloud processes on coral bleaching.	Analyses confirm that large scale weather patterns shape dynamics the energy balance at the ocean surface, affecting incoming solar radiation and evaporative cooling (123, 124). New results reveal that coral bleaching on the GBR in 2022

	was triggered by a repeated pattern of specific atmospheric disturbances that disrupted local trade winds and inhibited evaporative cooling of sea surface temperature.
Evaluate efficacy of cooling and shading methods for reducing coral bleaching stress and mortality.	Refined and analysed the regional hydrodynamic and biogeochemical model to evaluate potential effects of potential marine cloud brightening over the GBR (125, 126). In the model, emitting ~1.5 kT day^{-1} of sea salt enhanced aerosol effects over the GBR and increase light reflection from clouds by 9.4% which, in turn, decreased the light reaching the sea surface by 5 W m^{-2}. Simulated changes were largely contained to the GBR and coastal regions of north-eastern Australia. Results show that average SST were 0.25 to 1°C lower in model simulations where cloud brightening was applied over the GBR. In the model, applying cloud brightening over just 10% of the GBR decreased cooling by ~33% demonstrating that cloud brightening can still be effective even if deployed over relatively small areas of the GBR. In addition, hindcasts of the potential efficacy of cloud brightening during previous bleaching events revealed that deploying this technology could have lowered heat stress on the GBR to below the level where severe bleaching occurs.
Identify the target wavelength of solar radiation to be reflected via fogging.	Revealed that under heat stress conditions the primary target should be to reduce the intensity of photosynthetically active radiation, particularly the blue and cyan wavelengths that are linked to bleaching (127). However, reducing the intensity of light outside of the photosynthetically active wavelengths can provide additional benefits. Broadband shading, covering the UV, visible light and near-infrared spectrum, is appropriate. The effectiveness of shading varies based on factors such as coral species, local water movement, light wavelength, and shading duration (113).
Design and implement aquarium-based shading experiments to evaluate how fogging might improve mortality outcomes	Tested, and modelled, responses of corals to heat stress under different levels and mechanisms of shading (including via small-scale production of fog) during 7 separate aquarium-based experiments (128–132). Showed that shading for as little as four hours significantly decreased coral bleaching and lowered mortality risk in corals that were already bleached, but that effects were larger as shading duration increased. Corals under more shade had lower levels of cellular damage but the benefits of shading were most evident at lower temperatures and diminished under prolonged heat stress. However, results were highly variable among coral species, ranging from shading being beneficial to neutral and negative. Collectively, results show that intermittent shading of 20-30% of light can delay the onset of bleaching and lower rates of mortality for some species of corals. Monitoring of non-target species is needed to ensure that shading from fogging does not inadvertently harm other species (113).

Identify the target droplet diameter to maximise the scattering of target light wavelengths by fog	The viable nozzle technologies for fogging produce droplets between 0.2 to 3 μm diameter depending on nozzle design, sprayer operating conditions, and ambient humidity (113). At 80% relative humidity, photosynthetically active radiation wavelengths are most efficiently scattered by droplets that are 0.5 and 1 μm in diameter. The energy required to create fog from seawater depends on water pressure and volume. Taken collectively, these properties indicate that fogging should use a sprayed droplet size of 0.8 μm exiting the nozzle which equates to aerosol particles that are 0.2 – 0.4 μm. This droplet size is large enough to scatter visible light efficiently, particularly in the blue and green portions of the spectrum, while also being small enough to remain suspended in the air for a considerable time under typical environmental conditions. Preliminary results from field trials of a fogging system with these design parameters show that the system can generate sufficient seawater droplets to form a fog plume with the desired light scattering properties (113, 129).
Determine if fogging can alleviate bleaching stress, and reduce coral mortality, and build a preliminary fogging intervention deployment strategy.	Fogging during doldrum conditions is technically feasible as an intervention to mitigate coral bleaching and mortality (113, 124). Production of fog comprised of sea water aerosol particles ~0.3 μm diameter can produce up to 30% shading of UV and visible light and reduce damage to corals. However, preliminary analyses indicate that, throughout a fogging intervention, time-averaged shading of 10-50% is likely over areas spanning hectares to tens of hectares. To increase the area shaded, or to shade >30% of light, multiple spraying sources can be positioned so that their plumes overlap. In the future, a fogging pilot deployment should test efficacy of this intervention on the reef during a marine heatwave. A pilot deployment is recommended to implement fogging over a high-value reef site ~2-3 ha in area during doldrum events that coincide with marine heatwave conditions (113). Site selection would need to account for reef size, shape, depth and prevailing wind condition and deployment tactics would necessarily be co-designed with Traditional Owners and aligned with any local site stewardship and/or tourism operations. The recommended fogging pilot deployment would be subject to outcomes of intervention risk assessment and would require regulatory approvals.
Develop preliminary scenarios of logistics for achieving fogging at a target reef location	Successfully deploying fogging to mitigate coral bleaching at a target reef requires strategic deployment of fogging systems based on local environmental conditions, including prevailing winds, target area dimensions, and dispersion dynamics. Three fogging deployment strategies were considered: • Mobile Vessel-Based Fogging: Deploy multiple vessels equipped with fogging systems to generate localised shading over target reef areas. • Fixed Station Fogging: Deploy permanent or semi-permanent fogging stations, such as floating platforms or barges, to continuously release fog in strategic locations.

	• Combination of Mobile and Fixed Systems: Deploy fixed stations to maintain continuous shade production supplemented with mobile units to respond to changing wind conditions. Based on field observations during fogging trials, mobile vessel-based fogging is recommended because it enables rapid responses to fluctuations in wind direction and plume behaviour (109, 113). Moreover, mobile systems can be deployed to areas experiencing the highest heat stress and they do not require permanent seabed anchoring or structures that can damage benthic habitats. The portable fogging systems developed by RRAP can be deployed on existing vessels to reduce capital expenditure.

DEVELOP A FRAMEWORK FOR OPERATIONALISING PROPOSED COOLING AND SHADING TECHNOLOGIES

OBJECTIVE	ACHIEVEMENT
Generate and analyse atmospheric data to quantify conditions over the GBR	Successfully characterised spatial and temporal variability in key drivers of cloud formation over the GBR in summer during four years of monitoring (126, 133). Generated comprehensive datasets reporting atmospheric composition (aerosols, cloud physics) turbulence, thermodynamics, and radiation. Atmospheric chemistry data span greenhouse gases, biogenic volatile organic compounds, sulphate and black carbon, and cover gas- and particle-phase measurements.
Assess cloud climatology and precipitation characteristics over the reef during summer	Determined that low-level clouds over the GBR are not strongly affected by the presence of the Reef (134). Instead, high-level clouds are dominant over low latitudes in summer and low-level clouds are dominant over the ocean and coast during winter (133). In some years, meteorological conditions cause cloud cover to decrease during summer but in other years tropical cyclones increased cloudiness. Rain cloud properties were generally consistent between the GBR and adjacent open ocean but there was a strong latitudinal dependence of total rainfall with highest falls near Cairns.
Evaluate potential efficacy of cloud brightening through analyses of background concentrations of cloud condensation nuclei	Developed and validated a new satellite-based method to assess how concentrations of cloud condensation nuclei (CCN) change with water vapor supersaturation over the GBR. Applied the new method to reveal that background CCN concentrations range from ~50 to ~200 cm^{-3}. These concentrations are within the range where clouds can be made considerably more reflective through addition of aerosols. These data and analyses are essential for ensuring that background CCN levels are realistically represented in models that quantify how making clouds brighter can reduce heat transfer to the ocean.

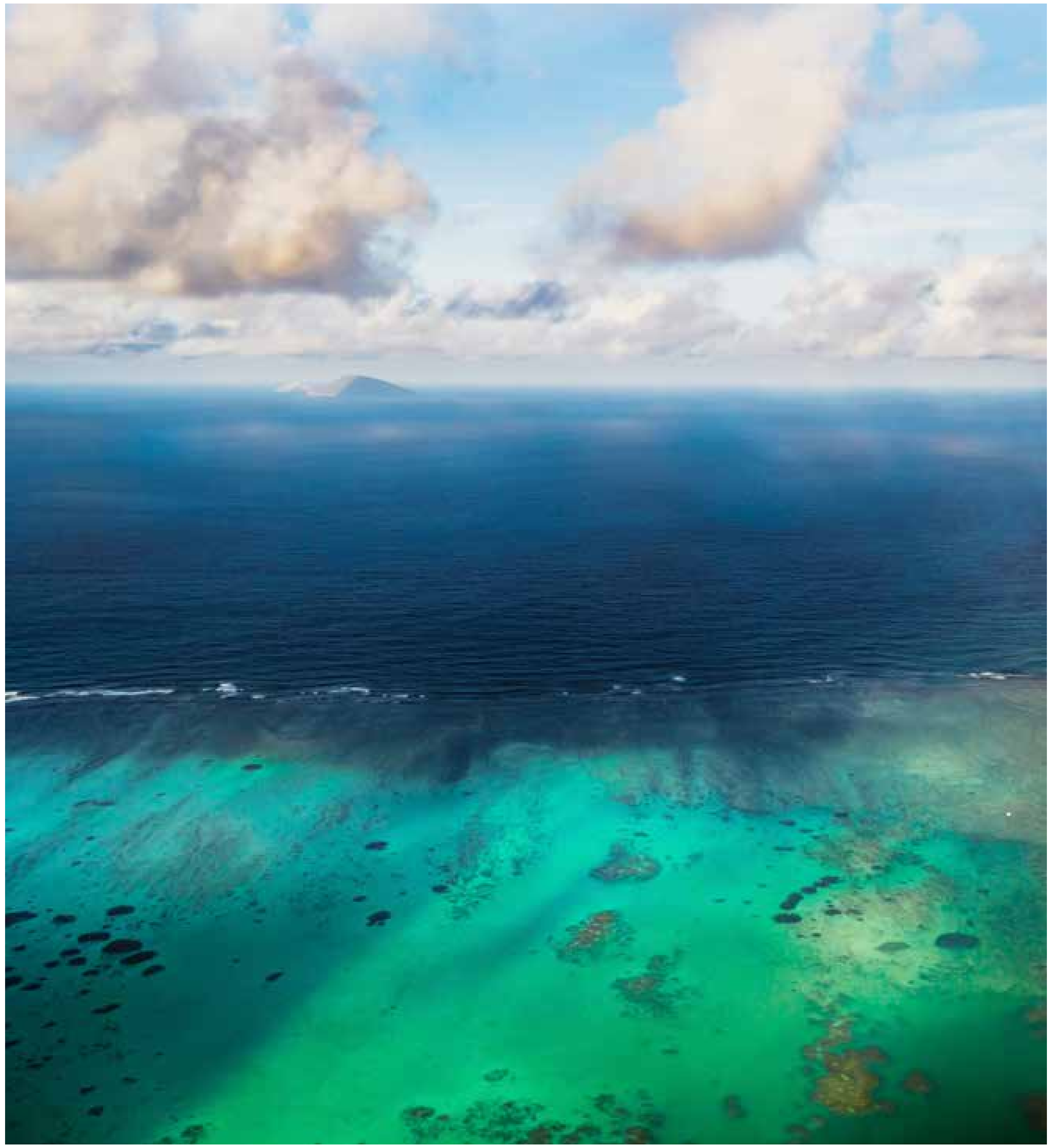
Cross-validate satellite derived cloud metrics against measurements for the GBR region.	Successfully measured how CCN concentrations depend on water vapor supersaturation over the GBR (133). Demonstrated a strong correlation between satellite-derived CCN data (see above) and these new high-resolution measurements over the Reef. These analyses confirm that satellite-based methodologies can be used to retrieve CCN data in remote marine environments. Additional analyses of these data reveal that, during summer, the southern GBR has the most frequent occurrence of suitable low-level clouds that are susceptible to seeding.
Generate surface-based measurements of cloud, aerosol, and precipitation properties that complement weather data	Quantified cloud and precipitation properties across all field sites, successfully distinguishing between precipitating and non-precipitating clouds (133). Revealed that precipitating clouds generally have higher, cooler tops with larger droplets, and that warm clouds with larger optical depth are mostly found offshore. Analyses of vertical profiles for aerosols revealed that light absorption and scattering in the atmosphere was highly variable during the day and detected aerosol layers with high absorption/scattering (>0.05 km^{-1}) extending beyond 2 km altitude which may be associated with evaporation from clouds (135).
Characterise climate and atmospheric relevant gases, air-sea gas exchange, black carbon, and scattering properties	Provided the first direct quantification of aerosol chemical composition in the air over the GBR during summer (136, 137). Measured levels of biogenic volatile organic compounds during summer months which included a marine heatwave. Results show that the central GBR is a net source of volatile organic compounds, with all concentrations increasing with proximity to the coast (138). Ammonia concentrations varied substantially, ranging from 7 - 483 ppb, with concentrations increasing significantly soon after rainfall events due to bird guano. Non-refractory aerosols were dominated by sulphate (63%) and organics (30%) including marine dimethyl sulfide. Alongside rainfall, wind speed had strong effects on concentrations of sulfuric acid, methanesulfonic acid, halogens and ammonia (139).
Measure cloud microphysical properties	Quantified cloud microphysical properties using a sophisticated array of sensors to measure cloud droplets within a size range of 3 - 960 μm. Applied the method during field trials to demonstrate that marine cloud brightening using sea salt aerosols increased aerosol concentrations ~3-fold and the estimated cloud optical depth of seeded clouds increased ~15% on average (133).
Measure upwelling and downwelling light above and below clouds to determine cloud albedo and relate it to cloud microphysics.	Developed and trialled new approaches for measuring cloud brightness accounting for differences in size, shape and patchiness of clouds (133). Successfully combined data from instruments that measure light radiation with hyperspectral imagery to inform radiative transfer modelling that resolves properties such as cloud top height, CCN and effective radius based on the specific light wavelengths in each measured image.

Assess aerosol size distribution, concentration, composition, optical, and hygroscopic properties	Showed that, between 2016 and now, the GBR typically experienced low aerosol and CCN concentrations and that clean marine air dominated the airmasses over the Reef (133). However, brief periods with higher CCN and total aerosol number concentrations occurred when air masses passed over the continent before reaching the GBR. Found a strong correlation between CCN concentration and total particle number concentration which suggests that the availability of aerosol particles is a key driver of CCN concentration over the GBR (140). Collectively these analyses support the feasibility of cloud brightening interventions because lower background aerosol concentrations make it easier to achieve a meaningful change in cloud reflectivity.
Generate vertical profiles of the atmospheric boundary layer for temperature, humidity and aerosol size distribution	Revealed that marine air masses over the GBR predominantly originate from the east to southeast and were transported by the trade winds (115). Aerosol concentrations were generally low below cloud bases (200-300 cm^{-3}) but high concentrations (up to 1200 cm^{-3}) were observed when winds transported continental air masses eastwards over the GBR. Developed novel methods for mapping temperature and humidity changes with altitude using Lidar and drone-based observations, finding that boundary layer heights were generally between 700-900 metres altitude during summer on southern mid-shelf reefs (135). Elevated aerosol layers frequently occurred around 1 km altitude consistent with the natural presence of sea salt aerosols.
Develop Large Eddy Simulation (LES) modelling of cloud microphysics processes to inform design and evaluation of marine cloud brightening technology	Configured a new Cloud Model to assess the factors that influence how aerosol addition affects cloud brightness (126). The model comprises a Large Eddy Simulation that represents trade wind conditions over the GBR in summer. Simulations of movement of sea salt aerosols released from a vessel on the GBR revealed that: aerosol availability is dependent on the distance from the source; aerosols are activated into cloud droplets with a complex three-dimensional structure that changes constantly over time; aerosol concentrations decrease with altitude but stronger winds mix aerosols more rapidly to higher altitudes and increase the chance they can act as cloud condensation nuclei.
Develop and analyse atmospheric aerosol model to capture aerosol sources, sinks and transport over the Reef.	Successfully developed a modelling framework that uses the Weather Research and Forecasting Model coupled to chemistry (WRF-Chem) to assess aerosol sources, sinks, and transformation over the reef. Simulated weather for eastern Australia and the Coral Sea, including the GBR, using nested locations where processes are modelled with higher spatial resolution (135). This approach allows for simulations of cloud brightening deployments in specific small areas of the GBR to be scaled up to assess regional effects. Results demonstrate that the model performs well for simulating wind speed and direction at specific locations, and it captures average differences in temperature and relative humidity among months but not among days. Model predictions of average concentrations of nitrogen dioxide, formaldehyde and ozone in the atmosphere were generally

	consistent with observations except for predictions for areas close to urban centres. Analyses of this model also show that decreasing light and heat energy reaching the ocean surface by 11 W m^{-2} can reduce heat stress experienced by corals by as much as 3DHW (126, 133). ACCESS-EMS-GBR was also developed to assess aerosol over the GBR and has been shown to capture observed meteorology, seawater temperature and irradiance, and aerosol number concentration and composition well.
Optimise the cloud microphysical modelling framework for multi-scale analyses that resolve reef, region and GBR-wide dynamics.	Conducted a comprehensive series of simulations to identify optimal model configuration for shallow cloud and precipitation modelling over the GBR (134, 141). Results show how trade wind clouds over the GBR respond to local atmospheric and sea surface conditions as well as mesoscale wind patterns. In addition, these models reveal that cloud properties are highly sensitive to aerosol levels, coastal topography and local wind regimes. Overall, research findings indicate that aerosol injection can influence cloud properties but local topography and winds should be considered when selecting timing and areas for cloud brightening interventions.
Utilise nested models to bridge between the regional coupled atmospheric modelling and the LES scale simulations.	Applied the modelling framework to evaluate how cloud-aerosol interactions depend on varying aerosol concentrations with different spatial distributions over the GBR. Results reveal that simulated release of sea salt aerosols can increase aerosol particles up to 450 cm^{-3}, particularly over aerosol source stations. Spacing source points more closely together creates a larger overall enhancement in surface aerosol concentration across the modelled area. However, there can be widespread dispersion of aerosols beyond the target domain extending both downwind and upwind area.
Configure a new regional atmospheric model coupled with GBR hydrodynamics and biogeochemistry and that includes improved aerosol and cloud microphysics data	Developed and analysed a coupled atmosphere-ocean model (ACCESS-EMS-GBR) which can evaluate effectiveness and potential impacts of marine cloud brightening at local to regional scales over the GBR (126). The model consists of a regional configuration of the Australian Community Climate and Earth System Simulator (ACCESS) with detailed aerosol and cloud microphysics, coupled to the CSIRO Environmental Modelling Suite (EMS) hydrodynamic and biogeochemical marine model of the GBR. Major new capabilities include: • Regional coupled aerosol and cloud microphysics schemes to capture aerosol-cloud interactions at convection-permitting resolution. • Improved representation of observed aerosol charaterisatics in the GBR through new particle formation processes and revised emissions of anthropogenic aerosol, primary marine organics and biogenic precursor gases. • Implementation of a new mechanism to simulate sea salt aerosol emissions for marine cloud brightening, that enables any deployment scenario to be simulated in a realistic manner.

	• Ability to simulate the effects of sea salt emissions on cloud microphysics, precipitation, radiation, temperature and subsequent ecological responses in the coral reef, including coral bleaching (the first regional model with such capability). • Captures feedbacks in sea-air fluxes of heat and moisture that may arise as a result of surface shading and cooling. • Derived new metrics to compare sea salt emission efficacy as the ratio of the change in a quantity of interest to the mass of added sea salt. The model has been used to simulate several marine cloud brightening scenarios, helping to identify the optimal sea salt emission parameters (emitted particle size and mass).
Improve heat flux modelling within eReefs to capture atmospheric and underwater light field.	To improve modelling of how heat and light energy is transferred through seawater, the HydroLight optical model and associated RADTRAN-X simple atmospheric model have been added to the CSIRO Environmental Modelling Suite (126). These modifications provide new capability for evaluating intervention efficacy: • Enhanced resolution of light spectra to include ultraviolet and infrared light and refraction at the sea surface • More accurate formulation of downwelling light at the seabed that captures absorption, transmission and reflection of light by the benthos. • Capturing both downwelling and upwelling light in model calculations. • Incorporating atmospheric variables that influence heat and light transfer underwater. • Improved metadata and alignment of inputs and outputs to increase transparency and reproducibility of model predictions.
Scenario testing to examine potential continental scale impacts on rainfall	Simulations demonstrate that changes in modelled rainfall in response to moderate to high sea spray aerosol injections were negligible in comparison to the background variability in rainfall over north-eastern Australia and the GBR, even in response to a maximum deployment scenario that is beyond what is feasible (126). Moreover, the scale of sea spray aerosol injections being considered by RRAP are several orders of magnitude smaller than the background range of sea spray emissions from the Coral Sea and Pacific Ocean. Results demonstrate the regional marine cloud brightening can be achieved without significant impacts on regional precipitation during the 2022 summer. Further work is needed to assess impacts under different climate regimes and years. (126).
Build social, cultural, and regulatory frameworks required to support novel Cooling and Shading interventions	Coordinated technical and operational research in conjunction with parallel development of community engagement, regulatory compliance, and governance frameworks that ensured outcomes were legitimate, compliant, and socially informed (109). Embedded First Nations participation in research design

	and implementation wherein employment pathways, fieldwork participation, and cultural consultation activities were jointly delivered. Built long-term partnerships with industry to enable collaborative use of marine and aviation infrastructure, support services for researchers, and enhanced field access. Developed an award-winning Workplace Health and Safety system with daily reporting during campaigns and comprehensive documentation across all operational platforms. Together, these achievements have positioned RRAP Cooling and Shading as a credible, ethical, and operationally capable initiative.



ENHANCED CORALS AND TREATMENTS

AUGMENT CORAL THERMAL TOLERANCE AND THE CAPACITY OF CORALS TO ADAPT TO FURTHER CLIMATE CHANGE

The RRAP Enhanced Corals and Treatments subprogram ('ECT') delivered new approaches to enhance coral heat tolerance and boost coral survival and reproduction during propagation and after deployment. Between 2020 – 2025, ECT focused on three main goals:

- **Genetics of adaptation** to understand the intrinsic potential for coral populations to respond and adapt to climate change
- **Assisted evolution to enhance resilience of corals** used for restoration purposes to increases in seawater temperature
- **Probiotic and nutrition treatments** during propagation to enhance coral settlement and increase survival of baby corals after deployment.

Throughout Phase 1 of RRAP, ECT has demonstrated the technical feasibility of enhancing heat tolerance of symbionts and corals but significant further work is needed to deliver the level of heat tolerance that will be required under climate change. A simple, accurate and reliable assay to identify coral brood stock with high heat tolerance, that can be passed on to the next generation, also remains elusive. There is strong social support for the use of coral aquaculture and seeding in field trials but additional risk evaluation and research underpinning the trait and environmental trade-offs of heat tolerance is needed prior to large-scale deployment of heat-tolerant offspring. The ability to seed healthier and more heat-tolerant corals in the future will mean that fewer corals need to be deployed to support reef resilience, thereby improving economic viability of these interventions.

GOAL AND SPECIFIC OBJECTIVES

Achievement within project scope

Genetics of Adaptation

Quantify natural variation in heat tolerance phenotypes and genotypes
Develop methods to quickly and reliably quantify heat tolerance in corals

Evaluate assisted evolution methods for heat tolerance

Develop managed breeding to enhance coral bleaching tolerance
Assess various breeding interventions to generate coral offspring with enhanced heat tolerance
Test performance of offspring from heat-tolerant parents in the lab and field
Evaluate trade-offs between heat tolerance and other traits
Enhance coral heat tolerance by manipulating algal symbionts
Develop new heat-evolved algal symbiont strains
Test heat-evolved strains in multiple life stages of corals in lab and field

Coral Propagation and Nutrition

Microbial inducers for coral larval settlement
Identify microbial treatments that enhance coral settlement
Generate treatments that can be applied to settlement devices
Probiotics and nutrition to enhance growth and survival
Produce a library of probiotics with expected benefits for coral.
Evaluate ability of probiotics to enhance coral performance
Evaluate a variety of diets with expected health benefits for corals
Develop encapsulated diets that promote coral health

At a Glance

Understand the counterfactual, benefits and risk of interventions → Understand current perceptions, and reach alignment between science, industry, community, Traditional Owners and government → Develop large scale interventions with targeted effects on reef functioning (restoration, adaptation, protection) → Establish value-based framework to foster industry and funding for reef protection, adaptation and restoration

AUGMENT CORAL THERMAL TOLERANCE AND THE CAPACITY OF CORALS TO ADAPT TO FURTHER CLIMATE CHANGE

Uses knowledge from Ecological Intelligence and methods from Cryopreservation, linked to Indigenous Partnerships

Genetics of Adaptation → Assisted Evolution → Coral propagation and nutrition

Delivers knowledge and methods to Coral Aquaculture & Deployment, Moving Corals, Cooling and Shading

Genetics of Adapation

Developed and evaluated rapid heat stress assays for wild and cultured corals.

Detected 3°C - 7.3°C variation in heat tolerance among corals of the same species from the same reef.

Combined genetic data with experimental assays and bleaching observations to identify robust predictors of heat tolerance.

Develop and mature a series of ecosystem models

Showed that cross-breeding corals from different regions can enhance heat tolerance but outcomes are complex and species-specific.

New genetic management framework for preserving functioning reef ecosystems.

Trade-offs between heat tolerance and other traits (growth, fecundity) were observed for some coral species in some experimental treatments.

Selective breeding success varied among coral colonies and species, and efficacy was influenced by conditions at deployment sites.

Implemented experimental evolution to successfully create strains of three Symbiodiniaceae species with enhanced heat tolerance.

Developed new and reliable method to introduce new symbiont types into corals.

Demonstrated that heat-evolved symbionts can endure within corals for at least two years.

Showed that hosting heat-tolerant symbionts can improve heat tolerance of baby, young and adult corals.

Coral propagation and Nutrition

Identified microbes that successfully control the settlement of nine coral species and developed methods for application to settlement devices.

Candidate probiotics formed stable associations with baby corals, demonstrating potential for establishing microbial symbioses with health benefits for corals.

Validated standardised procedures for feeding baby corals with a zooplankton mixture during propagation and grow-out.

Developed novel microencapsulated feeds that were ingested by baby and adult corals and that supported growth of baby corals of certain species.

ASSESS THE ADAPTIVE POTENTIAL OF CORAL POPULATIONS BY IDENTIFYING CHARACTERISTICS THAT UNDERPIN HEAT TOLERANCE.

OBJECTIVE	ACHIEVEMENT
Measure phenotypic variation in heat and bleaching tolerance for a set of coral species across the Reef	Results reveal extensive natural variation in heat tolerance that can drive natural adaptation, and that can be leveraged through selective breeding and conservation aquaculture to generate heat tolerant stock for deployments. Heat tolerance thresholds for two fast-growing branching coral species differed by 3°C - 7.3°C among colonies sampled from the same reef (142, 143). Overall, for fast-growing branching corals there is high standing genetic variation between and within species. In future, achieving rapid gains in coral heat tolerance via shifting phenotypes through assisted evolution will require targeting phenotypic traits with higher heritability and/or the combined effects of many loci rather than relatedness per se. Given the time required to reach second (and further) generations of cross-bred corals, additional work evaluating fitness in wild corals is recommended.
Identify coral host and symbiont genetic markers linked to heat and bleaching tolerance.	Observed variation in heat tolerance was linked to sea surface temperature and recent heatwave events across the GBR but within reefs, additional variation in heat tolerance among individuals was not explained by environmental predictors (144). Preliminary results for three fast-growing branching coral species show that heat tolerance, as measured by photochemical efficiency and chlorophyll content under acute heat stress, is controlled by multiple genes (polygenic) (144).
Develop assays, DNA markers or combined polygenic predictors to rapidly identify candidate coral colonies for selective breeding.	Tested new molecular (eDNA-based) approaches to quantify coral community composition in coral spawning slicks, finding different relative abundance of coral genera in different GBR regions (145). Successfully developed and evaluated methods to rapidly test heat tolerance in coral colonies both in the wild and in aquaculture facilities using rapid heat stress assays. However, for some coral species, traits commonly measured in rapid heat stress assays do not consistently identify coral genotypes that survive bleaching : the duration of the test and metric used influences predictions of which coral will survive (144). Ongoing analyses of genetic data for corals across 30 reefs with known bleaching history across five years will soon reveal predictors of heat tolerance and survival for fast-growing branching species. In addition, offspring from bulk-crosses of a branching coral species have been outplanted to a common environment and future analyses of heat tolerance and genetic relatedness will provide better estimates of heritability and parental breeding values.

ASSISTED EVOLUTION FOR ENHANCED HEAT TOLERANCE

OBJECTIVE	ACHIEVEMENT
Measure phenotypes of purebred and hybrid offspring from broodstock sourced from different regions	Broodstock from reefs modelled to have heat-tolerant genotypes did not always produce heat-tolerant offspring (146). Although higher survival was observed in some crossbred corals from different regions compared with crossbred corals from the same region, results depended on measured traits and were species specific. Offspring of heat-tolerant corals have enhanced heat tolerance but effects depend on species, life stage and environment (147, 148).
Assess genetic traits underpinning phenotypic trait variation in purebred and hybrid offspring.	Crossbreeding corals from different regions did not consistently generate distinct stock with enhanced heat tolerance (148). However, there are conserved and unique genes that are differentially expressed under elevated temperatures that could serve as potential markers for selection of heat tolerant broodstock. A genetic management framework was developed for preserving functioning and integrity of coral communities (148).
Measure trade-offs between growth, survival, and other traits in offspring bred for enhanced thermal tolerance	Evidence for a trade-off between heat tolerance and other measures of performance (growth, fecundity) was mixed depending on species and experimental treatments. Batches of related coral spat that had higher survival under heat stress (~13 – 31 DHWs) in the laboratory had reduced survival as spat in the field, but the level of stress was much lower (~4 DHWs) (148). Coral spat with heat-evolved symbionts had better survival and bleaching resistance at high temperature but slower growth under ambient conditions. Heat tolerant broodstock did not have lower fecundity.
Estimate the scope of trait enhancement via selective breeding in corals.	Selective breeding success varied among broodstock, and efficacy depended upon environmental conditions at deployment sites. In some cases, selective breeding successfully enhanced coral recruit but not larval heat tolerance (147). In other cases, using selective breeding and inoculation with heat-evolved symbionts in tandem was beneficial for some corals in certain environments but was counterproductive in others (148). The extent to which these findings depend on the method used to select coral broodstock remains unclear.
Develop high-throughput tools for the assessment of heat tolerance and growth of coral larvae, juveniles and adults.	A machine learning pipeline was successfully developed and applied to measure coral juvenile growth and survival (149, 150). In addition, protocols were developed to maximise quantity and quality of cellular material extracted from young corals (151). High-performance computing pipelines were also developed for efficient pre-processing and mapping of sequence data, and data processing pipelines were developed for robust, repeatable and efficient analyses of gene expression data. Novel data sets with unprecedented spatial coverage and number of sampled

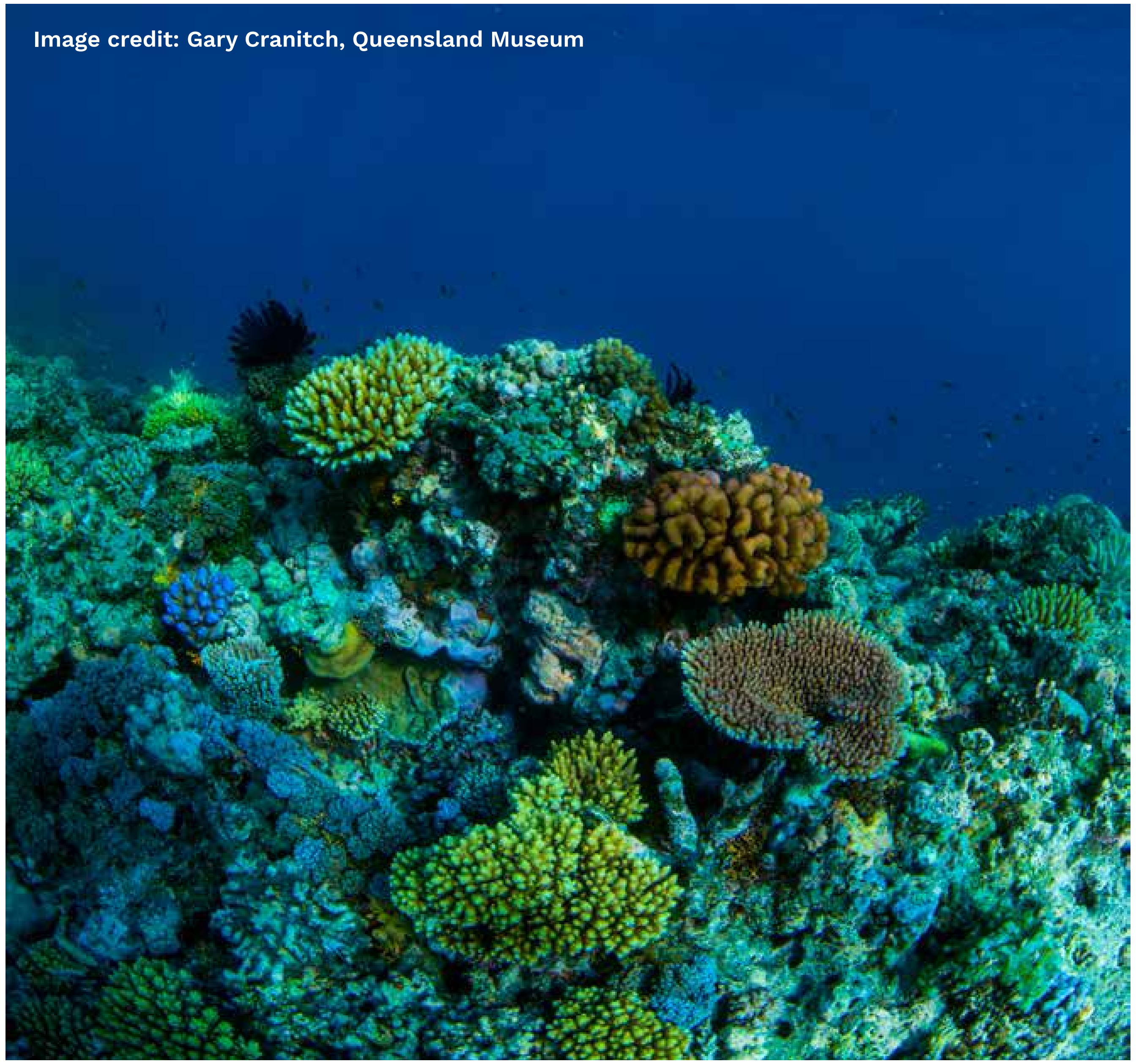
	corals have been produced with whole genome sequencing, with bioinformatic analysis pipelines developed to characterise coral host and symbiont genotypes (64).
Select and screen new Symbiodiniaceae strains with established and new methods.	Experimental evolution methods were used to generate heat-evolved strains of three Symbiodiniaceae species, all three of which had enhanced performance under heat stress. However, symbionts of one heat-tolerant strain had slower growth at both ambient and elevated temperatures. Results also demonstrate that selection of symbiont strains under rapidly fluctuating temperatures was successful to widen their thermal niche (152, 153). Finally, draft genome assemblies of the heat-evolved symbiont strains were generated as a foundation for identifying heat tolerance markers (148).
Test feasibility of chemical bleaching and re-inoculation with heat-evolved algal symbionts for multiple coral taxa.	A reliable chemical bleaching method was developed to successfully manipulate the Symbiodiniaceae communities of adult corals (154, 155). Mild chemical bleaching facilitated uptake of heat-tolerant symbionts in 5-25% corals with high survival and recovery. Severe chemical bleaching facilities uptake in ~69% of corals but results in higher mortality. Results also clearly show uptake of Symbiodiniaceae from the environment by adult corals.
Inoculate larvae and juveniles of a range of coral species with cultures of wild type or heat-evolved Symbiodiniaceae and assess performance and trait trade-offs.	Multiple experiments were progressed for different species and treatments, with mixed results. For *Galaxea* corals, heat-evolved symbionts enhanced heat tolerance of adult coral fragments without compromising growth at ambient temperature (156, 157). Experiments on young *Platygyra* corals inoculated with different heat-tolerant and wild-type symbionts show that hosting multiple heat-evolved symbionts can enhance bleaching resistance +6 DHWs (148) . However, these benefits depend on which symbiont strains are present. Bleaching was less severe in adult *Platygyra* corals inoculated with heat-evolved *Cladocopium*, though only when that symbiont was present as the dominant strain. However, for baby *Acropora* corals, heat-evolved symbionts enhanced survival and bleaching resistance under elevated temperature but reduced growth under ambient temperatures. Finally, field trials over 1 year, which included a heatwave, demonstrate that corals with heat-evolved symbionts performed better than those hosting native symbionts.
Assess long-term stability of symbioses with selected Symbiodiniaceae	Symbioses with selected (heat-evolved) Symbiodiniaceae strains persisted throughout the entire experiment and/or deployment (148). In the laboratory, symbioses with selected strains persisted for at least 2 to 24 months. In the field, symbioses with selected strains persisted for at least 10 to 12 months (148).
Determine the adaptations that underpin bleaching tolerance for multiple heat-evolved corals.	Identified several biomarkers for coral heat-tolerance (152, 156, 158), including: • Exposure to daily temperature fluctuations increased thermal breadth and exposure to elevated temperatures led to a higher thermal optimum. • Corals with heat-evolved symbionts showed reduced symbiont protein degradation or sustained protein and lipid synthesis under heat stress (159). • Corals with heat-evolved symbionts had different levels of pigments involved in photosynthesis and different oxidative stress markers • Coral larvae with heat-evolved symbionts had lower expression of algal photosynthesis genes and higher expression of carbon fixation genes. • Heat-evolved symbionts had low levels of reactive oxygen species, low levels of mitochondrial activity and high levels of reduced glutathione.

ESTABLISH SCALABLE AND COST-EFFECTIVE AQUACULTURE METHODS FOR PRODUCING BOTH SEXUALLY AND ASEXUALLY PROPAGATED CORALS

OBJECTIVE	ACHIEVEMENT
Identify microbial taxa that induce settlement and metamorphosis of three to five non-Acroporid coral species	Biofilms on coral settlement tabs were extremely diverse with 69 prokaryotic phyla and 525 families represented across all treatments. Mature biofilms, particularly those conditioned under natural light-dark cycles, promoted the highest levels of coral settlement. Numerous specific bacterial taxa that either increase or inhibit settlement were identified (160). In addition, putative microbial functions that may attract coral larvae and initiate settlement, including pigments, gaseous compounds, and neurotransmitters, as well as toxins and other compounds that may deter settlement were evaluated (161).
Develop a suite of bacterial treatments that can be applied to devices to enhance settlement success.	Bacterial isolates induced settlement across nine coral species, with several inducing settlement in as many as five different species, including coral species that are typically difficult to settle (162). To improve practical application for reef restoration, methods were established to apply bacterial treatments as a non-living bacterial coating that preserves inductive activity in a stable, biosafe, and reproducible format that can be stored for weeks without affecting settlement success (163).
Produce a library of probiotic candidates with expected nutritional and health benefits for coral.	A large, taxonomically diverse culture collection of more than 900 new bacterial isolates was established as a foundation resource for ongoing coral probiotics research (164). Antibacterial activity and production of enzymes that may enhance digestion were confirmed in several isolates
Assemble probiotic consortia and test their ability to enhance the performance of corals in captivity	Successfully manipulated the microbiome of baby corals of two species through inoculation with probiotics. Some candidate probiotics formed stable associations with baby corals, providing proof-of-concept for the potential to establish enduring microbial symbioses with health benefits for corals (165).

Identify live feed enrichments, nutritional formulations, and supplements with expected health benefits for corals	Combined feeding with zooplankton and a commercial liquid feed did not enhance survival or growth relative to the zooplankton mixture on its own for any species, validating standardised feeding procedures used during propagation and grow-out (166). New encapsulated diets enriched with specific fatty acids, and which can incorporate probiotic treatments, were developed for coral feeding experiments.
Develop a palatable microencapsulated diet and test its ability to promote coral growth and condition	Microencapsulated diets were ingested by multiple species of captive corals when combined with an attractant to enhance palatability and adjust buoyancy. The encapsulated diets supported survival and growth of baby corals of certain species but did not enhance performance relative to standard live feeds (162). Research for this objective was paused during RRAP Phase 1 but the approach might become more important if regulatory requirements prevent the use of live feeds in the future.

Image credit: Gary Cranitch, Queensland Museum



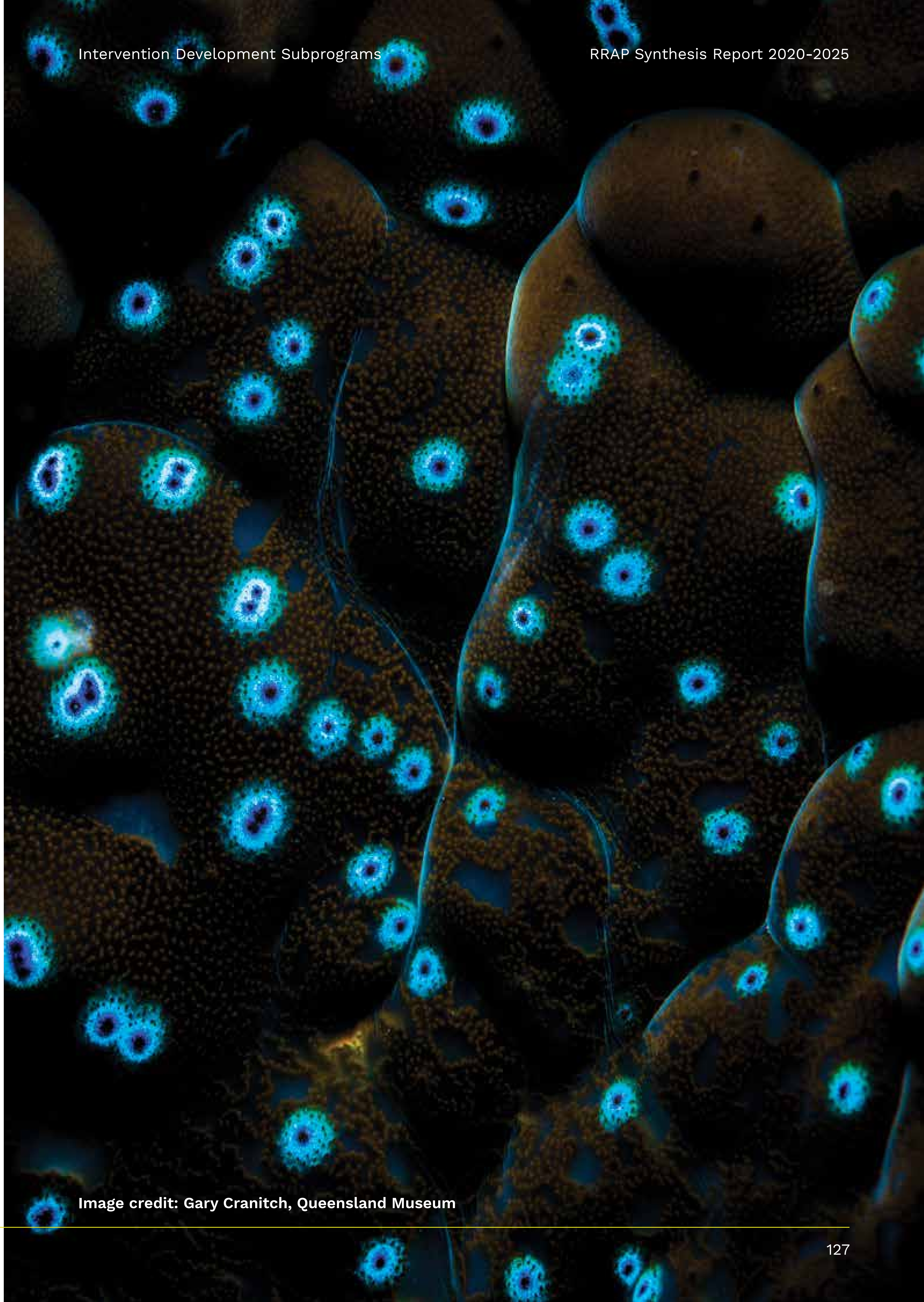


Image credit: Gary Cranitch, Queensland Museum

CORAL AQUACULTURE AND DEPLOYMENT

PROPAGATE UP TO 100 MILLION CORALS IN CAPTIVITY PER YEAR, AT LOW COST AND USING SEXUAL AND ASEXUAL METHODS

The Coral Aquaculture and Deployment R&D subprogram ('CAD') delivered a step-change in scalability of coral aquaculture by optimising processes for the propagation, settlement, symbiont inoculation, and survival of baby corals.

Between 2020 – 2025, CAD focused on three main goals:

- **Optimise methods for scaled propagation** (sexual and asexual), gamete capture, fertilisation and embryo/larval rearing, settlement, symbiont infection, grow-out and deployment that maximise survival of baby corals deployed on the reef
- Develop **scalable methods for detecting pests and pathogens** and maintaining genetic diversity of coral progeny, and **identify bottlenecks in production and deployment** processes
- **Improve understanding of the post-deployment survival challenges faced by seeded corals** through large field trials

Throughout Phase 1 of RRAP, CAD demonstrated the technical feasibility of large-scale spawning, settlement, grow-out and deployment of multiple coral species. The end-to-end process has been demonstrated but further field-based research is needed to optimise coral survival and ensure species are matched to appropriate habitats at deployment, with average survival of corals on devices after a year varying between 25 – 60% across experiments. There is strong social support for the use of coral seeding and natural breeding, and for their use in field trials. A prototype high-throughput coral aquaculture facility is now operational with potential for additional development and automation to further decrease costs.

GOAL AND SPECIFIC OBJECTIVES

Achievement within project scope

Coral Propagation and Deployment

- Develop high-throughput culture systems to optimise production
- Optimise coral settlement and maximise post-settlement survival

Large Scale Coral Aquaculture

Coral aquaculture facility prototype and design

- Automated gamete handling, from spawn capture to larvae
- Design high-throughput, high density coral aquaculture facility

Companion species and co-culture methods

- Develop co-culture practices to enhance early coral survival and growth

Health assurance and quality control

- Evaluate genetic diversity of corals throughout production
- Develop targeted diagnostic assays for pathogens and pests

Post-deployment survival and Large Field Trials

- Safely and successfully deploy >100,000 coral seeding devices
- Establish site selection metrics for maximising coral survival

At a Glance

Understand the counterfactual, benefits and risk of interventions → Understand current perceptions, and reach alignment between science, industry, community, Traditional Owners and government → Develop large scale interventions with targeted effects on reef functioning (restoration, adaptation, protection) → Establish value-based framework to foster industry and funding for reef protection, adaptation and restoration

RELIABLY PROPAGATE UP TO 100 MILLION CORALS IN CAPTIVITY PER YEAR

Informed by Ecological Intelligence, Cryopreservation and Enhanced Corals and Treatments, linked to Indigenous Partnerships → Optimise coral propagation and deployment → Deliver large-scale coral aquaculture → Test and refine methods via large field trials → Delivers knowledge to Modelling and Decision Support, Intervention Risk Management and Pilot Deployments Program

Optimise coral propagation and deployment

Successfully spawned 56 species of corals and timelines and methods to control settlement of 25 species

Developed new methods to culture coral larvae at densities up to 3 times higher than those used previously.

Developed and tested five new products that reduce fouling by up to 75% and increase baby coral survival by 10 – 100% in the field.

Designed novel ceramic devices for coral seeding that remain in place and protect baby corals.

Developed a new method for directing larval settlement at mm scale using microtopographic references coupled with chemical settlement cue, offering a potential nine-fold decrease in tank space needed for settlement.

Deliver large-scale coral aquaculture

Delivered novel tank designs that deliver up to a 24-fold increase in space-use efficiency within the coral aquaculture facility.

Improved cost-efficiency of coral grow-out by switching to a semi-recirculating system that reduces water usage.

Developed scalable methods for extracting bacterial and pest DNA from coral aquaculture water samples that can return results for biosecurity checks within ~4 days.

Optimised design of deployment devices and settlement tabs for compatibility with automated assembly in the future.

Identified compatible co-culture organisms and optimal stocking densities during coral grow-out.

Test and refine methods via large field trials

Deployed >16,000 coral seeding devices across >30 sites on 7 reefs over 4 years, using an integrated multifactor sampling design to maximise learnings.

Quantified highly variable survival of baby corals depending on species, deployment location and method. The average percentage of devices that had living corals remaining after 9 – 27 months ranged from 8 - 89%.

Demonstrated that wave exposure and sedimentation predict early post-settlement survival.

However, species-specific deployment strategies must be linked to high resolution environmental data.

Maintaining broodstock genetic diversity prevents genetic bottlenecks during culture and for up to two years in the field.

Worked with Indigenous Partnerships team to obtain Free, Prior and Informed Consent for all fieldwork, including opportunities for participation in project planning and research.

OPTIMISE METHODS FOR SCALED PROPAGATION (SEXUAL AND ASEXUAL) AND DEPLOYMENT THAT MAXIMISE SURVIVAL OF BABY CORALS DEPLOYED ON THE REEF

OBJECTIVE	ACHIEVEMENT
Facilitate the reliable and upscaled production of coral recruits	Successfully spawned 56 species across nine taxonomic families (*Acroporidae, Poritidae, Merulinidae, Diploastreidae, Lobophylliidae, Fungidae, Dendrophylliidae, Pocilloporidae* and *Euphyliidae*) in captivity (167).
Develop, test and assess larval culture systems for six coral species.	Designed tank systems and culture conditions, and tested recirculation systems for larval cultures, that can generate 500,000 larvae per 1 m^2 footprint of facility. Demonstrated successful larval culture at densities up to 2-3 larvae mL^{-1} for corals with small larvae, and at densities up to 1 larva mL^{-1} for species with larger larvae (168, 169).
Develop methods to control and optimise the settlement of coral species	Developed effective inducers and timeline for culture and settlement for 25 species, including 12 species that previously could not be induced to settle (170, 171). Identified species-specific settlement on different types of CCA for 15 coral species to control their settlement (172–174).
Optimise the production of coral larvae and recruits through symbiont infection at scale	Clearly demonstrated that survival of early life stage corals is enhanced by inoculation with microalgal symbionts (175). Established juvenile stage as the optimal early life stage to inoculate corals with symbionts at scale. Established optimal symbiont densities for inoculation (176).
Optimise post-settlement survival and growth through controlling substrate biofilm and algal communities	Identified light regime during culture to control CCA that are dominant in the aquarium facility and highly aggressive to coral spat (177, 178). Developed methods for preserving settlement tiles to kill competitors that overgrow coral spat while still preserving cues for settlement (179). Demonstrated that when competition is reduced, coral spat can grow 4 times larger with 2 times higher survival (yield of devices with living corals remaining) at one-year post deployment.
Develop and assess methods to optimise production of “coral tissue sheets” for six coral species	Demonstrated that material type and texture, and angling position of sheets, controls fouling to maximise coral tissue growth rates (180). Showed that continuous feeding during nighttime hours increased coral growth compared to daytime feeding. Identified *Montipora* and *Porites* species as good candidates for coral tissue sheets whereas *Acropora* have comparatively high mortality. Revealed that growth of secondary fragments cut from tissue sheets is much slower which reduces the effectiveness of this approach (181).
Identify deployment device materials for optimal design flexibility and recruit survival	Revealed that material type affects coral settlement and survival more than surface roughness. Identified concrete settlement tabs as a practical balance between high larval settlement and acceptable post-settlement survival (182, 183).
	Optimised methods for conditioning of tiles with specific CCA that maximises larval settlement and early post-settlement survival (184).
Test a range of eco-friendly chemical antifoulants to reduce competition and improve survival rates of corals post-settlement.	Demonstrated that five Foul Release Coatings (FRCs) reduce fouling by up to 75% for ~1 year in the field (185–187). Showed that coating device cores, but not arms, protected corals while allowing rapid colonisation of the device to adhere it to the reef (188, 189). Identified that FRC treatments increased coral survival by 10 – 100% in the field (177). The greatest protection was at inshore algae-dominated sites and over the first six months when spat were <1cm diameter.
Evaluate if regulating light can control fouling and enhance recruit survival.	Showed that using low light intensity during preparation of settlement tabs and post-settlement increases coral survival by limiting competitors. Demonstrated that vertical orientation of tiles during grow-out modulates light to reduce competition and increases facility holding capacity (178).
Develop and test deployment device designs to optimise retention on a range of seafloor rugosities	Developed ceramic devices, with high density and specific gravity, that sink rapidly, remain in place, and resist damage. Demonstrated high retention of devices (61-89% remaining after 1 year) with up to 80% of devices having living corals after 1 year (190). Showed that device shape had minimal influence on retention but the structure of the reef at the site of deployment did affect retention. Quantified similar retention and coral survival whether devices were deployed by divers or released from vessels at the sea surface (190).
Engineer access of coral propagules to deployment device (shapes, complexities, and topographies) to maximise survival.	Demonstrated that larval settlement can be directed onto specific structures using chemical inducers and device microtopography (191). Successfully identified a neuropeptide that induced settlement in eight of 13 species tested. Showed that application of inducer to protrusions in devices can be used to direct larval settlement, offering a potential nine-fold decrease in tank space needed for settlement.
Develop and test biomimetic glues to retain deployment devices on the reef.	Developed bioadhesives that are effective for securing settlement tabs to deployment devices (192). The developed underwater adhesives successfully retained coral settlement tiles within coral seeding devices (100% retention). Coral survival and growth on these devices were not negatively influenced by the bioadhesives. Showed that cotton filaments coated with bioadhesive can connect deployment devices and anchor them to reef rubble (193, 194). The developed bioadhesives are suitable for a range of reef restoration uses such as out-planting of coral fragments, serving as a non-toxic alternative to resins for coating submerged metal frames used in coral restoration, and acting as a replacement for plastic zip ties used to attaching coral fragments to underwater structures.

Evaluate the optimal design(s) of deployment devices that maximise survival and growth across environments and for six to nine species.	Demonstrated that coral survival is higher on devices that had been designed to include protective features with tabs in vertical orientations, and optimised placement of coral spat within devices (195, 196). Showed that coral microfragments generally have higher survival than coral spat (197, 198). Quantified highly variable survival outcomes among species, among reefs, and among deployment methods. Across numerous field deployments in different locations, the average percentage of devices per site that had living corals remaining after 9 – 27 months ranged from 8 – 89%.

DEVELOP SCALABLE METHODS FOR DETECTING PESTS AND PATHOGENS AND MAINTAINING GENETIC DIVERSITY OF CORAL PROGENY, AND IDENTIFY BOTTLENECKS IN PRODUCTION AND DEPLOYMENT PROCESSES

OBJECTIVE	ACHIEVEMENT
Design a prototype aquaculture production facility to output large numbers of high-quality corals.	Designed systems that have been used in the ReefSeed containerised aquaculture facility, and are now being used in other parts of the world (199). Produced 4 AutoSpawner systems and designed and assembled a high-throughput coral aquaculture facility to produce coral spat to populate 30,000 deployment devices during the 2025 summer coral spawning (200).
Create systems and methods for the automated handling and processing of coral gametes, including collection, fertilisation, rearing and settlement.	Developed a modular coral aquaculture system, the AutoSpawner, for automated coral spawning and fertilisation (200). Optimised coral larval culture tanks and integrated with new technology to reduce manual labour, increase holding density and simplify the harvesting procedure. • Coral larvae produced using the AutoSpawner were of equal quality to larvae produced using traditional manual methods. • Successful for nine hermaphroditic species releasing egg-sperm bundles and one hermaphroditic species releasing eggs and sperm separately. • Stand-alone AutoFertilizer system for smaller operations.
Develop systems to reliably mass culture corals through to deployment at sea.	Demonstrated benefits of higher water velocity during grow-out for *Acropora* recruits (201–203). Optimised coral rearing using settlement tiles angled at 90° to minimise fouling and maximise space efficiency. Improved cost-efficiency of long-term rearing of coral recruits by switching to a semi-recirculating system that reduces water usage by 9.5-fold (204).
Systems for the transport to sea of settlement units and devices for deployment.	Designed, produced and tested concrete settlement tiles with modular racks and moulds for efficient transfer of coral spat without damage. Successfully developed and implemented a modular transport system for devices. Integrated device design and transport systems that are compatible with the design and development of an automated Deployment Guidance System.

Develop systems to settle coral larvae on large surfaces suitable for large scale production.	Developed a suite of shallow tank systems that deliver high throughput of >11,000 settlement tiles per m2 for >10 coral species (167, 205). Demonstrated that settlement tiles can be conditioned on up to a 60° angle without affecting number and distribution of larvae settled. Delivered a 24-fold increase in space-use efficiency through tank racking, tile angle and hydrodynamic design solutions (206).
Design systems suitable for high level of automation for the handling of coral settlement substrates and integration into deployment devices.	Designed and tested semi-permanent reusable moulds that reduce the unintentional breakage of tiles and enable increased holding densities in the facility. Conceptualised and tested the Coral Growout Robotic Assessment System (CGRAS) and the Coral Spawn and Larval Imaging Camera System (CSLICS) developed in collaboration with the Translation to Deployment subprogram (96). Optimised the design of the deployment devices for automated loading of settlement units. This has also included providing input and testing of the tile cutting and device assembly jigs.
Develop methods for co-culture to increase the survival and early growth of propagated corals.	Identified compatible co-culture organisms for different coral species and/or growth-forms from immediate post-settlement to the juvenile stage. Developed methods to sustainably culture appropriate species of micro-herbivores within coral aquaculture facilities, to control fouling during grow-out (207, 208).
Identify the drivers of early coral survival in aquaculture, and evaluate co-culture factors.	Demonstrated that competition with algae (both fleshy algae and some CCA species) represents a major driver of mortality of coral spat in aquaculture (209, 210). Developed guidelines for tank system design appropriate for different co-cultured organisms. Suggested stocking densities are provided for the different companion species (~40 individuals m^{-2} tank area) (182, 208).
Identify problem organisms (disease, pests) that need monitoring within a coral aquaculture setting.	Identified *Vibrio* and total bacterial abundance as useful microbial indicators to monitor in coral aquaculture environments. Demonstrated that coral-eating flatworms are a pest organism of primary concern and identified broodstock coral tanks as the primary monitoring point. Determined that corallivorous nudibranchs were not a major risk to corals in the tested aquaculture environments (204).
Develop diagnostic tests to detect and quantify selected coral pests and potential pathogens.	Delivered a new sensitive and accurate method to detect and quantify coral-eating flatworms from small volumes of aquarium water (211). Developed a new assay for total bacterial and total *Vibrio* abundance in aquarium water samples. Calibrated a machine-learning model that can forecast risk of compromised coral health from the bacterial abundance assays (204).

Experimentally validate and implement robust assessments of coral genetic diversity across the coral breeding program.	Revealed that different approaches for measuring genetic diversity (parental assignment, effective population size, heterozygosity) were comparable estimators to characterise genetic diversity in cultured corals (212). Demonstrated that maintaining broodstock genetic diversity is key to preventing major genetic bottlenecks during aquaculture and field survival offspring corals up to two years in the field (212). Demonstrated that differences in gamete volumes have a strong link to the evenness of parental contributions in larval cultures that are bulk-fertilised by multiple coral parents (204).
Develop the quality assurance and quality control standard operating procedures to meet the project objectives.	Delivered scalable extraction methods for bacterial and pest DNA from water samples. With appropriate staffing, data on bacteria and pest abundances for biosecurity checks prior to deployment can be returned within ~4 days (213). Compiled guidelines for choosing broodstock corals to target high genetic diversity in offspring corals to avoid reduced effective population sizes.

IMPROVE UNDERSTANDING OF THE POST-DEPLOYMENT SURVIVAL CHALLENGES FACED BY SEEDED CORALS THROUGH LARGE FIELD TRIALS

OBJECTIVE	ACHIEVEMENT
Sub-program plans for education and training, and business development	Designed and implemented Traditional Owner internships and training placements to build capacity for Traditional Owner groups. Extensive research training and capacity building activities.
Implement engagement and communications specific to the Large Field Trials.	Worked with the AIMS Indigenous Partnerships team (IP) to obtain Free, Prior and Informed Consent (FPIC) for all fieldwork, including opportunities for participation in project planning, research, and knowledge sharing. Engaged constructively with stakeholders within the Cairns-Port Douglas Reef Hub during planning and implementation of Large Field Trials.
Undertake multiple-day field access to key Reefs across the GBR, three times per year across four years	Successfully conducted a total of 60 field trips across the GBR. The field trips ranged from shared large-ship trips, and land-based day trips to research-station based field trips. Implemented fieldtrip and experimental planning meetings to optimise use of experimental and ship space and resources based on evolving project needs and workplace health and safety requirements.
Design collaborative experimental plan for the Large Field Trials consistent with RRAP objectives	Implemented a sequence of collaborative workshops to design the Large Field Trials to maximise science learnings. Shared oceanographic, benthic and environmental data across field experiments to enhance science learnings and integrate knowledge. Facilitated monthly meetings across the subprogram and also other subprogram and project Partners, to promote integration and knowledge exchange across disciplines and institutions (214). Responded to two cyclone impacts to the Large Field Trials with agility and learned that cyclone impacts affected deployments in a spatially heterogenous way, improving future deployment approaches.
Deploy 10,000 devices (20,000 to 60,000 coral spat) in year two across sites at one reef.	Deployed ~1200 devices across 10 sites at one reef in Year 1 to test different device shapes across a wave energy gradient. Deployed ~2250 devices across nine sites at one reef to test device performance across an environmental gradient, and to identify pinch points for upscaling deployment. An additional ~2200 devices were deployed across 30 sites for various experiments across the subprogram in the first two years.
Deploy 100,000 devices (200,000 to 600,000 coral spat) in year four across multiple reefs.	Deployed ~9500 devices across 24 sites at three reefs. In addition, for a separate set of field experiments, deployed ~3070 devices across 21 sites at four reefs. Whilst these deployments weren't at the scale originally proposed, they provided critical data to evaluate deployment outcomes across several environmental gradients and provided critical process data to drive improvements in speed and scale of production.
Improve understanding of post-deployment survival to support decisions regarding what, when and how many corals to deploy at a location	Demonstrated that survival is highly variable and depends on fine-scale environmental conditions, benthic assemblage structure, coral species, life-history stage, and timing of deployment (197, 198). Revealed that other organisms living on settlement tabs influence coral survival (215, 216). Showed that seeding devices should be populated with tabs that each have five to ten coral spat to increase the likelihood of achieving 1 living coral per device after 1 year (217). Demonstrated that reef fishes can cause up to 95% mortality of coral spat if seeding devices do not have features that protect spat from fish grazing (195, 196). Demonstrated that mortality continues beyond one year post-deployment, but at a slowed rate (218).
Determine the drivers of survival and growth of juvenile corals across environmental gradients	Identified that wave exposure and sedimentation were strong predictors of early post-settlement survival in some taxa (196, 219). Showed that species-specific responses require tailored deployment strategies linked to high resolution environmental data. Revealed that sites with abundant small fishes can support seeded coral survival whereas unconsolidated rubble and macroalgae are detrimental (195, 196). Identified that the drivers of mortality were often best predicted at the finest spatial scales (198, 202).

CASE STUDY: CORAL SEEDING AT SCALE

One of the greatest challenges in coral restoration and adaptation intervention is achieving scale across a vast and complex ecosystem like the Great Barrier Reef. To address this, RRAP focused significant research and development on advancing a suite of aquaculture-based coral seeding approaches, improving the efficiency of sexual coral production, settlement, and deployment so that restoration efforts can expand from small experimental plots to ecologically meaningful areas of reef.

Coral production in aquaculture through to deployment has been designed as a two-part coral seeding system. With automated spawning tanks, high-density larval settlement and rearing systems, and facility layouts optimised for space, labour, and water use, researchers can now produce millions of fertilised eggs per species in a single night and maintain up to 30,000 coral settlement units in land-based facilities. Coral larvae are settled onto purpose-built ceramic devices and then transported and deployed onto reefs.

Large-scale field trials deploying thousands of devices have demonstrated strong retention of devices and coral survival yields of around 25-60% after more than a year. Importantly, devices released from the surface performed comparably to those deployed by divers, significantly reducing costs and enabling restoration to scale to hectares of reef.

These trials form the foundation for high-throughput coral production and deployment facilities already being developed and built under international projects such as ReefSeed.

Image: Dr Mikaela Nordborg watches over the Autospawner - a fully automated aquaria system designed to harvest and aid in the fertilisation of coral eggs and sperm, producing millions of coral larvae. Credit: Marie Roman, AIMS

Image: Researcher with coral seeding devices that were delivered to the reef during the first Large Field Trial of a two-part coral seeding system. Credit: Marie Roman, AIMS

CRYOPRESERVATION

ESTABLISH SCALED BIOBANKING CAPABILITY TO SUPPORT GREAT BARRIER REEF CONSERVATION AND RESTORATION

The Cryopreservation R&D subprogram ('CRYO') transformed methods for the preservation of coral sperm, larvae and symbionts required to scale-up reef restoration and adaptation, and to preserve the biodiversity of the Great Barrier Reef.

Between 2020 – 2025, CRYO focussed on three main goals:

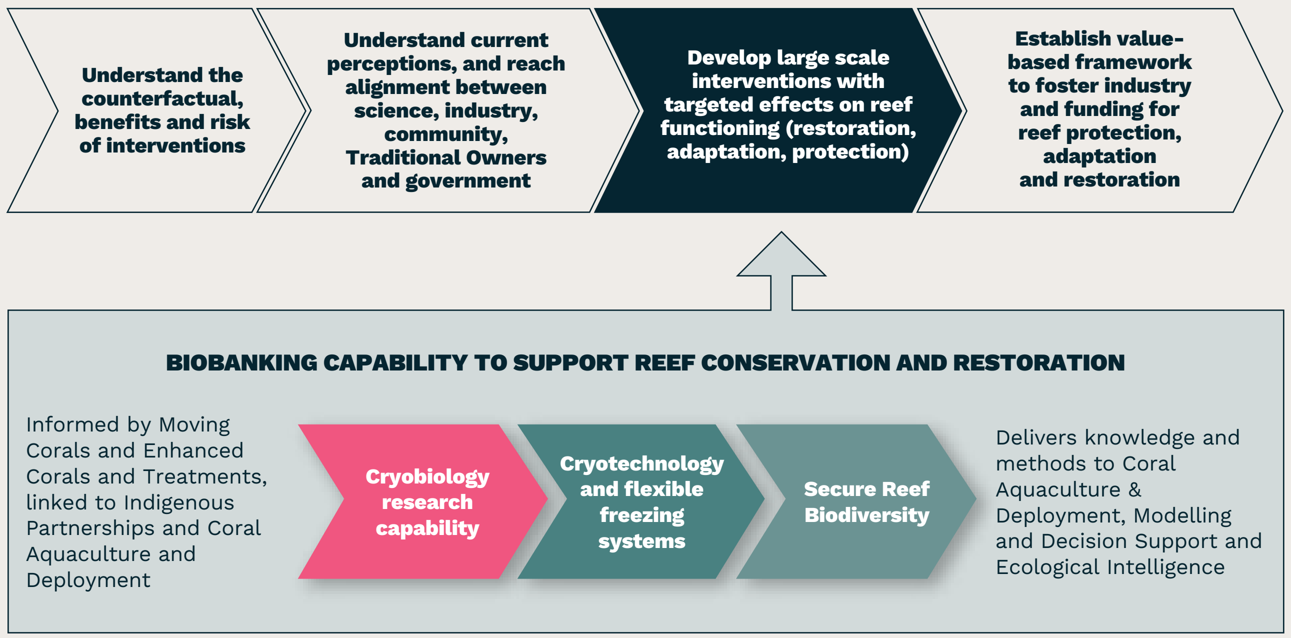
- **Establish cryobiology research facilities and expand biorepository capacity** for Australia's coral reefs
- **Secure reef biodiversity** through targeted biobanking of coral gametes, tissues, and symbionts from prioritised species, populations, and reefs
- Develop **new cryopreservation technologies and flexible freezing systems** to enable high-throughput cryopreservation methods for coral tissues, gametes and larvae

Throughout Phase 1 of RRAP, CRYO demonstrated the technical feasibility of freezing coral sperm and symbionts for later use in conservation aquaculture, but additional work is needed for coral larvae and some heat-adapted symbiont strains.. The end-to-end process from cryopreserved sperm to living corals deployed in the field has been demonstrated, with baby corals surviving up to surviving up to 12 months with monitoring ongoing. There is strong social support for the use of cryopreservation approaches in reef conservation, and culturally safe practices have been co-developed with Traditional Owners. Future integration of cryopreservation methods into coral seeding and larval reseeding will help to further decrease intervention costs.

GOAL AND SPECIFIC OBJECTIVES

	Achievement within project scope
Establish cryobiology research facilities	
Establish and operate a coral reef cryopreservation laboratory	
Expand biorepository capacity to support coral biobanking in Australia	
Secure coral biodiversity through targeted biobanking	
Database system for sample and metadata tracking	
Develop and implement long-term strategy for biorepository growth	
Audit biobank and facilitate genetic analyses to evaluate biodiversity	
Technologies for large-scale preservation of coral gametes, tissues and symbionts	
Optimise sperm cryopreservation methods and high-throughput pathways	
Develop and apply post-thaw fertility assessments for coral sperm samples	
Adapt new technologies for preservation of coral larvae	
Establish basis for symbiont and microfragment cryopreservation	

At a Glance



Cryobiology research capability

Expanded biorepository systems and facility to maintain an additional 12 thousand coral samples with capacity to grow in the future

Co-developed a culturally-safe biobanking process that ensures samples maintain links to Country in perpetuity

Cryotechnology and flexible freezing systems

Novel semi-automated approach for sample processing and metadata management using computer-assisted sperm analysis.

Delivered an 100-fold increase in sperm use efficiency for producing coral recruits using cryopreserved sperm via new high-density fertilisation method.

Significantly advanced methods for cryopreservation of coral larvae and symbionts necessary for potential year-round deployment of coral recruits in future.

Secure Reef Biodiversity

Successfully generated viable coral recruits using cryopreserved sperm with effects of sperm preservation on recruit survival in the field over three months.

Maintained the largest coral biobank in the world, adding >1000 cryopreserved samples from 13 species to existing >2600 samples from 30 species.

ESTABLISH CRYOBIOLOGY RESEARCH FACILITIES

OBJECTIVE	ACHIEVEMENT
Establish cryobiology research facilities	Expanded research facilities and capabilities, including dedicated research space, cryopreservation equipment, and a Computer Assisted Sperm Analysis system, to support cryopreservation R&D and accommodate additional biorepository storage (220).
Expand biorepository capacity to support transfer of cryopreservation technologies for coral to Australia.	Expanded biorepository systems at Taronga to accommodate up to twelve thousand samples with capacity to grow in the future. Developed a modular approach using multiple adjacent sample storage systems for cost-effective biorepository expansion that facilitates growth while reducing unused space and allowing for samples to be isolated where needed (220, 221).
Create of a cross-cultural approach to coral biobanking to ensure that samples maintain links to Country in perpetuity	Successfully co-developed a framework for culturally safe biobanking in partnership with Woppaburra Traditional Custodians, the AIMS Indigenous Partnerships team, and Traditional Custodian representatives from Cammeraygal and Wiradjuri Country (222). Key elements include designation of the Cultural Custodians of the samples, inclusion of Country and contact information in the sample database, and inclusion of FPIC requirements in the Materials Transfer Agreement for any sample requests.

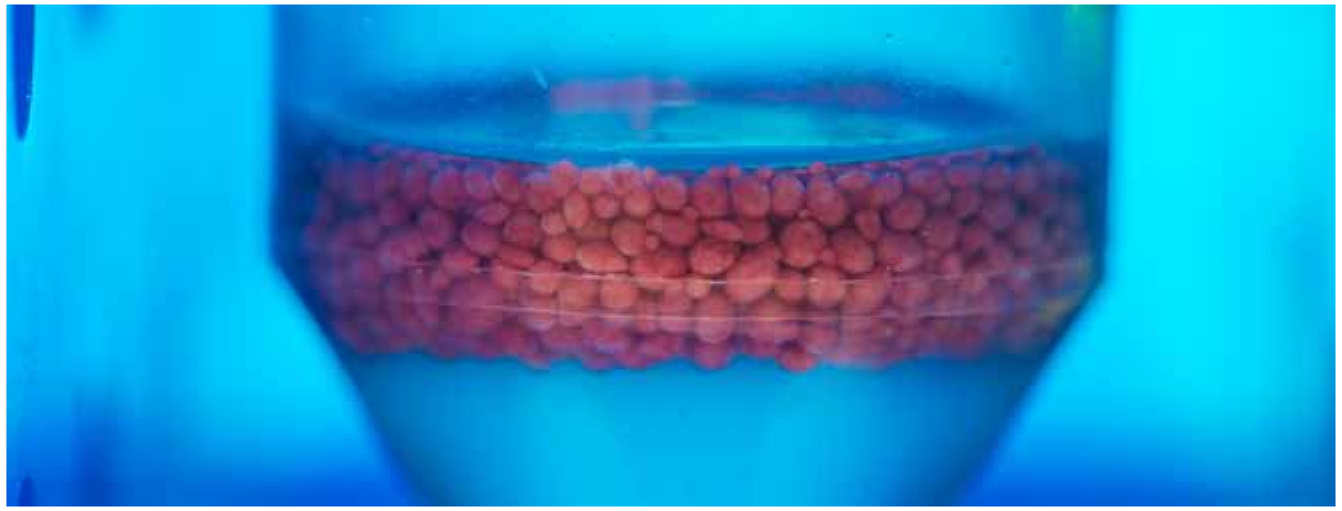
SECURE REEF BIODIVERSITY THROUGH TARGETED BIOBANKING

OBJECTIVE	ACHIEVEMENT
Biobanking of coral samples of coral gametes, tissues, and symbionts from prioritised species, populations, and reefs	During annual spawning in 2021, 2022, and 2023, a total of 1035 gamete samples were cryopreserved and banked from 152 colonies across 13 species of coral. These samples were collected from corals that originated from the Bindal, Manbarra, Gunggandji, and Woppaburra sea Countries. These samples are a secure resource that can be used to support research on developing resilient corals and for the production of new coral recruits for restoration (223).
Develop and apply post-thaw fertility assessments for coral sperm samples	Delivered a new method for high-density fertilisation using a standard sperm concentration (1 x 10^6 mL^{-1}) with higher egg densities (1000 eggs mL^{-1}). Trials of this new approach revealed that there was no difference in settlement or survival of baby corals created using either fresh or cryopreserved sperm (224). Coral recruits produced using cryopreserved sperm survived on 44% of devices deployed in the field after three months. Monitoring is ongoing.

OBJECTIVE	ACHIEVEMENT
Audit biobank and facilitate genetic analyses to evaluate biodiversity	Audited historic sample collections to reveal that the pre-existing repository held 2614 samples of cryopreserved sperm from 381 coral colonies collected from 30 identified species of hard coral that originated from 10 sea Countries across the northern, central, and southern regions of the GBR Marine Park (225).

DEVELOP NEW CRYOPRESERVATION TECHNOLOGIES AND FLEXIBLE FREEZING SYSTEMS TO ENABLE LARGE-SCALE CRYOPRESERVATION OF LIVING CORAL GENETIC SAMPLES

OBJECTIVE	ACHIEVEMENT
Optimise sperm cryopreservation methods and high-throughput pathways	Developed and trialled a semi-automated approach for assessment, handling, and cryopreservation of coral sperm. Improved efficiency of sample processing and metadata management using computer-assisted sperm analysis, barcoded cryovials, and a series of auto-linked datasheets (224, 226, 227).
Adapt new technologies for cryopreservation of coral larvae	Significantly advanced understanding of the cryobiology of coral larvae from a range of species. During preliminary experiments, larvae from the mushroom coral (*Fungia fungites*) were cryopreserved using cryomesh technology and recovered with a 70% survival rate (228). Progressed larval cryobiology to successfully apply the technology to coral species that have larger larvae. Revealed species differences in how coral larvae respond to cryoprotectants, and that larval quality is a key factor affecting outcomes of experiments.
Establish basis for symbiont and microfragment cryopreservation	Developed cryopreservation protocols for cultured symbionts. Successfully used a slow-cooling protocol with cryo-straws to preserve and recover viable cells from a broad range of symbiont cultures across all the major Symbiodiniaceae genera that associate with coral, including some heat-evolved strains of *Cladocopium* (228).



CASE STUDY - ADVANCING CORAL CRYOPRESERVATION FOR REEF RESTORATION

RRAP's Coral Cryopreservation team is part of a global alliance working to safeguard the genetic diversity of coral reefs and provide restoration practitioners with a ready supply of coral gametes and larvae.

RRAP'S CORAL CRYOPRESERVATION TEAM HAS ADDED OVER 1,000 NEW SAMPLES FROM 152 CORAL COLONIES ACROSS 13 SPECIES, BRINGING THE TARONGA CRYODIVERSITY BANK TO MORE THAN 4,000 SAMPLES FROM 35 SPECIES, INCLUDING ~4 TRILLION SPERM CELLS.

Beyond storage, RRAP has pioneered methods to reanimate and use cryopreserved sperm for fertilisation, demonstrating that a single vial containing one billion sperm cells can produce viable larvae when egg concentrations are optimised. These larvae have been deployed onto reefs in small-scale field trials, demonstrating that cryopreservation has the potential to be both a preservation strategy, and practical means to support reef recovery at scale.

The team have also developed and trialled new systems to make current cryopreservation methodology more streamlined and cost efficient. Computer-assisted sperm analysis and barcoded cryovials have increased processing capacity on busy spawning nights while reducing labour demands, and linked data systems now allow for faster more efficient sample tracking.

CROSS-CULTURAL APPROACH

A cross-cultural approach to biobanking was developed through collaboration between Woppaburra Traditional Owners, RRAP's Cryopreservation team from Taronga, and AIMS researchers working under the Woppaburra Coral Project. The approach recognised the cultural sensitivities of collecting and transporting coral material from Woppaburra Sea Country on the Great Barrier Reef to Taronga's CryoDiversity Bank on Cammeraygal Country, where cryopreserved samples are cared for until needed.

Co-designed with the Taronga Aboriginal Advisory Group, the Taronga Cultural Programs Team, the Australian Institute of Marine Science Indigenous Partnerships team, and the Gamay Rangers of the La Perouse Local Aboriginal Land Council, the process has pioneered culturally safe protocols that maintain the connection of living coral samples to their originating Country. These procedures provide a model for future consultation with other Great Barrier Reef Traditional Owner groups, supporting reef restoration while ensuring long-term custodianship and cultural continuity of biobanked coral material.

Image: Coral seeding devices on the reef, with coral recruits fertilised from cryopreserved sperm. Credit: Sophie Stephenson, AIMS

MOVING CORALS

PRODUCE AND DEPLOY MILLIONS OF GENETICALLY-DIVERSE CORAL LARVAE WITH ENHANCED ENVIRONMENTAL TOLERANCE

The Moving Corals R&D subprogram ('MC') harnessed the restoration potential of the vast slicks of coral embryos that are produced during mass spawning events and developed, tested and refined methods to culture and deploy heat tolerant larvae at scale.

Between 2020 – 2025, MC focussed on three main goals:

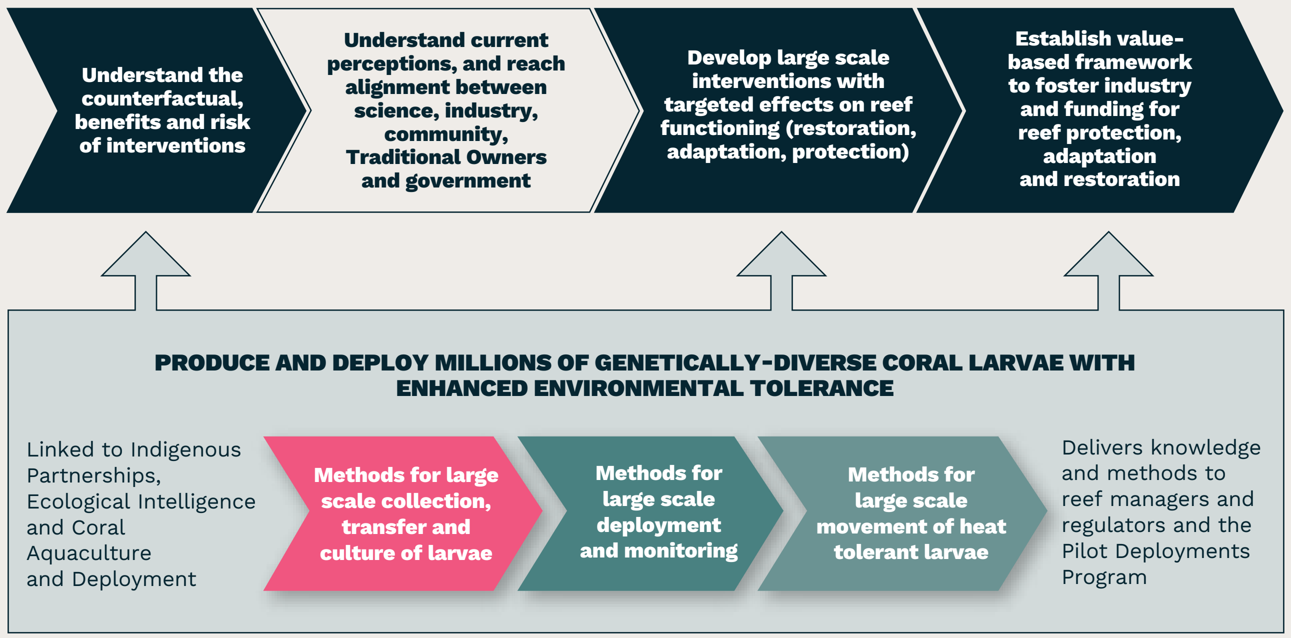
- **Deliver methods to efficiently collect** large quantities of coral spawn and embryos **and culture coral larvae** at high densities to maximise survival and readiness to settle.
- **Develop simple and scalable technologies to** deliver coral larvae directly onto reefs
- **Integrate heat tolerant larvae** to boost restored populations' adaptation potential by collecting and reseeding spawn from corals that had survived bleaching events.

Throughout Phase 1 of RRAP, MC demonstrated the technical feasibility of capturing many millions of eggs and embryos from coral spawn slicks, and successful deployment of clouds of coral larvae via benthic delivery systems or pre-settled onto devices. Reef-based larval restoration methods have been demonstrated to be effective but further research is required to realise gains in coral heat tolerance using assisted gene flow. Larval restoration methods can boost coral replenishment but there is a need for further monitoring of survival of young corals following bleaching events. There is strong social support for the use of natural coral breeding approaches in reef conservation, and culturally safe practices have been co-developed with Traditional Owners. These methods can be implemented both by small community groups or using industrial-scale infrastructure with costs of free larval releases potentially as low as $0.5 per 1 year old coral.

GOAL AND SPECIFIC OBJECTIVES

Objective	Achievement within project scope
Develop methods for large scale collection, transfer and culture of coral larvae	
Test and refine coral spawn and slick collection methods	
Evaluate potential use of ASVs for coral spawn collection	
Refine larval culture methods in pools	
Develop methods for large scale deployment and monitoring of cultured larvae	
Equipment and methods for bulk transfer of coral larvae to the reef	
Methods for settlement of coral larvae on tiles or on CADs	
Macrophotogrammetry approaches for detecting baby corals	
Analytical tools for predicting larval delivery and settlement	
Methods for large-scale movement of heat tolerant coral larvae to restore damaged reefs	
Assess efficacy of vessel-based methods for assisted movement	
Evaluate costs per 1 year old coral delivered to the reef	

At a Glance



Methods for large scale collection, transfer and culture of larvae

Developed and refined equipment, methods and workflows to routinely collect tens to hundreds of millions of coral gametes with >618 million fertilised coral eggs produced by the program.

Demonstrated that Autonomous Surface Vessels can efficiently collect coral spawn from the sea surface.

Showed that, across 5 years the survival of larvae between stocking through to settlement ranged from 30 – 68% yielding >5M - >78M million settlement-ready larvae each year.

Revealed that a stocking density of ~5 embryos ml-1 is optimal for producing competent coral larvae.

Methods for large scale deployment and monitoring

Developed fine-scale (~30 m resolution) hydrodynamic models for predicting larval dispersal in both surface slicks and benthic environments.

Built and tested scalable systems to successfully deliver >24M coral larvae to the reef benthos, and a new larval 'seedbox' that enhanced coral settlement 24-fold.

Demonstrated dense settlement of coral spat on CADs positioned in larval pools within a 24-hour immersion period.

Created a new technique for high-resolution mapping of baby corals that captures 10 – 20 times more individuals than diver-based surveys.

Methods for large scale movement of heat tolerant larvae

Developed a mobile, vessel-based larval culture system to enable potential long-distance movement of coral larvae in the future.

Demonstrated that reproductive output and larval settlement success for coral broodstock were not affected by heat stress. Results revealed that corals that survived bleaching produced gametes and spawned at the same time as unaffected corals and with high fertilisation rates (>80%).

Costs per surviving one-year old coral grown from free larval releases could be as low as $0.5 per coral in 2027. Up to ~80 million coral larvae that are ready to settle on the reef can be produced by a small team of experienced personnel.

METHODS TO EFFICIENTLY COLLECT LARGE QUANTITIES OF CORAL EMBRYOS AND CULTURE CORAL LARVAE AT HIGH DENSITIES TO MAXIMISE SURVIVAL AND READINESS TO SETTLE.

OBJECTIVE	ACHIEVEMENT
Develop, test, and adapt coral spawn and slick collection equipment and transfer methods	Successfully developed and refined equipment, methods and workflows to routinely collect tens to hundreds of millions of coral gametes and produce diverse coral larvae assemblages for deployment onto reefs (229). Over the course of the program, >618 million fertilised coral eggs were produced. The workflow is robust to differences in reef state (healthy versus post-bleaching) and to timings of mass spawning (single versus split event). Broadly, the workflow involves: (i) in-water surveys to identify locations where coral densities are high and many corals have mature eggs; (ii) application of high resolution particle tracking models with localised weather and oceanographic monitoring to locate likely spawn convergence zones; (iii) collection of coral gametes (see below); (iv) culture of gametes in larval pools at sea or in vessel-based tanks; and (v) field deployment of larvae and/or coral spat settled onto devices in larval pools (230, 231).
Optimise coral spawn and slick collection equipment methods for different reef habitats and environmental conditions	A low-cost scoop-net has been the most successful technique for collecting coral spawn due to its simplicity and ability for multiple people to operate nets simultaneously on the same vessel (230). Typically, three people staff a small vessel – one skipper and two attendants operating the nets. Coral spawn is scooped into a 250 L fertilisation tub and subsequently transferred to larval culture pools or tanks. In addition to the scoop-nets, new tools and methods were developed to identify areas where spawn slicks converge and concentrate a high number of coral gametes, and optimise the deployment of passive spawn catchers to efficiently collect bulk quantities of gametes (230, 232).
Evaluate potential use of ASVs for coral spawn collection	Demonstrated that Autonomous Surface Vessels can efficiently collect coral spawn from the sea surface in very shallow environments or other areas where piloted vessels cannot access. Field trials of this new technology revealed that ASV runs covering 800 m collected ~170 L of coral spawn within ~50 minutes (233).
Develop and test methods for pumping spawn slicks from the ocean surface into culture tanks or pools	Successfully developed a pumping system with a customised intake mouth that fed through two diaphragm pumps into each of two 1,500 L tanks on a small barge (234). The system required one skipper, one coordinator, and one assistant to collect >35 million coral embryos in a single run (229). Sampling revealed that pumping had minimal effects on embryos if conducted within the first hour after spawning but caused some embryo breakage if conducted five to eleven hours after spawning (235). There were no effects of the pumping system on larval settlement three to six days following spawning.
Develop, test and refine larval culture methods to enhance production and the survival and growth of resulting coral spat.	Refined larval culture methods, primarily using floating larval pools temporarily anchored on site (230), which can now routinely up to 18 million larvae per pool that are ready to settle on the reef with an average survival rate in higher water flow habitats of 65% between initial stocking and readiness to settle. Across 5 years of field trials, between >5 million and >78 million settlement-ready larvae were produced each year (229). Experiments show that a stocking density of ~5 embryos mL-1 (equivalent to 40-50% of pool surface area) is optimal for producing competent coral larvae (236). In addition, a new method for staining coral larvae with a dye was developed to track dispersal, and reliably detect settlement, of larvae reseeded onto reefs (237). Showed that shading larval pools can improve larval production when sea surface temperatures are above 30°C (289).

METHODS FOR LARGE SCALE DEPLOYMENT AND MONITORING OF CULTURED LARVAE

OBJECTIVE	ACHIEVEMENT
Design, test and refine equipment and methods for increasing scales of bulk transfer of larvae to the reef using direct and indirect approaches onto target areas.	New and fine-scale (~30 m resolution) hydrodynamic models were developed and parameterised to predicted larval dispersal in both surface slicks and benthic environments. These models accurately pinpointed slick convergence zones, and sites with protracted periods of low water currents that are most likely to allow retention of larvae for sufficient duration to allow localised mass settlement onto a reef (232). Short term (2 – 3 hours) larval retention can increase settlement up to 40-fold compared to ambient reef conditions. Retention via larval tents (2 - 24 hours) yielded four to seven times more settlers than free-release methods, and up to 300-times more settlers than untreated controls (238). However, initial gains in settlement did not persist; by three months, differences in recruit densities had diminished due to high post-settlement mortality and the yield of surviving corals spat per supplied larvae was much higher on natural reef substratum compared to on settlement tiles.
Free-release of larvae from tanks and pools	Large-scale free releases of larvae from both vessel-based culture tanks and floating pools yielded a detectable elevation of recruit densities compared to natural recruitment at control sites. However, free-release approaches yielded low overall settlement compared to benthic delivery systems (see below) and elevated settlement did not consistently result in elevated abundances of recruits compared to controls (229).
Benthic delivery systems	Built and trialled two scalable benthic deployment systems to successfully deliver >24 million coral larvae to the reef benthos. Both the ‘hose’ and ‘octopus pipe’ systems were successful in producing measurable settlement above background levels (230). Settlement efficiency per million larvae was comparable between the systems (7.2–10 settlers per million larvae released were

	detected on settlement tile arrays, noting that most of the larvae would have settled on the adjacent reef). The choice of which method to use depends on local environmental conditions, and particularly the flow regime with lower flow conditions resulting in increased larval retention on target reef areas (229).
Modular 'Seedbox' system	An innovative 'larval seedbox' system was designed and built, offering a compelling balance of simplicity, scalability, and performance for seeding ~14 million coral larvae over 3,000 m^2 of reef. The 'larval seedbox' was successful for retaining coral larvae close to the reef benthos, and enhanced settlement on 84% of tiles within a ~10m radius from each modular unit. On average, settlement was enhanced 24-fold above background rates (239).
Trial and refine methods for settlement of coral larvae on tiles or one coral attachment devices (CADs)	Limestone settlement tiles and CADs (see CAD subprogram) were effective for evaluating the success of new MC methods and workflows, demonstrating: • Clear spatial gradients of increased coral settlement onto tiles close to the release point of larval clouds that were freely released onto the reef (239). • Dense settlement of coral spat (10s to 100s per device) on CADs that were positioned in larval pools to allow direct out-planting of diverse coral spat to targeted locations on the reef. A 24-hour immersion of tiles and CADs was sufficient to achieve high settlement of diverse coral larvae (240). • High settlement (10s to 100s per device) of diverse coral larvae onto tiles and devices positioned on a settlement table enclosed within a containment net of fine mesh (229). However, after 21 months, survival of corals on CADs and tiles was low across three sites due to smothering by sand, unstable rubble, and low structural complexity. Corals on unattached devices had higher survival than attached ones, supporting the potential for free-release deployment. Overall, these results highlight that local environmental conditions have a major effect on survival of corals seeded onto the reef (as per CAD subprogram) (240).
Develop and apply macrophotogrammetry approaches to detect and monitor cryptic coral recruits	Developed and refined an innovative technique for high-resolution mapping of newly-settled baby corals that captures 10 – 20 times more individuals than diver-based visual surveys (241). The method is highly effective for early detection of very small corals less than 1.5mm in diameter. Importantly, the method provides essential data on growth and survival of corals throughout their first year of life which is required to evaluate success of restoration and adaptation efforts (238).
Develop analytical tools for spatially-explicit prediction of larval delivery and settlement	Successfully integrated data on larval development and settlement from experiments, larval mortality rates, and high-resolution hydrodynamic information to simulate dispersal of larvae from natural spawning and from larval reseeding, and their settlement across different reef habitats. This new tool, called *CoralSeed*, estimates the spatial footprint of larval

	delivery and settlement and serves as a decision-support tool for operational planning (242). The model enables users to virtually test alternative deployment scenarios before committing field resources, helping align seeding strategies with biological and environmental information.

METHODS FOR LARGE-SCALE MOVEMENT OF CORAL LARVAE WITH ENHANCED HEAT TOLERANCE TO RESTORE DAMAGED REEFS

OBJECTIVE	ACHIEVEMENT
Develop and assess the efficacy of vessel-based methods for relocation and settlement of coral larvae from corals with enhanced heat tolerance	Developed a new mobile vessel-based culture system for potential future use for large-scale transfer and translocation of coral larvae among remote reef locations (229). The system consisted of four 10,000 L tanks with wide diameter and low-profile to maximise surface area for buoyant embryo culture, and adjustable water flow systems to ensure optimal water quality for high-density larval culture. Tanks had an integrated outflow system to allow efficient transfer of larvae to the reef benthos using 3-inch hoses.
Assess reproductive capacity and larval survival and settlement for corals that have survived a bleaching event	Demonstrated that heat-stressed but surviving coral colonies can retain strong reproductive potential, offering a promising avenue for adaptive restoration strategies that harness naturally resilient broodstock. Quantified the effects of bleaching on reproductive and larval settlement success for coral broodstock on heat-affected reefs compared to corals of the same species on nearby reefs that weren't severely bleached after exposure to heat stress. Results revealed that both colonies that survived bleaching and unaffected colonies produced gametes and spawned at the same time, with high fertilisation rates (>80%) across >7 million eggs from both groups. Larvae from both bleaching-survivor and unaffected colonies developed at similar rates, with comparable numbers of larvae that were ready to settle onto the reef after five days of culture (~55% survival). Larval settlement success was higher in larvae from bleaching survivors compared to larvae from unaffected colonies, and post-settlement survival was similar across both groups after 107 days (243).
Evaluate cost per one year old coral delivered to the reef via larval reseeding	Applied detailed cost and logistics modelling for reef-based larval reseeding based on Moving Corals data from 2022, 2023 and 2024 coral spawning and larval restoration campaigns. After accounting for all costs (including equipment, labour and vessel operations) costs per surviving one-year old coral grown from free larval releases could be as low as $0.5 per coral in 2027. Larval reseeding can also deliver corals at ecologically relevant scales for targeted restoration and adaptation, with >50 million coral larvae that are ready to settle on the reef able to be produced by a small team of experienced personnel within one week of coral spawning (229).

RUBBLE STABILISATION

DEVELOP A PREDICTIVE APPROACH FOR ESTIMATING CORAL RUBBLE GENERATION AND PERSISTENCE, AND NEW METHODS FOR RUBBLE STABILISATION

The Rubble Stabilisation R&D subprogram (‘**RS**’) delivered new understanding of when and where unconsolidated reef rubble and a lack of structure impair natural reef recovery and ecological function, and new methods to stabilise rubble and enhance coral replenishment.

Between 2020 – 2025, RS focussed on three main goals:

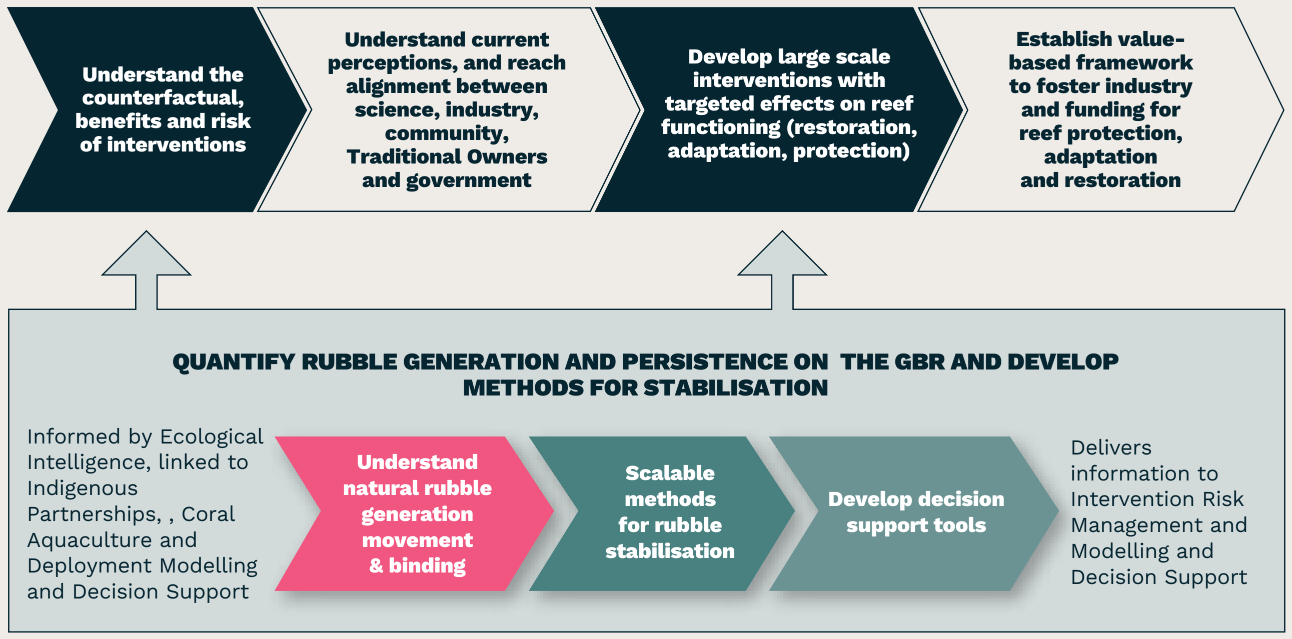
- **Understand natural rubble generation, movement and binding rates** to determine when and where rubble will hinder recovery of the reef after disturbances
- **Develop scalable approaches for effective rubble stabilisation** by testing existing methods and advancing novel underwater bioadhesive materials for reef restoration
- Develop **user-oriented resources to support local decision-making** and promote the effective application of rubble stabilisation as a coral reef restoration strategy

Throughout Phase 1 of RRAP, RS demonstrated that rubble generation, movement, binding and recovery potential can be measured and predicted with accuracy. Small scale trials showed rubble stabilisation can increase coral settlement but additional testing is required across a wider range of reef habitats. There is widespread social support for the use of rubble stabilisation methods (e.g. tourism operators) and there is strong interest and engagement by Traditional Owners. A novel underwater bioadhesive (initially developed for the Coral Aquaculture and Deployment subprogram) has been further developed in RS to now have multiple potential applications for reef restoration, and proof-of-concept for efficacy established. However, structures for rubble stabilisation (e.g. plastic/metal mesh, Reef Bags, rebar structures) are too labour intensive to be viable at large scales and prioritisation of locations for effective use of these methods at small scales is recommended.

GOAL AND SPECIFIC OBJECTIVES

Objective	Achievement within project scope
Understand natural rubble generation, movement and binding	
Assess rubble generation via breakage of live and dead coral colonies	
Assess rubble binding rates and strengths at inshore and offshore reefs	
Evaluate how rubble binding impacts coral recruitment and recovery	
Assess rubble movement based on rubble bed size and wave energy	
Assess where on the GBR rubble is most likely to be generated and persist	
Develop scalable approaches for effective rubble stabilisation	
Evaluate efficacy of existing methods for rubble stabilisation	
Assess whether reef bags and rebar methods enhance ecosystem recovery	
Develop, test and refine a novel bioadhesive for reef restoration applications	
Evaluate efficacy of coral seeding and larval reseeding on stabilised rubble	
Conduct binding experiments using sponges, microbes and electric stimuli	
User-oriented resources to support local decision-making	
Develop tools to help users assess where and how to stabilise rubble	
Produce comprehensive guidelines for rubble stabilisation interventions	

At a Glance



Understand natural rubble generation movement & binding

Maps and databases for end-users to assess reef damage risks and access rubble movement model results across the GBR.

Reef-Risk model for end-users to visualise the risk of rubble generation, breakage, movement and persistence across the GBR and identify key areas to monitor for signs of reef damage.

Traditional Owner ranger engagement workshops to train the use of Rapid Rubble Assessment to identify rubble bed types and predict rubble bed recovery risk.

Integrated laboratory and field measurements to predict coral rubble stability based on future conditions and GBR-scale wave and hydrodynamics models.

Scalable methods for rubble stabilisation

Trialled rebar structures that showed rubble was 2 to 6 times more likely to be transported in control plots compared to under structures.

Developed underwater bioadhesive materials which use bio-based and non-toxic materials that are 75% biodegradable and 25% degradable. These new materials can adhere coral rubble pieces together with a binding strength that resists water flows of greater than 1.2 m s^{-1} and that are suitable for multiple reef restoration applications (including seabed stabilisation, outplanting and rubble binding).

Develop decision support tools

Created a set of rubble stabilisation decision support tools that can be used independently or in tandem.

Produced and refined an expert-based, interactive Bayesian Belief Network to predict stabilisation method efficacy. Users can input local site conditions and the decision tool automatically updates to display likely outcomes.

Developed an interactive map of the GBR that predicts natural recovery potential based on a 70-year dataset of the wave environment and then classifies reefs into three levels of recovery potential to inform management actions.

UNDERSTAND NATURAL RUBBLE GENERATION, MOVEMENT AND BINDING

OBJECTIVE	ACHIEVEMENT
Measure the rate of dead coral converting to rubble as a function of the physical environment.	Based on field, desktop and laboratory studies, conversion rates from coral to rubble are strongly event-driven (cyclones and storms) and are near instantaneous compared to ecological timescales. For instance, damaging wave conditions linked to STC Debbie produced rapid and near complete conversion of branching corals to rubble along affected reef crests and created extensive rubble fields (~1m thick, ~3,800 m^2 (244)). Outside of episodic weather events, rubble conversion occurs continuously through fragmentation and loss of dead corals, through micro- and macro-bioerosion, and particularly under moderate to high everyday wave climates. In addition, a small-scale study showed that, of 92 branches tagged across four dead corals, 35% of branches were completely broken away after 17 months, 26% were present but broken and shorter as a result, and only 39% were intact (245).
Assess the hydrodynamic drag and shear forces required for damage, breakage and motion for different types of corals, both live and dead and rubble.	Field studies, laboratory experiments and numerical modelling were conducted to characterise coral size and morphology, material properties, including tensile strength, and hydrodynamic breakage thresholds. Results showed that the threshold wave-induced flow velocity that caused breakage of 90% of live branching corals was 1.7 m s^{-1} for corals from deep water and 5.0 m s^{-1} for corals from shallow water (246). Live tabular corals, in contrast, did not detach from the substrate even under extreme flow conditions of up to 7 m s^{-1}. The probability of breakage increased with increasing bioerosion of the coral skeleton, while the 'sheltering' effect of upstream coral colonies was found to be negligible.
Structural and hydrodynamic testing of specimens to determine mechanical properties and force coefficients using experiments in wave flumes	Field and laboratory experiments were conducted to quantify coral morphology and mechanical properties. For the skeleton of branching coral without bioerosion, the measured tensile strength was 19.1 MPa. In contrast, bioerosion observed in the stem part of the branching coral reduced the tensile strength to 14.9 MPa (246). Three-dimensional coral models were developed to represent colony morphology and to predict total hydrodynamic forces and bending moments. Model outputs were calibrated against flume experiments, demonstrating good agreement with measured forces and bending moments (247, 248). By comparing the predicted results with the measured strength, the probability of coral breakage was then predicted as a function of near-bed orbital flow velocity. To account for uncertainties associated with bioerosion within the coral skeleton, breakage probabilities were further evaluated based on borehole size and location.
Quantify parameters for hydrodynamic-structural modelling of large reef areas and map the rates of rubble generation incorporating possible regeneration of dynamic rubble.	Confirmed that persistent rubble fields with reduced structural complexity are a potential end-state of reefs following damage (249). Repeated or high-magnitude disturbances prevent rubble cementation and consolidation, likely leading to higher persistence and production of rubble in the future (250). Successfully developed and parameterised models that predict probabilities of colony breakage and coral rubble motion under everyday wave conditions, cyclonic conditions and current and future wave climates. Hydrodynamic–structural thresholds derived from laboratory and field experiments were scaled to reef- and GBR-wide applications by integrating mobility and breakage criteria with long-term wave climate models, enabling spatial mapping of rubble generation, persistence and recovery windows. Used time series data for hydrodynamics on the GBR between 1950 – 2022 to calculate duration of rubble stability and instability periods and frequency of exceedance of motion and breakage thresholds.
Combine 3D mapping of reef habitats with additional small-scale field measurements to parameterise and evaluate ecological models.	Revealed that current iterations of RRAP's 3D coral habitat maps were not suitable for hydrodynamic modelling of branching corals due to difficulties in scaling images. Consequently, integration of EcoRRAP and RS data for this purpose was not progressed and other approaches were instead used to parameterise hydrodynamics for rubble stabilisation assessment.
Compare binding mechanisms and rates for rubble pieces that are experimentally stabilised, to binding rates for those in natural rubble beds.	Binding incidence was assessed at both inshore and offshore locations, at different levels of exposure (sheltered vs exposed), depth (deep vs shallow) and in rubble beds of different types (e.g., loose, interlocked), to identify predictors of rubble bed recovery potential. Rubble size and rubble bed thickness were identified as key metrics in predicting binding potential and the natural recovery potential of a rubble bed. Compared to small, loose rubble, larger rubble in thicker rubble beds is more likely to be stable, through interlocking or part burial, and thus more likely to be bound, and provide a stable substrate for coral recruitment (251). With more severe storms and increased bioerosion on future reefs there will be increasingly smaller recovery windows between successive disturbances potentially leading to persistence of unstable rubble beds. Ultimately, increased rubble on reefs will negatively impact coral larval survival as rubble movement can abrade and smother corals, and rubble beds typically experience altered environmental and ecological conditions compared to consolidated reef (252). From observations on the GBR, 98% of tagged coral-rubble units (i.e., young corals that had settled onto rubble pieces) experienced movement within 16 months, and 66% of units disappeared from the loose beds. When coral-rubble units remained stationary, the survival rates of the corals were similar across loose rubble, interlocked rubble and hard carbonate habitats. Growth rates of corals in the loose bed were also similar to growth of corals on interlocked rubble but significantly lower compared to the hard carbonate (253).

	Overall, in some physical environments, conversion to rubble leads to long-term habitat state change with limited potential for rapid recovery.
Establish timelines for fragment attachment in both fast- and slow-growing species and whether live coral is a viable binder under certain conditions	Fragments of corals, including fast and slow growing species, attached themselves to the experimental substrate with sufficient strength to withstand typical ambient water flow within 40 – 70 days. There was high variation among species in their attachment mechanism and speed, with *Pocillopora* generally more susceptible to detachment compared to *Acropora* and *Montipora* (254). Surveys investigating rubble binding on the reef, and measurements of binding rates and strengths in aquarium experiments, showed that live coral can be a viable binder of rubble fragments. In rubble beds in the Maldives, rubble bound by coral (predominantly *Porites rus*) was found in sheltered and exposed deep (6-7m) sites and exposed shallow (2-3m) sites. Coral binders were most prolific at exposed shallow sites where they contributed to binding in 23% of bound rubble, but no corals were found binding on the reef flat (1-2m) (255). When rubble was stabilised experimentally, hard corals (mostly *Porites rus* and *Pocillopora verrucosa*) were found to bind by month 10 (following deployment of stabilised rubble grids), mainly in exposed, shallow sites, and still not in the reef flat. On the GBR, hard corals were rarely found binding rubble in natural beds (251), with only a few examples from exposed shallow sites (4-8m). When rubble was stabilised experimentally on the GBR, hard corals bound rubble mostly at exposed shallow (inshore and offshore) and sheltered deep (9-12m) locations (256). On these stabilised rubble grids on the GBR, hard corals began binding between rubble fragments as early as four months at exposed, inshore shallow sites, from 8 months at exposed, offshore shallow sites, and from 12 months post-deployment in sheltered sites (inshore and offshore) (256). In the context of attachment (settlement) of baby corals, experimental deployment of standardised tiles that mimic stabilised rubble revealed that coral settlement was greatest in structurally complex habitats but declined 2 to 4-fold in habitats with interlocked rubble and declined 8-fold in loose rubble. Post-settlement mortality was high regardless of habitat. Low settlement and low post-settlement survival on stable rubble pieces within loose rubble beds means these beds are likely to have low recovery prospects (257, 258).
Field studies to investigate binding in high-energy and highly mobile seabed settings to identify the successful binding species and mechanisms of binding.	Results from multiple field studies demonstrate that rubble size and shape and the local biophysical environment are major drivers of recovery potential. Moreover, substrate stabilization is key for supporting coral recruitment in rubble-dominated areas. For instance, across four study sites in Indonesia, only 10% of rubble pieces were stable, and only 7 to 25% were bound to another piece. Crustose coralline algae was the dominant binding agent. Longer rubble fragments (>10cm), and thicker rubble beds, had greater stability, binding, and coral recruit abundance (259). In the Maldives, rubble binding was lowest on the reef flat (8%) and highest at ~6-7m exposed sites (38%) where flow was optimal for binder growth. When experimentally stabilised, all rubble pieces subsequently developed at least one natural bind within 6 months, but the number of binds only increased on the reef slope, not the reef flat (255). On the GBR, thin rubble beds, those with small, unbranched rubble pieces, and beds at the base of sloped rubble screes, had lower stability and binding likelihoods. However, even thick rubble beds with high recovery potential had different effects on recovery of coral cover depending on the abundance of other taxa that compete with corals for space (e.g. macroalgae). A rapid assessment of rubble length-while also considering shelf location, geomorphic zone, slope angle and underlying substrate indicates the likely recovery trajectory (251). Finally, the abundance of different binders varied across habitats. On the GBR, binding communities in rubble beds were dominated by sponges, particularly at exposed sites (4-12m) and sheltered deep (9-12m) sites (251). Inshore sites had more sponges binding and were also dominated by *Lobophora* spp., compared to offshore sites. CCA binds were most prevalent at exposed, shallow sites. When rubble was experimentally stabilised, inshore sites were still dominated by *Lobophora* binds, but at other sites, the dominance of sponges reduced, and stronger binders like tunicates, hard corals, vermetids and bivalves became more prevalent (256). In rubble beds in the Maldives, of the few bound rubble pieces encountered on the reef flat, 43% were bound partly by CCA, and a high percentage were bound by sponges (29%) and solid binds (32%) (255). On the reef slope, the most abundant binders were sponges (~50%) followed by CCA (22–41%), macroalgae (15–23%), solid binds (12–17%), and ascidians (6–14%). Collectively these findings allow identification of rubble beds that have low recovery potential and could be good candidates for rubble stabilisation interventions.
Strength testing of fragment grafting to establish what hydrodynamic conditions may inhibit fragment attachment, regrowth and survival.	Results from aquarium experiments and field observations showed that there are distinct differences in the mechanisms that different coral species use to attach themselves to the reef (260). Minor movements (<2mm) in either the reef substratum or the coral fragment can inhibit cellular processes occurring at the attachment interface and, in some cases, stop attachment altogether. Biological differences in attachment translate into differences in the strength of attachment, with small fragments of *Acropora* able to withstand 2.7-fold and 6.6-fold higher modelled wave force after 40 days of attachment compared with Pocillopora and Montipora, respectively (254). Future coral outplanting interventions should select species based on traits that include attachment speed and strength along with environmental compatibility.
Measure the force required to break the binding between pieces of coral rubble as a function of time	Successfully measured rubble binding rates and strengths throughout 18 months at both inshore and offshore locations. Revealed that the amount and strength of binding was lowest at inshore sheltered sites (breakage at ~1.4 m s^{-1} flow after 18 months of binding) increased at inshore exposed sites and was

	highest at offshore sites regardless of exposure (breakage at ~3 m s^{-1} flow at the same timepoint). The organisms responsible for the rubble binding were key drivers of bind strength, with weak binders (e.g., macroalgae) abundant inshore and stronger binders (e.g. tunicates, snails, oysters and hard corals) more abundant at exposed and offshore sites (256).

MODEL RUBBLE MOVEMENT BASED ON HYDRODYNAMICS AND IDENTIFY WHERE RUBBLE STABILISATION INTERVENTIONS CAN IMPROVE REEF RECOVERY

OBJECTIVE	ACHIEVEMENT
New hydrodynamic modelling of rubble motion to enable assessment of rubble motion at local and reef scales.	Models were developed to predict probabilities of coral breakage and coral rubble motion at reef and GBR scales under typical waves (everyday wave conditions), cyclonic conditions and current and future wave climates (261, 262). Influences of bioerosion on breakage are included. These models estimate near-bed water velocity and pressure gradients and are parameterised with field and laboratory data to generate spatial maps of rubble instability across the GBR (249). Model outputs are scalable and data-driven, and they can be integrated into existing modelling frameworks (e.g. eReefs) to support reef-wide restoration planning. The data and outputs can be explored through a dynamic user-driven web portal.
Use field and laboratory data from hydrodynamic sensors and tagged rubble of different types and sizes to calibrate and test hydrodynamic and force models.	Field calibration of rubble motion and force models used co-deployed hydrodynamic sensors (ADVs, pressure transducers) and individually tagged rubble of varying size and morphology, enabling direct linkage between near-bed velocities, local flow conditions and observed rubble motion (244, 247, 263). Data comprise measurements over >180 days of sensor deployments to link time-series of flow conditions to observed rubble motion (264).
Fieldwork to identify motion and forcing stratified across the environment at sites with relevant geomorphology, including direct measurement of forces required to initiate rubble motion at selected sites.	Successfully tracked rubble movement in the field, together with measurements of the hydrodynamic environment, to determine mobilisation thresholds for rubble pieces of varying size and shape parameters. Rubble movement was tracked every 24 hours over three-day periods at >16 sites in the central and southern GBR. Rubble mobilisation was strongly influenced by near-bed flow velocity, with more than 50% of rubble mobilised at velocities of 0.1 m s^{-1} and 90 to 100% mobilised at 0.4 m s^{-1} (264). Results were generally consistent across studies and conditions, whereby rubble had 50% and 90% chance of transport at near-bed flow velocities of 0.30 m s^{-1} and 0.4 m s^{-1} respectively in wave flume trials and 0.34 m s^{-1} and 0.55 m s^{-1} respectively on the reef (in the Maldives) (247). Smaller and more spherical rubble mobilised at lower flow velocity than large, flat and/or structurally complex morphologies, and travel further distances when on sand compared to on other rubble (264, 265).

Wave and flume experiments to assess rubble dynamics on different substrates as a function of flow, and thresholds of motion for displacement.	An extensive set of laboratory experiments was conducted in wave flumes to determine drag coefficients, effects of coral morphology, influence of sheltering, and utilised to calibrate the reef and GBR hydrodynamic and force models. Tilting experiments revealed that 50% of rubble moved when substratum was angled ~40° irrespective of substrate characteristics, and that rubble shape and spacing influence probability of movement (266).
Develop and test a model for coral breakage and rubble dynamics using Computational Fluid Dynamics coupled with structural models of different coral species.	Completed a suite of field measurements for different coral morphologies (47 branching colonies and 100 tabular colonies) in conjunction with measurements of tensile strength. Applied these data to develop 3D structural models that allow quantification of flow thresholds for coral breakage. These models can be adjusted to provide predictions for other coral species, shapes, levels of bioerosion, and locations (e.g., sheltered or exposed reef areas) and can be used to predict the level of expected damage and rubble generation in different areas (248).
Develop reef-scale models for both cyclonic waves (10-20 m grids depending on bathymetric resolution) and everyday waves and map probability of rubble motion	Reef scale hydrodynamic models simulating both cyclonic and non cyclonic wave climates at bathymetry dependent resolutions have been used to map the probability of coral breakage and rubble motion, with these outputs synthesised into a Bayesian Belief Network–based rubble intervention tool delivered via an online platform (267). The rubble motion model is based on calculating the probability of wave velocity exceeding threshold values required for motion. Model simulations used significant wave height values ranging from 0.3 to 12m, and rubble motion predictions can be generated for any wave condition on the reef (268).
Link regional wave cyclone and non-cyclonic waves statistics to on-reef hydrodynamics	Combined a process-based spectral wave model with >32 years of regional wave data and >1500 synthetic cyclone tracks to estimate high-resolution (20-200m) near-bottom wave velocity on more than 3000 reefs across the Great Barrier Reef (GBR). Applied a statistical model to predict reef damage based on cyclone strength and reef spatial arrangement and defined flow velocity thresholds for damage to nearshore reefs (2.5 m s^{-1}) and offshore reefs (3.1 m s^{-1}). Identified reefs across the GBR that are cyclone damage hotspots versus refugia (262). In addition, developed and calibrated a Random Forest machine learning algorithm to efficiently process large datasets describing reef hydrodynamics and related coral rubble instability. This approach provided estimates on the importance of specific variables in the classification of rubble stability (269).
Apply the calibrated rubble dynamics models to map where rubble motion is likely to hinder coral recruitment	Developed an interactive web portal that allows users to select appropriate wave conditions for any given location, or use wave climate information for that location, to generate maps of coral breakage and rubble stability at individual reefs and across the GBR under present and future wave climates for branching corals (270).

Integrate historical datasets on drivers of rubble generation with hydrodynamic data, reef structure and benthic mapping to develop *vulnerability maps* for individual reefs.	Identified five key drivers of rubble generation - cyclones, storm waves and tsunamis, ship groundings, bleaching and COTS invasions – and successfully summarised 40 years of data to generate a GBR-wide rubble vulnerability map with a spatial resolution of 0.05° x 0.05°. Key findings include: (i) on average, point locations across the GBR have a moderate risk of damage and rubble generation in the next 10-20 years under current climate conditions; (ii) vulnerability generally increases towards the central GBR with lowest vulnerability occurring in the Cape York and Mary Burnett NRM zones. (iii) Reefs within the Burdekin NRM have relatively high vulnerability compared to other regions; and (iv) the Mackay-Whitsunday NRM is affected by the widest range of damage and rubble generation drivers (268, 271).
Extend rubble vulnerability maps to local reef groups on the GBR, and to represent both rubble generation and rubble persistence.	Rubble vulnerability mapping identified four localised areas of high vulnerability to cumulative damage and rubble generation, with the Lizard Island and Swains Reefs being most at risk. An interactive tool was developed to enable stakeholders and end-users to interact with rubble vulnerability maps (271–273). In this tool, Benthic Habitat maps classify GBR substratum at a 10 m resolution based on satellite data and benthic data. Long-term monitoring imagery was reanalysed and provided proof-of-concept for the potential to use existing data to re-construct trends in rubble generation and persistence at decadal scales (274). The benthic habitat map was used to evaluate different predictors of rubble dynamics across the GBR, and also indicated that doubling DHW temperature stress on the GBR would increase the probability of rubble formation across much of the GBR (273).
Identify locations where hydrodynamic forcing can maintain mobility of sufficient severity and duration/recurrence that prevents natural recovery.	Formalised a conceptual framework to identify locations that are the clearest candidates for active intervention because conditions make passive recovery unlikely. Sites of 'most concern', and where stabilisation interventions are likely to be the most effective, are characterised by persistent and or frequent periods of high ocean bottom water currents or waves that cause very short windows where rubble is stable. Analysis of the spatial distribution of rubble bed recovery potential showed that around 75% of point locations experience conditions where natural recovery is likely without interventions but that 20% of point locations had few and short periods of time where natural rubble stabilisation could occur. The latter point locations were concentrated in reef crests, reef flats and exposed shallow slopes, particularly on the central GBR (275).
Field studies to constrain how disturbance events create different rubble volumes and characteristics that influence mobility and binding.	Field studies were completed in the Whitsundays to assess localised effects of a cyclone on rubble generation. Results revealed that Severe Tropical Cyclone Debbie reduced hard coral cover to <5% and coral loss was species and habitat specific. The cyclone deposited a rubble field that was >6,000 m^2 in area and up to 2 m on the reef flat. This rubble field remained largely mobile and unbound, and it migrated over an 8-year observation period (276).

	Field studies of rubble ecology in the southern GBR revealed that reef exposure and depth influenced rubble microhabitat complexity ('branchiness') and this, in turn, determined the abundance, diversity and size of motile cryptofauna living within the rubble (277). Additional multidisciplinary collaborative work was conducted to evaluate effects of mass-coral bleaching across varied ecological and spatial scales. Results showed overall reductions in coral growth across all sites and taxa, and higher bleaching prevalence in hard carbonate substrate as opposed to rubble habitats (278).

DEVELOP SCALABLE APPROACHES FOR EFFECTIVE RUBBLE STABILISATION

OBJECTIVE	ACHIEVEMENT
Evaluate efficacy of current rubble stabilisation methods by measuring binding rates, calcification and ecological responses to stabilisation at inshore and offshore sites over four years.	Review of the literature together with workshops with experts revealed that rebar structures that offer direct and/or indirect stabilization had potential for large scale use for restoration and should be evaluated in wave flumes and tested in the field. Other methods, including rock piles, were identified as effective but logistical challenges prevented use of this method at large spatial scales and it was, therefore, not tested further (279) . Field inspections at pre-existing sites were also undertaken to evaluate efficacy of coir mesh bags filled with coral rubble ('Reef Bags') at inshore and offshore sites. Results showed that most coir remained intact for one year but had completely biodegraded after 2 years leaving behind experimental rubble mounds. After 2 years, fish abundance was higher above mounds compared to surrounding rubble. After 3 years, rubble stability and binding were higher in rubble mounds than in surrounding control plots at one location but not the other. The increased stability and binding did not, however, translate to significantly higher coral recruitment on rubble mounds in either location (280). Reef Bags were subsequently redesigned to include a single layer of mesh and with larger holes to prevent coral recruitment being hindered by the thicker and less perforate mesh used in the original design.
Conduct a two-year field trial of the most successful method identified from review of the literature to evaluate how well the method stabilises rubble and supports coral recovery.	Three different rebar structures (flat mesh, pyramid with mesh base, and open pyramid) were designed and manufactured, and coated with a veneer of epoxy and sand to prevent rusting. Surveys of rubble tagged within and outside of plots with rebar structures showed that rubble was 2 to 6 times less likely to move when it was under flat meshes, and closed pyramids, respectively, compared to control plots (263). However, there was no difference in the degree of binding between control plots and the plots with rebar structures, with binding probability ranging from 7% to 13% at deployment, increasing to 20-34% after 2 year, regardless of structure presence and type. Coral surveys showed that soft coral cover reached 81% after 3 years, while hard corals

	decreased in abundance and remained small (<5 cm). Soft corals also proliferated more on the structures than in control plots, suggesting that rebar may facilitate their growth (281).
Test stabilisation method across a range of physical environments, and measure efficacy to increase natural coral recruitment in combination with enhanced larval supply and with deployment devices.	Rebar structures were only tested at one location. However, aluminium flat mesh (similar to the rebar flat mesh) were tested at a second location (Moore Reef), and Reef Bags were tested in two locations (see above). Field trials using 1 m^2 aluminium meshes indicated greater stability and binding of rubble stabilised by mesh compared to control rubble 4, 8, and 12 months after installation. However, increases in binding were mostly caused by turf algae and macroalgae. Further, the increased binding and stability of fragments fell back to pre-intervention levels within 4 months of aluminium mesh removal (274). No improvement in the number of corals was observed during the trial period. Future interventions using mesh should consider stablising larger areas and/or using larger mesh sizes that allow for greater herbivory. Stabilisation for longer periods (>12 months) may also be needed to realise gains in hard coral colonisation and growth. A mismatch in timing of finalisation of CAD device design which hindered regulatory approval meant that the rebar structures for rubble stabilisation were not tested in conjunction with coral seeding or larval reseeding.
Evaluate the potential for biogeochemical rubble stabilisation (including bio-cement and bio-rock) to be deployed at scale.	An extensive literature review examined rubble stabilisation approaches, including: sponge transplantation; rubble vacuuming; mesh stabilisation; grouting/cement; geofluid pumping; electrical stimulation; Reef Stars and other rebar structures; and reef balls/bags. Data were compiled for each method to assess: whether the method could be used alongside other approaches to improve or accelerate outcomes; ecological benefits; potential environmental impacts; cost; and efficacy. At that time (2021) the efficacy of these rubble stabilisation methods was either poorly documented, lacking independent peer-reviewed evaluation, or better suited to local restoration at high-value sites rather than able to be effectively scaled for large scale deployments (hectares) (282).
Undertake preliminary sponge and microbe seeding experiments under laboratory conditions to identify best species and rates of binding.	Experimental work tracking rubble binding rates and strengths revealed that vermetid snails, serpulid worms, bivalves, tunicates (solitary ascidians), crustose coralline algae, and hard corals themselves produced the strongest binds between rubble pieces (256). Molecular (DNA-based) analyses of binders observed throughout this experiment have been completed and are scheduled for publication in the future, with results expected to identify the most effective species contributing to rubble binding. Electrical stimulation and biogeochemical and/or microbial/sponge binding methods were not pursued due to concerns that these approaches would ultimately not being economically viable for large-scale deployments in future.

Build on outcomes of preliminary biomimetic glue initially developed for fastening coral settlement tiles to devices	Prior to 2023, there had not been any development of underwater bioadhesives for rubble stabilisation and reef restoration. The RS subprogram has now developed a suite of underwater bioadhesive materials that can be chemically adapted to suit different environments and surfaces and: • Use bio-based and non-toxic materials that are 75% biodegradable and 25% degradable (283). • Can adhere coral rubble pieces together with a binding strength that is >5-fold higher than the strength of the force that causes rubble mobilisation on the GBR. Flume tank testing has also shown bioadhesive-treated rubble resists current flows of greater than 1.24 m s-1. • Are suitable for multiple reef restoration applications including: coral fragment attachment and out-planting'; a non-toxic material to replace resins used to coat submersible metal frames for rubble stabilisation; a coating for filaments used to connect coral seeding devices; a cement to replace plastic cable ties used to secure small structures to the substratum (284).
Develop and test biomimetic glues to retain deployment devices on the reef	Through collaboration with the RRAP CAD subprogram, field trials revealed that application of the underwater bioadhesive successfully retained coral settlement tiles within coral seeding devices (100% retention) and that coral survival and growth on these devices were not negatively influenced by the bioadhesives (268, 282).

USER-ORIENTED RESOURCES TO SUPPORT LOCAL DECISION-MAKING

OBJECTIVE	ACHIEVEMENT
Convene a workshop of project personnel and key End-Users to synthesise the overall benefits of rubble stabilisation for reef management and ecosystem restoration.	Conducted an international Rubble Stabilisation workshop that involved researchers, industry practitioners, reef management agencies and tourism operators. Key themes across the workshop included: • Restricting rubble movement alone often promoted recovery in high-energy, clear-water sites where substrate instability was the primary barrier to recovery, whereas sheltered or high-sediment sites often required a combination of additional methods, such as elevated substrates above the rubble. Steep, sloping beds were considered the most challenging to restore. • Willingness of attendees – which included experts from Australia, Indonesia, the Philippines, Malaysia, Guam and the USA – to provide quantitative data on rubble stabilisation successes and failures (263). • Broad consensus about the need for a rubble intervention decision-support tool and practitioner guidelines.

Create a Rubble Stabilisation Intervention Tool, that integrates the research from RS to identify where rubble can be stabilised; and provides stand-alone functionality to end-users	Two rubble stabilisation intervention tools have been created which can be used independently or in tandem. The first tool comprises expert-based, interactive Bayesian Belief Networks (BBN) to predict stabilisation method efficacy. The first BBN estimates the predicted increase in coral cover at a restored site compared to an unrestored control. The second BBN captures expert opinions on the likelihood of restoration success across different environmental conditions. Users can input local site conditions, and the BBNs automatically update to display likely outcomes. Alternatively, users can specify desired outcomes to identify suitable combinations of site conditions and intervention types (285). The second tool is an interactive map of the Great Barrier Reef (GBR) that predicts natural recovery potential. Across the GBR, approximately 8 million reef points were assessed using a 70-year dataset of the wave environment (maximum bottom orbital flow velocity) to predict rubble binding rates and strength. This model estimates the proportion of time that rubble at that point was stable and binding successfully and then classifies points into three levels of recovery potential (267, 286). If a location on the GBR is identified as being of 'low recovery potential', the BBN and Rubble Stabilisation Guidelines can be used to evaluate local environmental conditions and determine the most appropriate rubble stabilisation method to employ in that area. Efforts are underway to transition the tool to a publicly accessible platform.
Consult with a diverse set of users with different needs to inform development of the decision support tool	Following the international workshop, RRAP RS conducted additional interviews and informal consultation to inform development of the Rubble Intervention decisions support tools. This included researchers along with industry and government representatives. Engagement with Traditional Owner groups occurred throughout 2023 and 2024 with involvement of the RRAP ENG subprogram. The intervention tools have also been shared with the Reef Authority to facilitate their use in assisting with potential ship grounding impact assessment.
Develop practitioner guidelines, manuals and web content, including for the online decision support tool.	Developed and communicated "*A Practical Guide to Restoration and Rehabilitation of Rubble Fields on Coral Reefs*" to support decision-making across all stages of a rubble stabilisation project. The guidelines provide a comprehensive resource that captures knowledge on rubble stabilisation, drawing from published papers, case studies, workshop insights, RRAP RS subprogram findings, and expert data from around the globe (285).
Integrate results with findings and outputs from RRAP M&DS.	To date the RRAP RS decision support tools and underlying datasets have not been directly integrated into the RRAP M&DS analytical suite but these outputs could be feasibly incorporated in future work.

Image: The rubble stablisation team convened a workshop in Bali to discuss and collate international rubble stabilisation intervention considerations. Credit: UQ

CASE STUDY: TRANSLATING RESEARCH INTO RESOURCES

Stabilising reef rubble is a familiar problem for reef restoration practitioners worldwide, with substrate instability and frequent motion inhibiting the ability of young corals to settle and grow.

While RRAP's rubble stabilisation team worked on developing new techniques, they have also focused on bringing together and consolidating decades of existing knowledge about rubble stabilisation interventions. The team drew on the expertise of project leads and experience and insights from international partners and restoration practitioners. Stabilisation techniques were systematically classified into four functional categories and evaluated for cost, complexity, maintenance and scalability.

The resulting guidelines and decision support tool has evolved into a comprehensive and accessible resource for the global reef restoration community. It provides users with practical guidance to assess whether rubble stabilisation is appropriate and how to select the most suitable methods based on habitat type, logistics, resources, timelines and suitability for local conditions.

PROGRAM PERFORMANCE INDICATORS

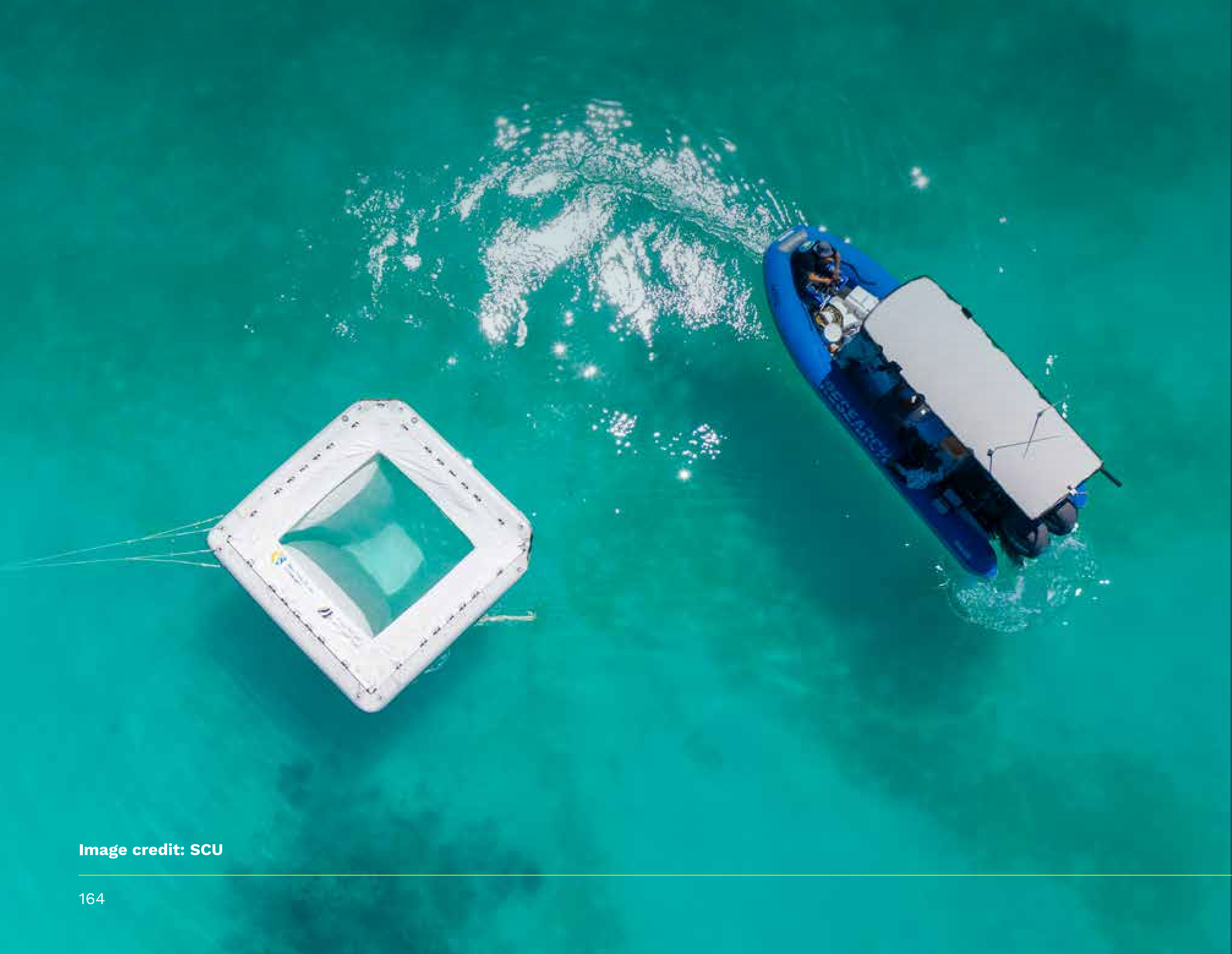


Image credit: SCU

A BLENDED INVESTMENT MODEL

RRAP Phase 1 has been resourced through diversified, blended funding rather than a single source – spreading risk, multiplying the reach of public funds, and demonstrating the mixed financing a future reef-restoration industry will require.

The cornerstone was the Australian Government's investment through the Reef Trust Partnership between the Reef Trust and the Great Barrier Reef Foundation ($143.2M – not including PDP), providing the multi-year certainty that anchored the program. This was substantially leveraged by co-investment from RRAP delivery partners ($68.7M) and further in-kind contributions spanning research infrastructure, vessel time, staff effort and intellectual property.

Corporate and individual philanthropy also funded and provided in-kind contributions to a range of program priorities, as direct investment in RRAP or through ancillary partnerships and related projects drawing on RRAP's science. Examples include:

Life-Space's direct investment in coral probiotics research, improving the survival and heat-tolerance of corals raised for restoration

The **L'Oréal Fund for Nature Regeneration** and **Garnier** partnerships with the Great Barrier Reef Foundation to develop a coral biodiversity credit and support restoration efforts

The **BHP–AIMS Australian Coral Reef Resilience Initiative** delivering the Woppaburra Coral Project with Traditional Custodians

McLaren Racing's partnership with the Great Barrier Reef Foundation, collaborating with AIMS and QUT to produce OSCAR (Operational System for Coral Assembly and Restoration), automating and accelerating the assembly of coral seeding devices.

Together these streams show public investment anchoring the program, co-investment multiplying capacity, and philanthropy and partnerships extending its reach.

PROGRAM PERFORMANCE METRICS

Metrics are reported for the time period between 1 July 2020 and 30 June 2025.

ENABLING TECHNOLOGIES	
Productivity increases achieved through science and engineering advances and/or semi-automated technologies and tooling	
Increased larval culture densities	10-fold
Coral eggs produced per system per day	Up to 7 million
Settlement density per m^2 facility floorspace	16,000
Time saved due to automated larvae monitoring	20-fold quicker
Time saved on counting coral larvae in aquaculture	7-fold
Improved water-use efficiency during grow-out	9.5-fold
Probiotic culture collection	1400 taxa
Aquaculture Method developed for coral species	56 species
Reduced Cryopreservation sample preparation time	1.6-fold
Average survival of baby corals on devices	25-60%
Increased larval settlement using SeedBoxes	24-fold
Seawater atomisation production output	10^{15} particles s^{-1}
Shading potential under fogging plume	27%
Retention of enhanced symbionts	1.5-2 years
Improved detection of very small newly-settled corals on the reef	10-20 fold

INTERNATIONAL, NATIONAL AND REGIONAL LINKS AND NETWORKS	
International research and advisory collaborations	
Number of international members of Intervention Risk Review Group	6 (50%)
Number of international institutions as coauthors on RRAP papers	55
Number of countries of international coauthors on RRAP papers	21
Papers with international coauthors	39 (25%)
Memberships of Boards and Advisory Committees	6
Number of government, industry and business interactions	
Community Panels (involving ~30 community members and 15 scientists)	10
Respondents on National Surveys about Reef intervention perspectives	>12,000
Stakeholder Advisory Group	11
Regulators Forum	19
Briefings with Government Agencies	>83
Participation in Reef 2050 Committee and Panel proceedings	>5
Public Outreach	
Potential Media Reach (across 25 select publications)	2.4 billion
Media Releases	51
Partner News Items	80

TRADITIONAL OWNER PARTICIPATION	
Traditional Owner groups engaged in FPIC process	>166 engagements with 24 groups
Participation of Indigenous Australians in RRAP research activities	>800 person days
Number of First Nations groups engaged in RRAP Reef Resilience Symposium	19 Groups, 52 participants

RESEARCH TRAINING AND PROFESSIONAL EDUCATION	
Number of Students contributing to RRAP Research	
Undergraduate students and Internships	13
Honours	7
Masters	42
Doctor of Philosophy	71
Number of Early Career Researchers employed	
Technicians	38
Research Assistants/Associates	43
Postdoctoral Fellows	98
Certificate III Aquaculture (Indigenous Trainees)	4

RESEARCH FINDINGS	
Publications in Journals with an impact factor >4	65 (42%)
Online views of RRAP publications (median across 97 papers)	2187
Publications featured in News Articles or Blogs (across 119 papers)	58 (49%)
Number of high impact papers (based on Altmetrics scores for 86 papers) Papers in Top 5% Papers in Top 25%	 29 (33%) 55 (64%)
Conferences presentations and posters	447
Technical Reports	29
Standard Operating Procedures	33

PROGRAM INTEGRATION	
Publications that have cross-institutional authorship	66%
Number of ECRs with multi-institutional supervision	133 (42%)
Number of decision-making meetings with cross-institutional attendance	
Board	32
Steering Committee	27
Program Management Team	49
Managing Entity – Quarterly Status meetings	46
Programmatic Research Planning Workshops	34
Volume and reach of cross-program communications	
Number of webinars with cross-institutional attendance	22
Number of program update newsletters (> 600 subscribers)	15
Number of whole-program Communiques (>500 RRAP members)	8

PROGRAM MANAGEMENT	
Milestones and deliverables approved	638 milestones, 2698 deliverables
Agreements and updates	115
Project variations	22

* shows percentage of meetings with attendance by all RRAP Partners

^ shows percentage of meetings with attendance by Independent Board Members

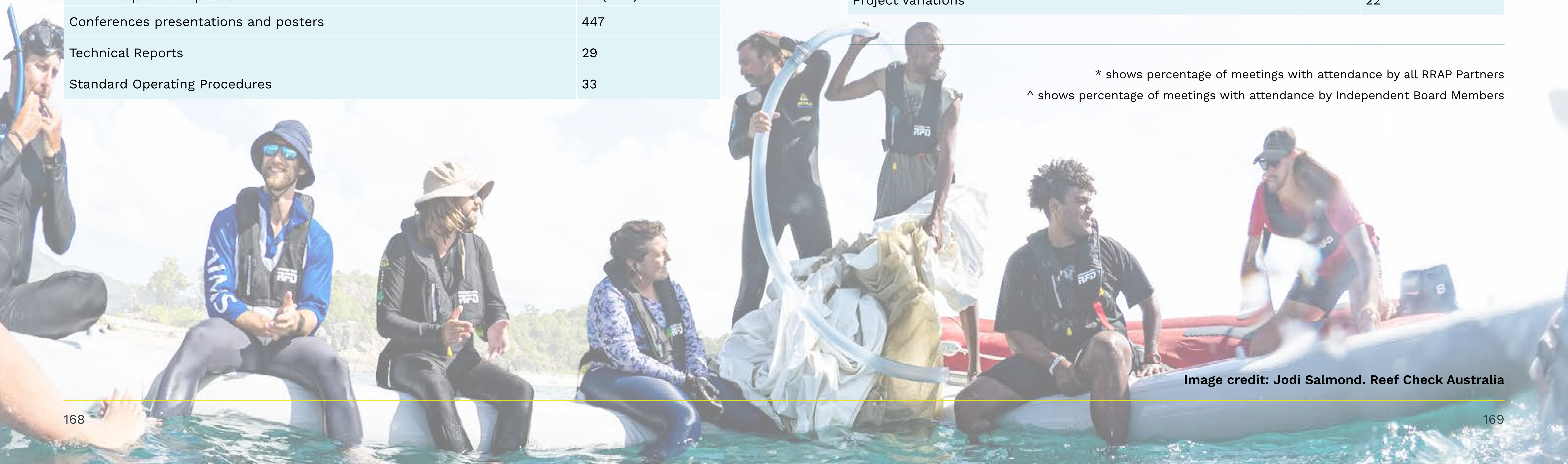
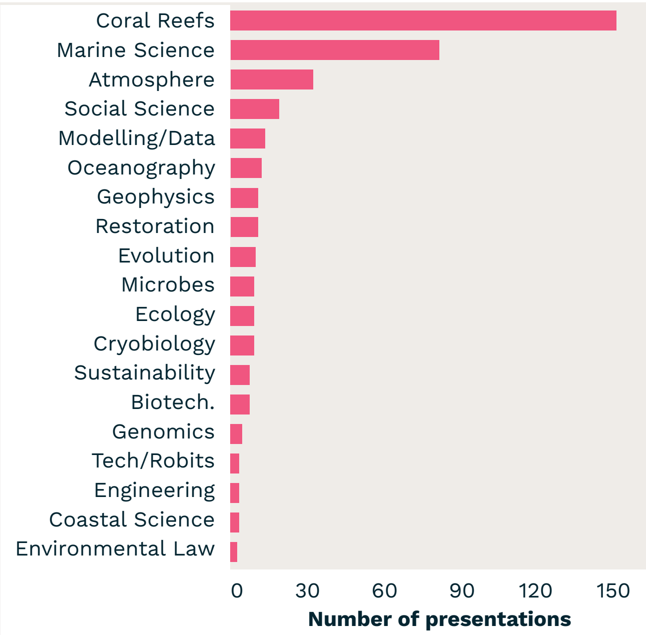


Image credit: Jodi Salmond. Reef Check Australia

NATIONAL AND INTERNATIONAL LINKAGES

RRAP has continuously expanded its formal linkages with numerous institutions and agencies around the world. These interactions have helped to create a cohesive network for the rapid advancement of coral reef restoration and adaptation science. Examples include:

- 500 presentations and poster presentations at scientific conferences and symposia, across diverse fields of research and including major international conferences that reach a global audience.
- 35 publications with cross-institutional authorship involving researchers from 55 institutions in 21 countries.
- >20 international working groups and events attended, and knowledge contributions made by RRAP researchers, including the UN Ocean Conference, the IUCN World Species Congress 2024, DAVOS World Economic Forum 2024, COP30 2025, and TED presentations in 2024 and 2025.



INFOGRAPHIC - NUMBER OF RRAP PRESENTATIONS AT SCIENTIFIC CONFERENCES FOCUSED ON DIFFERENT FIELDS OF RESEARCH

RRAP is at the forefront of a shift toward transdisciplinary and cross-institutional science that has global impact. In addition to formal agreements with many Australian and international universities (see below), RRAP researchers also collaborate extensively with numerous international government and non-government organisations including ICRI, CORDAP, USGS, NOAA IUCN, WWF, SHAMS as well as reef conservation initiatives including SECORE International, the Coral Restoration Foundation, the Coral Restoration Consortium, Nature Conservancy and Palau International Coral Reef Centre.

Highlights of RRAP's national and international collaborations over the duration of the ongoing research and development program include:

WORKING WITH TRADITIONAL OWNERS OF GBR COASTAL AND SEA COUNTRY

RRAP works closely with the dedicated Traditional Owner Reef Protection component of the Reef Trust Partnership, which supports the Reef Restoration and Adaptation Science and Crown-of-thorns starfish (RRAS-COTS) Traditional Owner Technical Working Group. Established in 2020, the Technical Working Group provides a platform for co-designing fit-for-purpose Traditional Owner–led programs that contribute to the overall goals of reef restoration and adaptation. RRAP researchers maintain regular engagement with the RRAS-COTS Working Group, contributing Program updates and insights while ensuring Traditional Owner perspectives were consistently represented in discussions.

RRAP collaborated with the RRAS-COTS Working Group in the development of the Reef Resilience Symposium 2024 to support the integration of biocultural perspectives into discussions on reef resilience and restoration. The Symposium program reflected the need to strengthen dialogue between Traditional knowledge systems and scientific research, and for approaches that recognise both ecological and cultural connections to Sea Country.

Traditional Owner perspectives are further embedded within RRAP's formal governance structures, including the Board and Steering Committee, ensuring cultural knowledge and priorities inform Program direction.

As the program moved into it's operational phase through the Pilot Deployments Program (PDP), the Deadly Reef Ecological Adaptation Murri Scientists (DREAMS) team was established to provide advisory support for ongoing activities and operations on Sea Country.

COLLABORATION WITH THE COTS CONTROL AND INNOVATION PROGRAM

RRAP has been closely aligned with the COTS Control and Innovation Program (CCIP), with overlapping partners and complementary objectives related to research and technology development of reef intervention beyond conventional management. The Programs have maintained alignment through RRAP's observer role on the CCIP steering committee, joint coordination of the Reef Resilience Symposium, and shared use and development of integrated modelling and decision-support systems.

AUSTRALIA'S NATIONAL MARINE SCIENCE PLAN 2025 – 2030

RRAP research leadership contributed expertise and Program insights to the National Marine Science Strategy (2026–2036) through active involvement in the development of white papers at the National Marine Science Symposium held in Canberra in June 2025. RRAP researchers led and contributed to papers focused coastal and marine ecosystem restoration and repair and enabling technologies for monitoring and intervention.

The Symposium provided a forum to test and refine recommendations before being synthesised into the national strategy. Outcomes and priorities emerging from the 2025 discussions will be embedded across several white papers, helping shape Australia's research agenda for coral reef protection, restoration, and long-term monitoring over the coming decade.

Image: Moving Corals international team during spawning field trials at Lizard Island. Credit: SCU

INTERNATIONAL CORAL REEF SYMPOSIA

RRAP has supported researcher attendance at major international reef conferences, including the International Coral Reef Symposium (ICRS), Asia-Pacific Coral Reef Symposium (APCRS), European Coral Reef Symposium (ECRS), and Reef Futures. These forums provide important opportunities to share research outcomes, connect with global experts, and ensure Australian-led RRAP insights can contribute to international reef science and management.

RRAP researchers have played leading roles across these events, delivering keynote and plenary presentations and convening special sessions and workshops to share knowledge with the global coral reef research and practitioner community.

Key highlights include:

- Plenary presentations at Reef Futures in 2022 and 2024
- Plenary presentation at the International Coral Reef Symposium (ICRS) in 2022

REEF 2050 ADVISORY COMMITTEE AND INDEPENDENT EXPERT PANEL

RRAP Executive Director and subprogram Leaders presented to the Reef 2050 Independent Expert Panel (IEP) on several occasions (2022 and 2024) and contributed to a 'Reef Restoration Deep Dive' session convened by the Reef 2050 Advisory Committee (2025). Three RRAP subprogram Leaders and prior Steering Committee members have been appointed to the IEP.

Additionally, RRAP research leads contributed to the Australian Academy of Science's Reef Futures Roundtables in 2023, to assess likely outcomes and identify new interventions for the GBR under three climate change trajectories and subsequently provide advice to IEP on updating the Reef 2050 Plan.

INDUSTRY PARTNERSHIPS

Industry engagement occurs in all RRAP subprograms, including partnerships with tourism operators for in-water deployments and monitoring; two-way knowledge exchange with the aquaculture industry about diverse topics including propagation and biosecurity; and commercial contracts with small specialist businesses and not-for-profits, including:

RRAP delegates at Reef Futures global symposium in Mexico 2024.

- Ron Allum Deep Sea Services - specialist underwater systems engineering and build.
- EmiControls – atomisation equipment specialists.
- Quaternium – drone design and build.
- Airborne Research Australia – airborne sensing technologies, platform integration and data processing.
- Numerical Optics – reef modelling and mapping.
- Social Ventures Australia – social return and impact evaluation.
- Eberhard Consulting – governance and engagement advisory.

INTERNATIONAL UNIVERSITIES

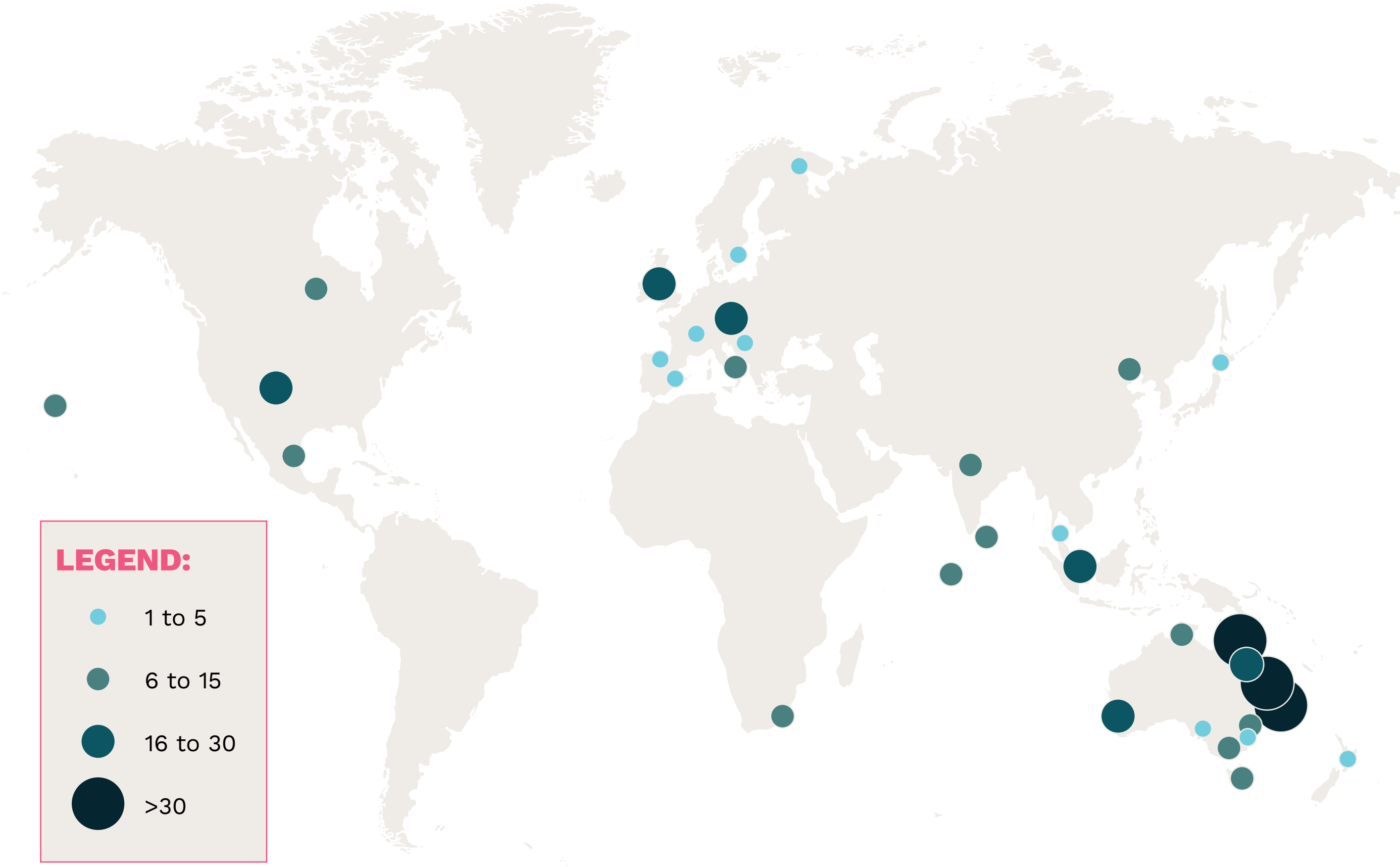
RRAP subprograms and projects have had both formal delivery agreements and informal knowledge and expertise collaborations with a range of universities, research institutions all contributing expertise outside of the core Partner consortium, including:

- University of Exeter - Climate modelling.
- University of Cambridge – development of electro spray and nozzle designs for cooling and shading.
- University of Minnesota - coral larvae cryopreservation engineering solutions.
- Hebrew University of Jerusalem - analysis of cloud microphysical and radiative properties.
- Smithsonian's National Zoo and Conservation Biology Institute – coral larvae cryopreservation methodology.

AUSTRALIAN UNIVERSITIES

RRAP research teams include staff from or collaborations with over 20 Australian universities and research institutions external to the joint venture. These broader collaborations bring unparalleled depth and breadth of expertise to RRAP restoration science, including:

- Australian National University - renewable energy systems for remote and reef environments.
- Deakin University – protein, lipid and carbohydrate nutrition.
- Griffith University – benthic ecology, physiology of crustose coralline algae.
- Macquarie University – assisted evolution and comparative genomics.
- Monash University – physics of clouds and precipitation.
- Sydney Institute of Marine Science – MCB spray and nozzle development.
- University of Melbourne – cell biology and symbiosis, modelling of atmospheric chemistry, clouds and precipitation systems.
- University of New South Wales – biology of stresses, disease and immunity.
- University of Sydney – mechanical engineering and particle modelling, carbon sequestration, biodiversity and structural complexity.
- University of Western Australia – ecosystem modelling and recovery dynamics.



INFOGRAPHIC: NUMBER OF RRAP RESEARCH PRESENTATIONS AT INTERNATIONAL SCIENTIFIC CONFERENCES. BUBBLE SIZES SHOW NUMBER OF PRESENTATIONS AT CONFERENCES WITHIN AUSTRALIA, AND WITHIN 22 DIFFERENT COUNTRIES AROUND THE WORLD.

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PUBLIC AND COMMUNITY CONTRIBUTIONS

THE ACHIEVEMENTS AND CONTINUED EVOLUTION OF RRAP BEYOND R&D HAVE BEEN MADE POSSIBLE THROUGH AN EXTRAORDINARY NETWORK OF CONTRIBUTORS EXTENDING FAR BEYOND CORE PROGRAM PARTNERS.

Volunteers, advisory group members, Traditional Owners, government representatives, research collaborators and community forum participants have all contributed their time, expertise, lived experience and critical insight to the program.

Many have contributed on a voluntary or semi-voluntary basis through sitting fees, consultation and review processes and field work participation. Their generous and collective contributions have helped to strengthen RRAP's research and deployment design and inform better decision-making, and improve engagement approaches.

STAKEHOLDER ADVISORY GROUP

Over a 12-month term, the RRAP Engagement Advisory Group brought together diverse representatives from reef restoration, tourism, policy, advocacy, natural resource management and Traditional Owner communities to deliberate on engagement gaps, community expectations and future opportunities for reef restoration activities.

Through workshops, site visits, webinars and direct interaction with RRAP leadership and researchers, members strengthened their understanding of RRAP while also shaping program thinking on transparent governance, Traditional Owner rights and participation, public communication, industry readiness, regulatory reform and community stewardship.

The Group's recommendations reinforced the importance of cultural and community leadership in future reef restoration activation across the Great Barrier Reef.

PUBLIC PERSPECTIVES

Biannual national surveys, community panels and in-depth 'deep dive' interviews enabled thousands of Australians to contribute their perspectives, values, concerns and expectations regarding reef restoration and adaptation. Through these contributions, members of the public shared insights on acceptable approaches to intervention, trust, governance, environmental responsibility and the future of the Great Barrier Reef.

These contributions have helped ensure that broader community voices, including volunteers, local leaders and interested citizens, were represented in RRAP discussions about reef restoration planning, governance and future deployment.

DEEP DIVE INTERVIEW FACTSHEET

COLLABORATIVE MONITORING PROJECTS

Throughout 2023 and 2024, researchers worked collaboratively with the Cairns Port Douglas Reef Hub and it's network of tourism operators, Traditional Owners and community participants to monitor coral seeding devices at Moore Reef.

Collectively, the pilot highlighted the value of collaborative monitoring in improving transparency, social acceptance, stewardship and operational efficiency, while also identifying regulatory and logistical barriers that will need to be addressed to scale future partnership-based monitoring approaches.

Complementary visitor surveys involving more than 700 reef visitors further showed that experiencing coral seeding efforts firsthand helped to lower concern about novel restoration technologies.

Image credit: Matt Curnock, CSIRO

TRAINING AND MENTORING FUTURE LEADERS

More than 300 students, trainees and Early Career Researchers (ECRs), who come from more than 31 different countries around the world, have made an enormous contribution to the program's national and global impact.

In 2023 a cohort of students and ECRs established a representative committee that met regularly to identify and address issues affecting early career researchers, providing mutual support and facilitating knowledge-sharing through strong cross-institutional connections. This RRAP Future Leaders group also played an active role in the design and coordination of the Reef Resilience Symposium in April 2024.

RRAP Future Leaders benefitted from multidisciplinary learning and career development opportunities with embedded industry and government experience. Consequently, RRAP has made a significant contribution to a pipeline of highly skilled reef restoration and adaptation scientists for subsequent employment in academic and non-academic roles around the world.

PSYCHOLOGY FOR A SAFE CLIMATE

The cohort identified emerging ecoanxiety impacts within the RRAP research community that subsequently launched a series of Climate Cafés for RRAP team members. The Cafés offered a safe, informal space to reflect on the impacts of working within the reef protection space. The cafes were focused on themes of climate emotions with guided discussions encouraging open conversation, peer connection, and shared support. The series recognised that caring for people is just as important as caring for the Reef.

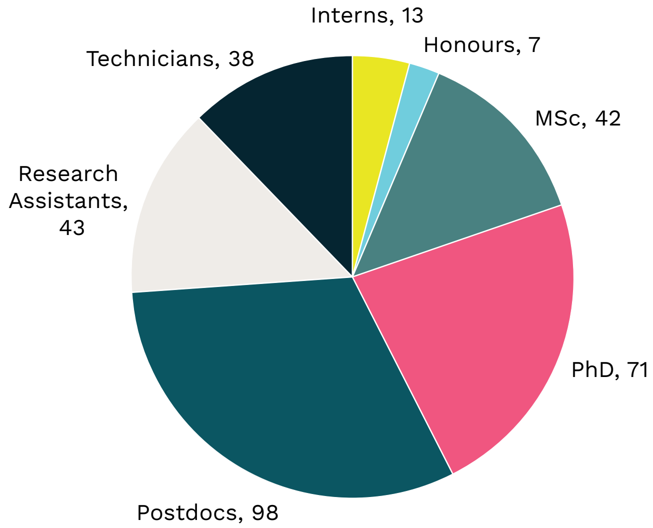
FUTURE LEADERS WORKSHOPS

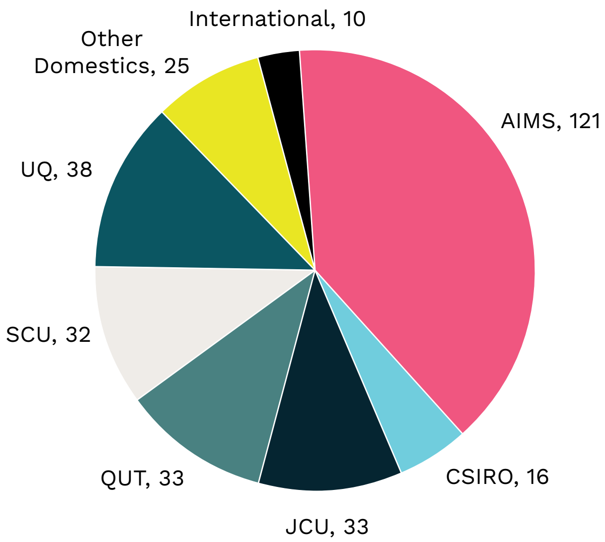
A dedicated RRAP Future Leaders event was held in 2023 to launch support for the cohort within the program. The event focused on promoting awareness of Traditional Owner acknowledgement, engagement, and involvement in research activities alongside academic impact and science communication.

WRITING RETREATS

Throughout 2023 and 2024, two writing retreats were held for Future Leaders on Magnetic Island (9 participants) and Stradbroke Island (15 participants). The retreats focused on strengthening academic writing practice through the use of the Pomodoro technique, with guided writing sessions designed to improve productivity. The retreats helped to build cross-institutional and interdisciplinary connections, providing participants with valuable opportunities for networking, peer support, and collaboration.

Image: Some of RRAP's Future Leader cohort during a writing retreat on Stradbroke Island, 2024. Credit: Jim Higgs AIMS





INFOGRAPHIC: DEMOGRAPHIC DATA DESCRIBING RRAP FUTURE LEADERS.

A) BREAKDOWN BY CAREER STAGE INCLUDING UNDERGRADUATE AND POSTGRADUATE COURSEWORK AND HIGHER DEGREE RESEARCH STUDENTS, AND EARLY CAREER RESEARCHERS EMPLOYED AS TECHNICIANS, RESEARCH ASSISTANTS OR POSTDOCTORAL FELLOWS.

B) DISTRIBUTION OF ECRS ACROSS RRAP PARTNER INSTITUTIONS AND COLLABORATORS.

COMMUNICATION, MEDIA AND PUBLIC OUTREACH

Communications and media has played a central role in building awareness, understanding and trust in RRAP's research. The communications mission has been to clearly articulate the program's collaborative approach, achievements and impact, and to share RRAP knowledge globally to support reef resilience efforts worldwide.

WEBSITE GBRRESTORATION.ORG

The RRAP website functions as an enduring reference point for RRAP with an annual visitation rate of approximately 21,000 active users. The site consolidates core program information and public-facing documents and publications in a single location. This has ensured that stakeholders, partners, and interested members of the public can access material that accurately represents the Program's scope, intent, and scientific insight and has reduced the risk of inconsistent or outdated information circulating across the partner channel network. As RRAP's public facing "source of truth," the website has been primarily archival and referential, providing a foundation for Program communications and external engagement. Additional updates and outreach activities have been delivered through other channels and forums.

APPROACH AND CHANNELS

The communications approach has been science-led, highlighting both the urgent decline of reefs and the emerging knowledge generated by the program, as voiced and represented by research leadership and expertise. Consistent branding and messaging across the partnership has ensured both internal and external-facing alignment under a shared program mission.

While RRAP partner's communications platforms and channels have been central to reaching large and diverse audiences, owned channels have helped to further connect directly with audiences and showcase program-specific highlights. This has included digital platforms like social media and newsletters and webinars to deliver timely updates on scientific outcomes.

Dedicated communications infrastructure and collateral have also provided the foundation for engagement with Traditional Owners, government, regulatory bodies and the reef research community. As piloting of RRAP interventions commences, the program has recognised that the interface between community and industry stakeholders and rights holders will continue to expand and become more complex, requiring continued dedicated two-way information sharing and engagement.

Image: Coral Aquaculture and Deployment researcher Taylor Whitman features on CNN's Tech for Good in 2024.

PUBLIC COMMUNICATION AND MEDIA

RRAP's media approach has been deliberately proactive, targeting experienced science journalists and prioritising high-reach, reputable outlets that could support clear and accurate reporting on reef restoration and adaptation science to key stakeholders. Where possible, the program aimed to support editorial that was credible and grounded in evidence, while avoiding oversimplification of complex research.

The RRAP Communications Working Group has coordinated and led more than 50 media releases and 60 news blogs on partner channels, with amplification across digital channels. Strong group coordination enabled alignment between partner organisations, and consistent messaging and acknowledgement of funding sources, delivery partners, and collaborators.

Media interest and coverage have been largely project-focused allowing for individual research milestones, field activities, and scientific advances to be showcased and celebrated. RRAP-related research and activities have received almost exclusively neutral-to-positive coverage across major international wire services as well as leading national and international outlets. This coverage has extended the reach of RRAP science to broad audiences while reinforcing credibility and transparency.

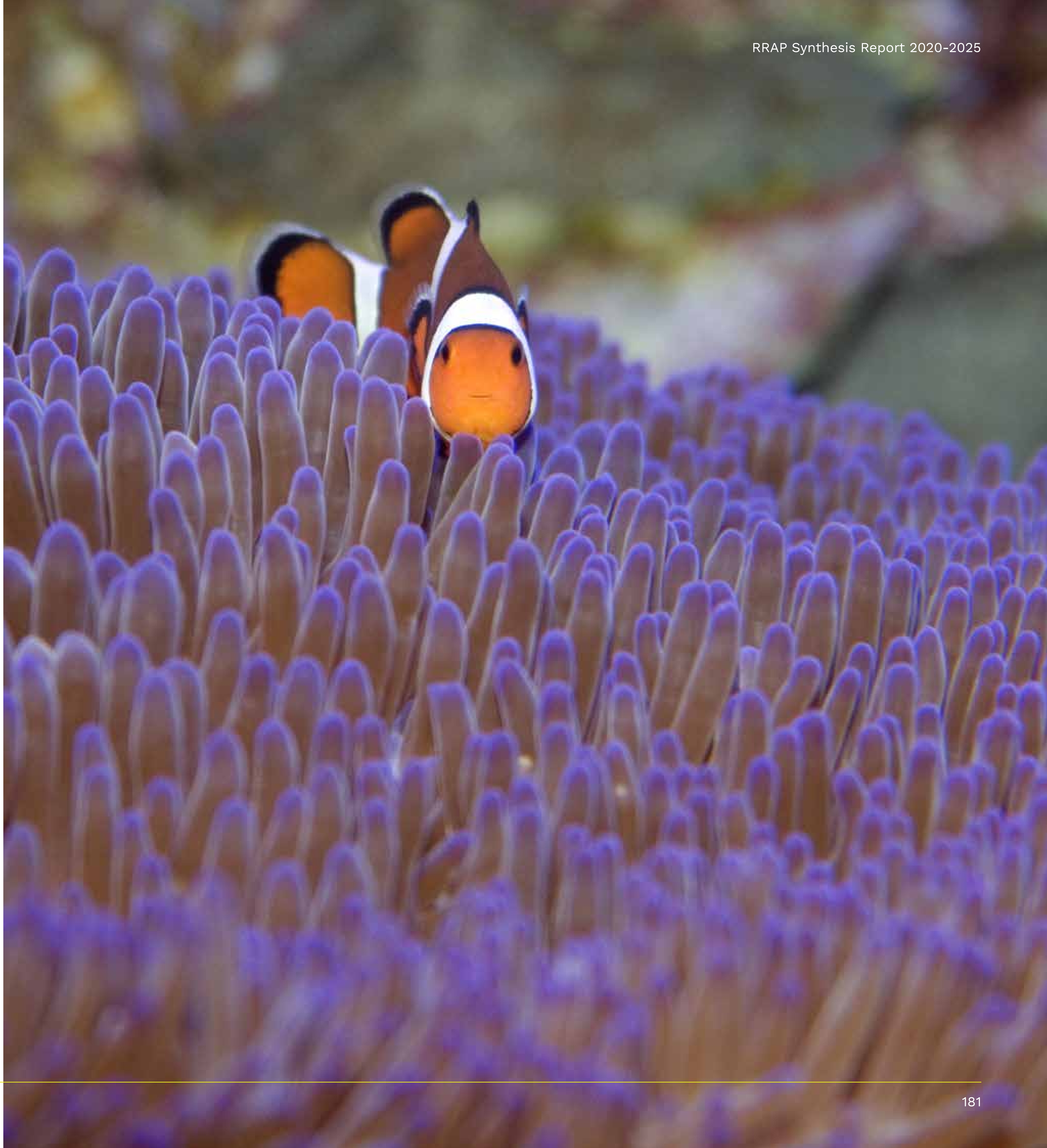
REEF RESILIENCE SYMPOSIUM

In 2024, RRAP worked with other reef protection and management initiatives to organise and facilitate the Reef Resilience Symposium. Bringing together more than 300 participants from across research, management, industry, engineering, and Traditional Owner groups, the Symposium created opportunities to share recent learnings and practical experiences in building reef and coastal ecosystem resilience.

The event's program and schedule focused on integrating traditional and western knowledge and highlighting the essential stewardship roles of First Nations peoples and the reef tourism industry. To ensure inclusive and diverse access, the Symposium was free to attend and was livestreamed globally.

The event also served to reflect on our progress since Australia's last resilience-focused symposium in 2018, and to identify new priorities and pathways for action. Held during the mass coral bleaching event that occurred on the Great Barrier Reef during the summer of 2024, the Symposium underscored the urgency of climate action and resilience-building efforts, while reinforcing the importance of collaboration across sectors and scales. The Symposium was delivered in partnership with RRAP, the Reef Rainforest Research Centre, the Great Barrier Reef Marine Park Authority, the Association of Marine Park Tourism Operators, and the Great Barrier Reef Foundation Crown-of-thorns starfish Control and Innovation Program.

Image: RRAP Executive Director Cedric Robillot speaks at the opening evening of the Reef Resilience Symposium 2024.



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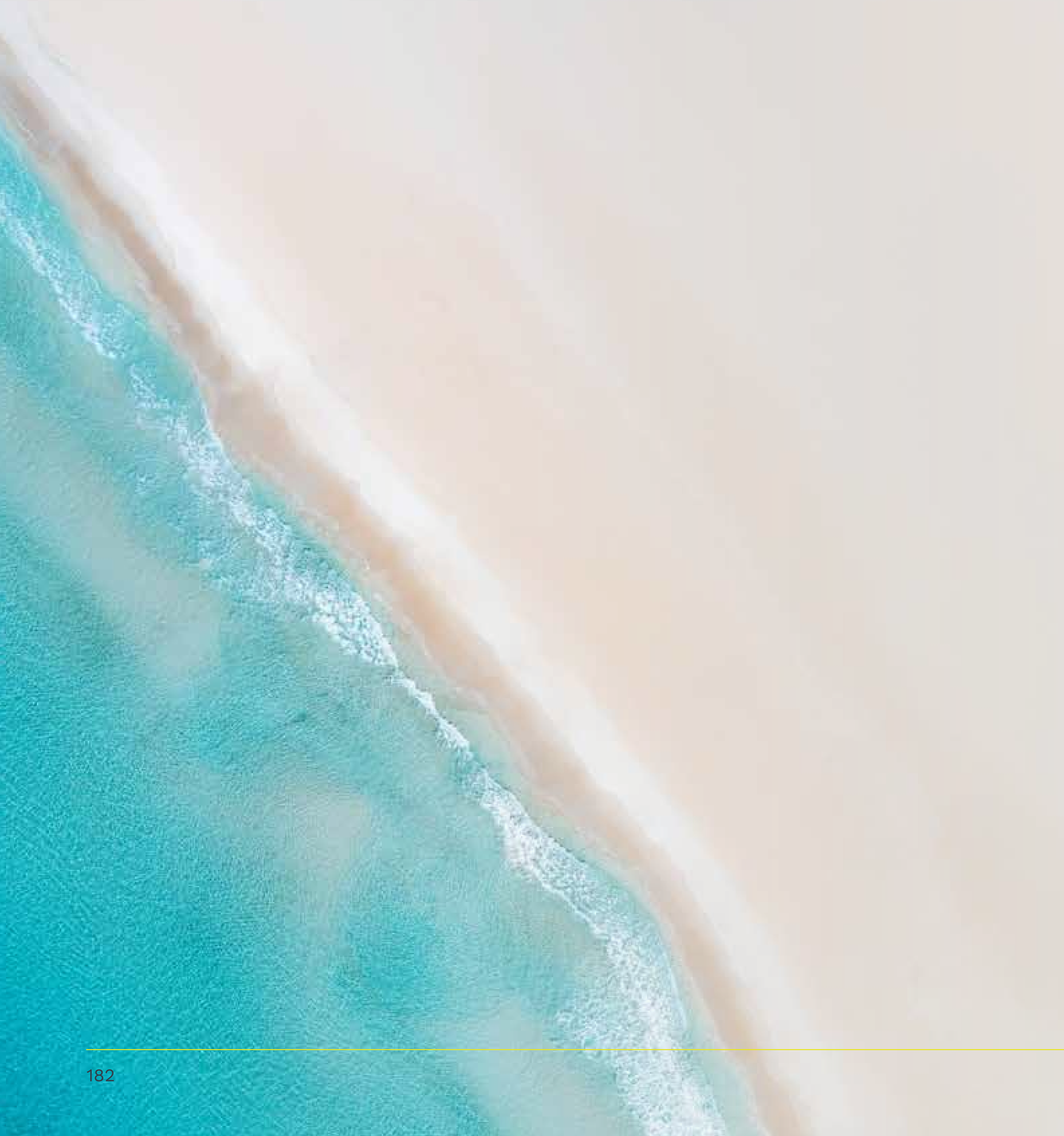
LITERATURE CITED



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