MANAGING THE ECOLOGICAL RISKS OF CORAL REEF INTERVENTIONS

CORDAP R&D TECHNOLOGY ROADMAP

cordap
Coral Research & Development Accelerator Platform

Australian Government

Australian Institute of Marine Science

Cefas

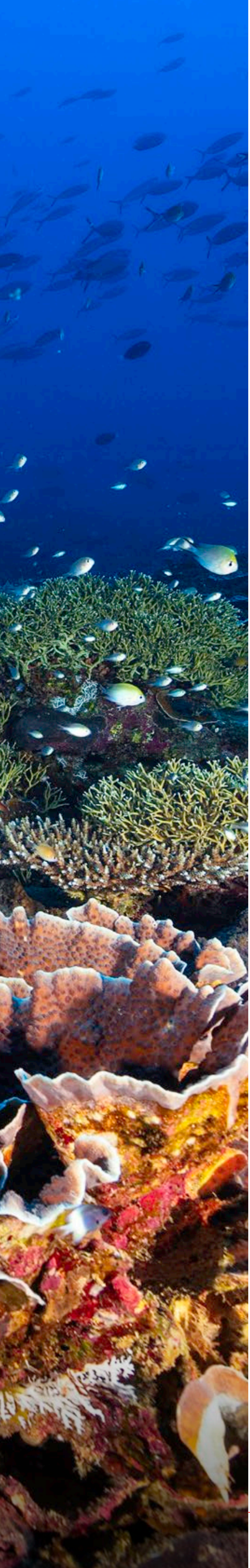

Table of contents

Credit: Gabriel Barathieu

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Scope of work

From the 22nd to 25th of January 2024, an in-person workshop was held in Brisbane, Australia.

This workshop brought together academic, industry-based, and technology experts from various fields, including coral reef ecology, marine restoration, coral genetics, intervention deployments and scaling-up, and coral reef management.

The workshop aimed to promote interdisciplinary dialogue among participants to identify areas where investments in research and development (R&D) are needed to enable coral reef restoration that considers and mitigates the ecological risk associated, and to do so at scale.

As a result of this collaborative effort, five priority areas were identified with associated R&D recommendations:

1. **Responsibly fast-tracking interventions**
2. **Investigating the ecological risk of reef interventions**
3. **Responding to risk (developing risk treatments)**
4. **Supporting decision making and communications, and**
5. **Developing emergency responses.**

In this Roadmap, we outline what each priority area entails and then provide specific details per recommendation.

Credit: Corinne Allen

SECTION 1:
Executive Summary

Coral reefs are among the most vulnerable ecosystems on the planet to climate change. As of 2024, tropical coral reefs are experiencing their fourth global mass bleaching event (Reimer *et al.* 2024). On Australia's Great Barrier Reef (GBR), five mass bleaching events have now occurred within the last eight years, and in Florida (USA) and the wider Caribbean, unprecedented levels of accumulated degree heating weeks (>20 DHWs), starting in mid-2023, resulted in widespread bleaching and subsequent mortality (Hoegh-Guldberg *et al.* 2023).

It is projected that by 2050, 70-90% of coral reefs are likely to disappear, given a warming scenario of only 1.5 °C; and with warming of 2 °C or more, 99% of all coral reefs could be lost in less than 30 years (IPCC 2023). Compounding the deleterious effects of climate change and associated factors are widespread diseases (e.g., stony coral tissue loss disease [SCTLD] in the Caribbean) and coral predator outbreaks (e.g., crown of thorn starfish [COTS] in the wider Indo-Pacific). Threats are further exacerbated from other pressures such as pollution, overfishing, habitat damage and rapid coastal development.

Due to these mounting pressures, substantial innovations have occurred within the active intervention space (e.g., van Oppen *et al.* 2014; 2015; 2017; Rinkevich 2019; 2021; Anthony *et al.* 2017; 2020; Suggett and van Oppen 2022), with several seminal reviews published in 2019 (Bay *et al.* 2019; Hardisty *et al.* 2019; National Academies of Science, Engineering, and Medicine (NASEM) 2019a; b). These reviews provided definitions of emerging active coral reef interventions and established the framework for understanding and documenting their potential risks, benefits, and feasibility of implementation. Examples of active interventions are categorised on page 7.

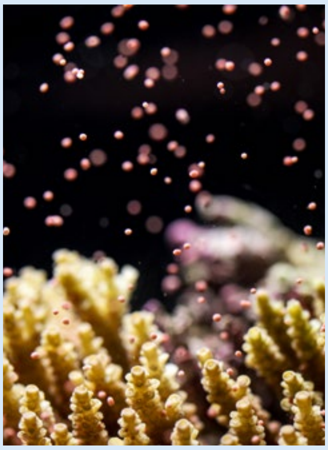
Despite this broad advancement and discussion on the use of coral interventions, knowledge gaps remain in understanding and managing biological and ecological risks to the environment arising from interventions, especially from emerging genetic, physiological and environmental manipulations. An ecological risk can be associated with interventions for coral reefs, either during their respective research and development (R&D) phase or during implementation at their targeted scale, and there are additional risks associated with uncertainty of outcomes, including undesirable and unexpected impacts.

Decisions on the implementation of interventions need to balance the real or perceived risks and benefits of intervening against the risk of not intervening. There is also an urgent need to progress from implementing intervention efforts at local reef scales to broader, regional-scale implementation, such as assisted evolution efforts aiming to enhance the resilience of coral populations (Voolstra *et al.* 2021; McLeod *et al.* 2022; Suggett and van Oppen 2022; Bay *et al.* 2023). Further research is now required to better understand associated ecological risks that will support responsible innovation and decision-making. Managers and researchers face the challenge of implementing interventions that are effective in the short term, and sustainable and adaptive in the long term (Gann *et al.* 2019; Hein *et al.* 2020; Shaver *et al.* 2020).

Examples of active interventions for shallow tropical coral reefs considered for this Roadmap, as informed from Bay *et al.* (2019), NASEM (2019a), and Bostorm-Einarsson *et al.* (2020).


Credit: Corinne Allen

Assisted evolution interventions include assisted gene flow and similar interventions, managed selection and similar interventions, microbiome and symbiont manipulations, conditioning and gene editing.


Credit: © AIMS | Marie Roman

Reproductive interventions include coral cryopreservation, gamete and larval capture and coral seeding, coral seeding on specific devices, and high-throughput conservation aquaculture of corals.


Credit: Anderson B. Mayfield

Physiological interventions include phage therapy, antibiotics, antioxidants, and nutritional supplements.


Credit: Southern Cross University

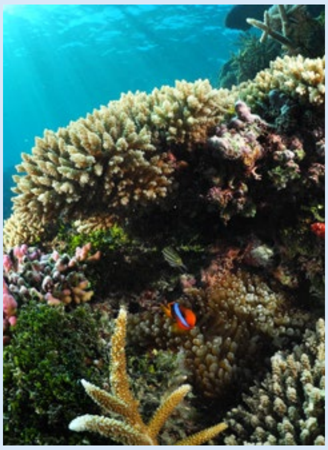
Environmental interventions include marine and atmospheric shading, cooling, biocontrol, and phytoremediation.


Credit: Austin Bowden-Kerby

Coral gardening interventions include direct transplantation, nursery creation, transplantation, fusion/chimerism, and micro-fragmentation.


Credit: Austin Bowden-Kerby

Reef structure interventions include substrate stabilization, substrate addition, substrate consolidation, and substrate enhancement.


Credit: Chris Brunner

Other interventions include genetic rescue and emergency responses.

For a further delineation of these active interventions with their respective definitions, refer to Bay *et al.* (2019), NASEM (2019a), and Bostorm-Einarsson *et al.* (2020).

We recognise interventions have several properties such as delivery mechanisms and potential scale of application and capabilities not captured in this list. However, such properties were considered in developing this Roadmap.

To address these issues, we evaluated ecological risks and risk management of active coral reef interventions. Specifically, we:

1) Systematically reviewed studies documenting the challenges and knowledge gaps in understanding and assessing the ecological risks of active coral reef interventions. We compiled these studies into a database, which (a) pertained to shallow coral reefs in tropical settings, (b) documented experiments of or the implementation of coral reef interventions, and (c) discussed ecological risk(s) associated with a specific intervention, or with the field of intervention science more generally.
2) Consulted key stakeholders (e.g., leading researchers, restoration program managers, reef managers, regulators, and practitioners) to understand regional and global needs and perspectives to inform the development of the Roadmap.
3) Elicited expert opinions from researchers, practitioners and reef managers from over a dozen countries and more than 20 organisations to discuss global and regional perspectives in addressing the complex management of ecological risks with active coral reef interventions. This was done in a four-day workshop in Brisbane, Australia (22 to 25 January 2024). As part of this we facilitated 'world café' style activities to gather and explore regional perspectives on key questions and elicit R&D recommendations. Several criteria were used to prioritise the most globally and regionally applicable areas for R&D investments.
4) Prepared this Roadmap of R&D recommendations informed by the systematic review of the literature, stakeholder consultations, workshop discussions, and pre- and post-workshop consultations.

This Roadmap is solely concerned with active interventions of shallow water coral habitat. Deep water corals (and cold-water corals) are the focus of another CORDAP Scoping Study. This is due to the more limited scientific knowledge base for those environments and reef interventions for deep and cold-water corals are at earlier stages of investigation.

Summary of the Priority Areas and R&D recommendations

We aimed for high global and regional applicability of the R&D Recommendations and found a high level of regional variability in relation to ecological risk management for coral and reef interventions. We explored factors that influence these needs, and socio-economic drivers and motivations, and found there is often no single solution that can be applied globally. In developing this Roadmap, we took account of these regional situations as well as global needs to ensure the R&D recommendations have wide applicability.

Over coming years and decades, new more beneficial intervention solutions and technologies will likely be required for corals and reefs that are step changes beyond currently available interventions. Risks of these new solutions will likely also be greater. Therefore, risk management efforts and R&D investments should have a focus on these new and emerging intervention solutions, not just on interventions that are already in use.

Credit: Anderson Mayfield

Priority areas for investment

With this global perspective in mind, five priority areas for investment were created to get recommendations for R&D from workshop participants on how coral reef intervention science can progress to make interventions more ecologically beneficial while reducing, managing, and/or better understanding the potential for ecological risks. The five priority areas for investing in are:

1) Responsibly fast-tracking interventions,

2) Investigating the ecological risk of reef interventions,

3) Responding to risk (developing risk treatments),

4) Supporting decision making and communications, and

5) Developing emergency responses.

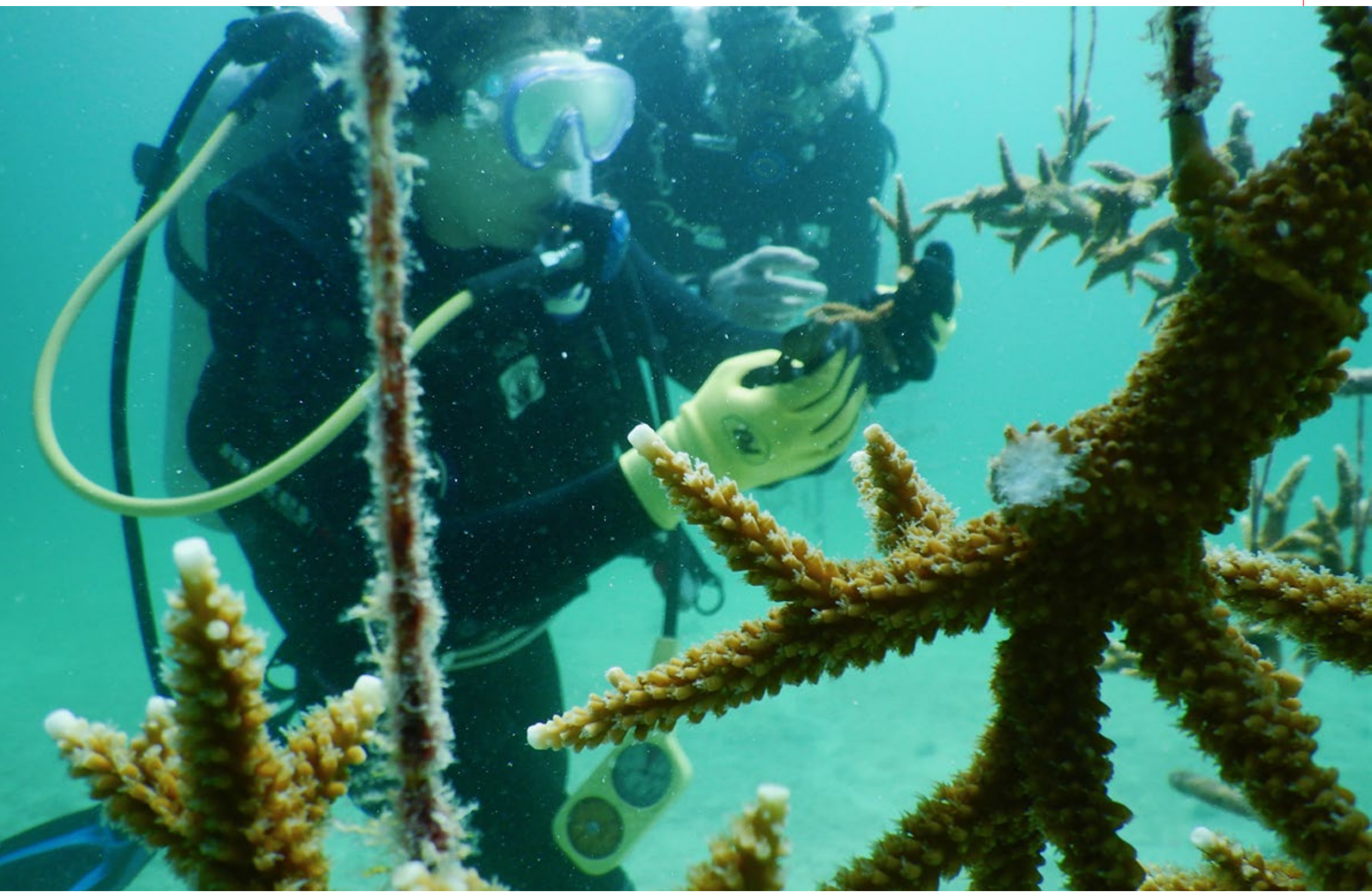
We note that a proposal for an R&D project may address more than one of priority area and associated recommendations detailed in the Roadmap, and we encourage such projects.

Figure 1. The five priority areas for investment.

Rationale for the identified recommendations for investment

- Practitioners, scientists and managers are extremely concerned about the future of coral reefs and the severity of impacts already occurring or soon-to-impact their reefs. As such, accelerating conservation actions and deploying novel coral reef interventions are both priorities.
- There is a need to provide clear and accessible information on the types of coral reef interventions and the nature and scale of the ecological risk associated with implementing that intervention (as in; Bay *et al.* 2019; NASEM 2019a; b).
- Intervention techniques have been applied in many coral reefs spanning multiple countries but, in many instances, this has occurred with little or no clear guidance and results have varied (Fox *et al.* 2019; Razak *et al.* 2022). Uncertainty about ecological intervention risks persists and requires a collaborative approach combining shared local and scientific expertise, and transdisciplinary methods. This foundational Roadmap drafted as an outcome from the workshop is intended to solidify guidance for future R&D investments and ultimately accelerate the implementation of resilient coral reef interventions globally.
- Coral reefs are facing rapid and unprecedented impacts around the world. Many are already severely impacted. Coral abundance has declined and several coral species are now listed as threatened species. Emergency responses to preserve genetic diversity and prevent species extinction has become one of the most important tasks facing the international community.

Credit: Corinne Allen



Outline for each priority area

PRIORITY AREA 1: Responsibly fast-tracking interventions

Responsibly fast-tracking coral reef interventions involves prioritising the rapid investigation, development and testing of promising methods that could be applicable in multiple places. This priority area aims to maximise benefits while minimising ecological risks, such as by using local corals. Risk avoidance for corals and reefs involves accelerating intervention R&D phases (from novel, early-phase ideas through to final proof-of-concept development and scaling up) for the most promising interventions.

Within this priority area we recommend developing guidance and training tools to build capacity and provide training on available interventions, including how to responsibly conduct them, with a focus on ecological risk management. Targeted training programs allow greater engagement at identifying, communicating and managing risks among diverse stakeholder groups. Capacity building is especially important for several of the regional perspectives explored during the workshop, thus such guidance is to be developed across the varied socio-economic contexts to which active interventions are applied.

We also identified a critical gap in providing support for global genetic monitoring and management and recommend establishing a centralised genetics facility. This research facility would rapidly provide genetic data to guide and monitor reef interventions and improve our understanding of associated genetic risks. It could also facilitate comparative studies to answer fundamental and applied questions of global and local importance.

Additional R&D recommendations included investigating and optimising protocols for translocating corals while minimising risk of invasive species and disease spread and developing guidance on species selection for interventions.

PRIORITY AREA 2: Investigating the ecological risk of reef interventions

Investigating the ecological risk associated with coral reef interventions improves the efficacy of conservation efforts by collating knowledge, standardised risk assessment practices, and advancing research into key ecological risk types and their implications across diverse intervention strategies, species and environmental contexts.

Within this priority area we recommend creating and/or maintaining a comprehensive database of known ecological risk types and studies. Building on outputs developed by this scoping study, this initiative would need to identify a mechanism to keep the database going (e.g., an organisation willing to take on that responsibility). The database would continue to catalogue outcomes, conclusions, knowledge gaps, and understanding of potential ecological risks related to various interventions.

Such a centralised resource would facilitate ongoing knowledge synthesis, identify research needs and guide future conservation strategies, as well as help practitioners, scientists and policymakers access relevant information quickly, and make informed decisions based on the latest knowledge.

Improving risk assessment methods and guidance for novel coral interventions would facilitate better-informed decisions and identify relevant factors that influence risk levels. This requires developing and implementing comprehensive risk assessment methods and associated guidance to identify, assess and quantify ecological risks, as well as guide stakeholders in the risks relevant to their specific situations. This is because the manifestation of ecological risks during the implementation or research of a coral reef intervention depends on various factors (e.g., the type and scale of interventions being deployed or tested, and the regional environmental conditions and biotic composition).

In addition, a critical need is to foster targeted studies that quantify the risks of active adaptation interventions. This includes desktop and large-scale studies of genetic risks and further research to quantify and clarify other ecological risk types, such as trait trade-offs, maladaptation, invasive potential of 'enhanced' corals, invasive species and disease risks from translocations, and unintended off-target effects on the coral microbiome.

PRIORITY AREA 3:
Responding to risk (developing risk treatments)

Identifying responses to risk involves the development of proactive strategies to mitigate adverse impacts when they occur, and effectively address unforeseen challenges. This includes investigating screening tools, treatments, and technologies which aim to prevent harm from diseases or pests that could be triggered by the intervention. Risks are higher if adverse impacts can't be reversed, as in most marine invasive species. It also includes developing response plans for intervention risks that are amendable to remediation, which may include R&D for clean ups of physical damage or removal of leftover structures for projects like coral gardening or substrate stabilisation.

A different type of proactive plan involves regional genetic management plans for changes in coral population genetic makeup. We recommend developing genetic management principles and diversity targets for diverse reef systems and species across different ecological contexts (e.g., rules of thumb applicable across species and regions). These guidelines should be informed by relevant conservation goals and specific regional socio-economic perspectives. Such plans are particularly important in areas where coral populations are rapidly declining or there are proposals for interventions that could seriously alter local genetic composition.

PRIORITY AREA 4:
Supporting decision making and communications

Supporting decision making and communication in coral reef interventions involves various R&D strategies aimed at enhancing informed decision-making, risk communication and collaboration among stakeholders.

Within this priority area, developing estimates and narratives of the risk of doing nothing is crucial for informed decision-making and integration into risk assessments. Democratising access to such information by developing streamlined data gathering methodology and analysis tools will help regions with limited resources make informed decisions about coral reef conservation.

The complexity of subject matter means high-quality science communication can improve the coherence, impact and reach of projects and programs. Diverse audiences will often be unfamiliar with key concepts that underpin the intervention technologies being investigated, the coral holobiont, how coral reef systems work, how ecological risks could arise, and the factors influencing risk levels. Workshop participants identified a high need for synthesis and science communication projects associated with this study's subject matter. This will provide stakeholders from diverse backgrounds with accessible information on the intervention technologies and key concepts for improved ecological risk management.

Drawing lessons from conservation genetics and successful interventions in terrestrial and other marine systems, a desktop study or workshop process can identify methodologies and strategies applicable to coral reef interventions.

Assessing and managing ecological risks associated with coral reef interventions require collaboration among diverse stakeholders. Establishing a community-of-practice approach fosters engagement and knowledge-sharing to address the challenges and uncertainties surrounding coral reef intervention risk management. Convening specialist workshops and working groups facilitates information exchange and collaboration among academics, restoration practitioners, NGOs, government agencies, and First Nations. Continued international engagement on managing intervention risks would improve technologies and solutions and support informed decision-making about intervention implementation.

PRIORITY AREA 5: Developing emergency responses

Developing emergency responses in coral reef conservation is becoming vital to slow severe losses and preserve diversity in the face of escalating and rapidly emerging threats such as intense marine heatwaves. In these instances, immediate action may be necessary to protect coral populations from irreversible damage. Emergency approaches may include low and high-tech solutions. This and all work within coral reef nations will require ongoing engagement with First Nations groups and the local community, where appropriate, to seek social approvals and create wider input about goals and methods. We advocate to develop triage measures and emergency response plans which consider the various circumstances and socio-economic contexts to which they may be applied. Within either approach (i.e., low, or high-tech) is an urgent need for R&D to investigate options and develop guidance. We acknowledge the challenges to fund emergency responses, and suggest CORDAP consider tactical funding approaches and nations and large-scale programs consider setting aside emergency response funding that can be quickly accessed for these purposes.

Undertaking trials and experiments using disturbance as a natural laboratory presents an opportunity to fast-track learning and better understand coral resilience to stress events. Testing interventions during major heat stress events enable their effectiveness to be assessed but require preplanned protocols.

Credit: The Ocean Agency

SECTION 2:

Roadmap

Credit: Yen-Yi Lee

Introduction

The G20 Coral Research & Development Accelerator Platform (CORDAP) brings together relevant experts to advance the next generation of science and technology necessary to improve the survival, conservation, resilience, adaptation and restoration of tropical and deep-water corals and reefs. CORDAP also aims to complement and support existing national, regional and international initiatives currently working on coral and reef conservation, resilience, adaptation and restoration.

The Australian Institute of Marine Science (AIMS) and the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) co-led a workshop for CORDAP in Brisbane, Australia, from 22 to 25 January 2024. The workshop involved researchers, practitioners and reef managers from more than a dozen countries and over 20 organisations discussing global and regional perspectives to identify knowledge gaps, challenges and opportunities to manage ecological risks associated with active coral reef interventions. The workshop identified actionable research and development (R&D) recommendations for inclusion in this roadmap and strategies for navigating the unknowns of intervention-related ecological risks.

The largest threats to coral reef health are climate change and pressures such as poor water quality. Addressing the impacts of increasing temperatures and poor water quality are primary policy needs for the future of coral reefs. In the short- to medium-term, the speed of action to address these pressures has not been sufficient to ensure functioning coral reefs into the future. Novel interventions to build coral reef resilience are also needed.

In 2020, 17 G20 nations launched CORDAP to accelerate global R&D of coral restoration and conservation while actions on climate change and other pressures are being progressed. A major area of innovation that could enhance the resilience and recovery of coral reefs is reef restoration and active adaptation interventions (Anthony *et al.* 2017; NASEM 2019a,b Suggett and van Oppen 2022). While there have been significant advancements in reef intervention techniques, research efforts must still be prioritised to better understand and manage their ecological risks.

Fast-tracking coral restoration and conservation is mission-driven and time-critical. It is important to recognise time constraints and spatial scale considerations as coral reef systems change rapidly in response to warming waters and multiple pressures. Negative trajectories are being reported for coral reefs across the world, with abrupt and rapid declines occurring and more projected, even if Paris climate targets are met (IPCC 2023). Disturbances can be annual or multi-annual, and predictions need to incorporate natural variability, warming waters and localised pressures. Management responses must consider the scale of changes, reef system resilience, timing required to detect positive feedbacks, and the requirement to scale-up for multiple reef systems to improve the future of coral reefs and the people dependent on them.

Similarly, Anthony *et al.* (2020) suggested reef interventions should be implemented when long-term benefits outweigh the risks associated with inaction. Such a calculation of the "risk of doing nothing" considers potential positive impacts on coral resilience, ecosystem services and societal values against the likelihood of negative outcomes from intervention implementation.

However, the risk of doing nothing is rapidly increasing, with climate change impacts, and the balance between risk and benefit changing over time. Management responses should therefore consider relative cost versus benefit and how this calculation changes as climate change impacts increase.

We are addressing challenges to managing ecological risks and balancing risks and benefits from these novel approaches. To do this, we used a literature review, workshop and stakeholder consultations to pinpoint research priorities for better understanding and managing the ecological risks of coral reef interventions (Table 1). The workshop involved experts who considered ways to manage risks, identify gaps and challenges, and shape future R&D directions. Such approaches are critical to recommend priority investment areas as resources are scarce and timely solutions are necessary (Anthony *et al.* 2017; 2020).

Better risk assessment and management will ultimately make restoration and adaptation projects/programs more successful and minimise potential unintended ecological consequences. A managed risk approach will support responsible innovation and decision-making about coral reef conservation and management. This study is intended to be relevant to programs and regions around the world and establish an actionable roadmap to coordinate global R&D. For CORDAP the study will guide the Scientific and Advisory Committee (SAC) on research priorities.

Credit: Grant Thomas

Table 1. Justification and proposed delivery methods of recommendations.

Priority Area	Justification	Proposed delivery method(s)
PRIORITY AREA 1: **Responsibly fast-track interventions**	This priority area seeks to prioritise rapid investigation, development, and testing of promising interventions while managing associated risks. It also considers the balance of benefits and risks, aligning with the objectives of the CORDAP Strategic Plan.	• Develop project proposals based on Roadmap recommendation(s) for open calls. • Secure new investment, in cooperation with key partners, for a commissioned Genetics Centre.
PRIORITY AREA 2: **Investigating the ecological risk of reef interventions**	This priority area seeks to address ecological risks associated with coral reef interventions via systematically cataloguing, evaluating and understanding potential negative impacts. Recommendations are given to improve risk assessment practices, and for ongoing research into key ecological risk types and their implications across diverse intervention strategies and environmental contexts.	• Develop project proposals based on Roadmap recommendation(s) for open calls. • Undertake desktop studies, and experimental research and investigations to understand these potential risks.
PRIORITY AREA 3: **Responding to risk (developing risk treatments)**	This priority area features proactive risk treatments to mitigate potential adverse impacts that may affect the environment. This includes recommendations to investigate screening tools, treatments and technologies to reduce risks of diseases and pests in intervention activities to as low as reasonably practical. Recommendations also aim to develop intervention risk response plans and regional genetic management plans and/or principles.	• Develop project proposals based on Roadmap recommendation(s) for open calls. • Establish links to the Genetics Centre.
PRIORITY AREA 4: **Supporting decision making and communications**	Providing support for decision-making and communications in coral reef interventions involves various R&D activities aimed at improving informed decision-making, risk communication, and collaboration among stakeholders.	• Develop project proposals based on Roadmap recommendation(s) for open calls. • Undertake small desktop study or workshop process. • Establish and run specialist workshop processes or working group.
PRIORITY AREA 5: **Developing emergency responses**	Emergency responses in coral reef conservation help mitigate severe losses and preserve diversity in the face of escalating and rapidly emerging threats, such as intensifying bleaching events. In these instances, immediate action may be needed to protect coral populations from irreversible damage caused by environmental disturbances.	• Develop project proposals based on Roadmap recommendation(s) for open calls.

Global and regional applicability of R&D recommendations

Our literature review and stakeholder consultations showed there is a high level of regional variability in relation to ecological risk management. There are vast differences between the plans and actions appropriate for resource-rich coral nations with central administrations, funding and science infrastructures, compared to the larger number of smaller, bottom-up capacity-strained coral nations with less science infrastructure and more need for capacity building.

Accordingly, at global and regional scales, implementing coral reef interventions and the potential for ecological risk or success vary along several continuums (Bayraktarov *et al.* 2019; Fox *et al.* 2019; Bostrom-Einarsson *et al.* 2020; Razak *et al.* 2022; Banaszak *et al.* 2023). These include:

- economic and socio-political status,
- reef condition and threats, and reef resilience,
- access to technologies and scientific support,
- existing and planned reef intervention(s) work,
- mix of stakeholders and government agencies responsible for decisions,
- what risk assessment is conducted (if any) preceding field activities and deployments, and the approaches used, support available, and type and maturity of risk governance and management in place,
- reef management systems and management frameworks, and
- ability to support long-term and higher-cost activities, technologies and interventions.

The diversity of different coral reef systems and the variability of socio-economic drivers and motivations means there is often no single solution that can be applied globally. It also means the type of interventions and risk understanding require customised solutions that accommodate diverse needs and regional contexts (i.e., ecosystem, environmental, economic, social).

This Roadmap accounts for these regional situations and global needs because our consultations showed R&D needs related to managing ecological risks of coral reef interventions often vary from place to place. To account for such variations, we applied a 'lens of regional difference' in the workshop process using the five groups shown in Table 2.

Lens A refers to regions where most reefs are highly degraded and some coral species are endangered, but there are higher levels of support and funding (e.g., the United States of America, specifically along Florida's Coral Reef and parts of the Caribbean).

Lens B refers to regions where reefs are degraded or in patchy condition. The focus is on people (e.g., habitats to support reef fish production to support local livelihoods), and funding and support is limited (e.g., Western Indian Ocean, Fiji and parts of the Caribbean).

Lens C refers to regions where reefs still exhibit resilience and abundant / diverse coral reefs, at least in some areas. Higher levels of support and funding are available (e.g., Australia and Saudi Arabia).

Lens D refers to regions where reefs still exhibit resilience and abundant / diverse coral reefs, at least in some areas, but levels of support are intermediate (e.g., parts of the Coral Triangle).

Lens E applies to global needs for a rapidly changing future and crisis situations. This perspective aims to gain ideas to safely test and enable more 'radical' and scalable interventions (e.g., large scale translocations, gene editing and environmental manipulations).

Table 2. Varied regional 'lenses' considered during the workshop and for our flexibility metric.

A	B	C	D	E
Most reefs are highly degraded and some coral species are endangered. Higher levels of support and funding available.	Reefs are degraded or patchy. Focus is on ecosystem services reefs provide and supporting livelihoods. Funding and support limited.	Reefs are resilient and feature abundant/ diverse corals, at least in some areas. Higher levels of support and funding available.	Reefs are resilient and feature abundant/ diverse corals, at least in some areas. Levels of support intermediate.	Aiming for rapidly changing future and crisis situations. This perspective sought to safely test and enable more 'radical' / scalable solutions.

We used 'world café' style workshop activities to share and develop ideas, 'visited' by small groups representing each of the five regional perspectives. Each group went to its first café for a facilitated discussion on a particular topic. Groups were then moved from one café to another after an agreed time until each had been to each of the cafés. At each café, successive groups built on the ideas of previous groups provided to them and summarised by the facilitator. This way, all groups contributed to all topics and then key points were shared and discussed with the full workshop. Several workshop participants also presented regional case studies and perspectives to inform workshop discussions.

Metrics used to assess R&D recommendations

During the workshop and in refining suggestions after consultations and the knowledge review, we considered all recommendations in relation to feasibility, delivery timeframes and cost-effectiveness. Additional metrics were also considered, including quality and flexibility of recommendations for application across regions considered during the workshop (detailed in Table 2). We also considered alignment with other CORDAP scoping study recommendations and the CORDAP Strategic Plan, as well as relevant global studies and other end user needs identified during consultation.

Summary of metrics used:

1. **Feasibility** – the likelihood the R&D recommendation will reduce the uncertainty of (or directly reduce the potential for) ecological risks resulting from implementing a coral reef active intervention (assessed as low, medium or high).
2. **Delivery timeframe** – how long it will take for action on the R&D recommendation to improve ecological risk mitigation efforts (assessed as <1 year, 1-5 years, or >5 years).
3. **Cost effectiveness** – estimated R&D funding required so the recommendation can be developed for wide adoption (assessed as low, medium or high).
4. **Quality** – potential that the recommendation promotes coral reef resilience and minimises ecological risk (assessed as low, medium or high).
5. **Flexibility** – potential the recommendation is applicable for various regional perspectives (as defined in Table 2) or globally (assessed as low for only one region, medium for two or high for more than two regional perspectives or global).

We aimed to ensure recommendations cover diverse regional situations and global needs identified in the workshop and from stakeholder consultations. However, the final list of recommendations presented here summarise these metrics into a single 'priority level'. Within this criterion, we note recommendations that are either a high, medium or low-medium priority.

Credit: Jason Vains

General considerations for the Roadmap

Consideration of the ecosystem approach

While the workshop, review, and consultation focused on identifying key knowledge gaps around ecological risk of coral reef interventions, many concerns raised in workshop discussions related to other pressures and impacts. The success of any coral reef intervention will also depend on mitigation and management of pressures such as pollution, overfishing and rapid coastal development. These pressures can be detrimental to the success of the intervention and must be considered and managed. Managing pressures is a foundational intervention and should be in place as part of an integrated approach to ensure success of the active intervention(s).

Climate change action is being tackled on a global front, and impacts are concerning and intensifying. Government decisions therefore must happen faster to meet global climate targets. At a national level, adaptive management of land-based pressures is essential. Agencies need to collaborate 'from catchment to coast' to reduce marine pollution and other pressures.

Data accessibility and other ways to value-add

To fast track the field, it is important to make data available from studies based on recommendations from this Roadmap and other CORDAP-funded Roadmaps. This may include data and information that can be used to monitor, audit, and assess ecological risks of active coral reef interventions. Better access to data and results saves time and money as well as coral reef ecosystems.

To enable long-term experiments, workshop participants identified a need for funding cycles longer than 3 years for some types of research. We also considered coordinated research projects (same protocols in multiple places) may provide stronger insights.

Overlapping and interlinked nature of our recommendations

This Roadmap acknowledges the overlapping nature of recommendations it presents. For example, genetic management, supporting decision-making, and capacity development are key concepts covered in almost all priority areas. Some overlapping recommendations were unavoidable given the key issues arising from the literature review, stakeholder consultations and workshop.

Some recommendations overlap with the previous CORDAP roadmaps (Assisted Evolution, Aquaculture). Objectives of other CORDAP roadmaps (published or in preparation) and this Roadmap differ. However, other key overlapping concepts include:

- building relevant capacity (e.g., for research) in developing economies and local communities,
- building and maintaining a global resource-sharing network and database,
- increasing research to understand genetic implications (adaptation and risk) of coral reef interventions,
- convening specialist workshops and work groups to continue discussions on intervention efficacy and implementation, and emergency response preparedness.

Some recommendations highly related to ecological risk under the Assisted Evolution Roadmap were also raised in our workshop, including calls for studies that characterise any trade-offs between coral heat tolerance and other traits that impact fitness, and the need for large genetic field studies.

There are also interlinkages across our recommendations. This means a proposal for an R&D project may be able to address more than one priority areas and associated recommendations detailed in the Roadmap. We encourage such projects.

R&D recommendations

Recommended priority areas that should be addressed in further studies are described in the following pages, and include the impact of each approach.

PRIORITY AREA 1: Responsibly fast-tracking interventions

1.1 Responsibly fast-track investigations, development and trials for the most promising interventions while managing risks

Background / justification

Workshop participants identified that a key strategy to maximise the benefits and minimise the risks of coral reef interventions is to responsibly fast-track investigations, development, and trials for the most promising interventions, including, but not limited to, those that come with lower inherent ecological risks (Box 1).

As climate change impacts intensify, risk avoidance for corals and reefs requires R&D phases (from novel early-phase ideas through to final proof-of-concept development and testing) to accelerate for the most promising interventions. This can maximise longer-term net benefits for these approaches, while managing risks, and determine their efficacy, applicability and the best way to combine or integrate suites of interventions and other reef management actions.

Impact

- Risk avoidance for corals and reefs by accelerating all R&D phases (from novel early-phase ideas to final proof-of-concept development and testing) for the most promising interventions.
- Accelerating the use of naturally occurring, heat resistant, local corals in regions with small intervention infrastructure.
- Conservation benefits obtained by co-applying lower risk interventions as part of integrated approaches. This also includes investigating further applications of promising intervention solutions, while managing ecological risks.

Credit: Mark Gibbs

Box 1. Examples of promising interventions with potentially lower inherent ecological risks.

Examples of potential promising approaches include: mass coral larval rearing and placement (de la Cruz and Harrison 2017; 2020; Harrison *et al.* 2021; McLeod *et al.* 2022), disease-free aquaculture-propagated corals deployed on seeding devices (Chamberland *et al.* 2015; 2017; Roepke *et al.* 2022; Whitman *et al.* 2024), algal symbiont manipulation (Quigley *et al.* 2020b; 2023; Nitschke *et al.* 2024), native microbiome restoration (Zhang *et al.* 2021; Peixoto *et al.* 2023; Delgadillo-Ordoñez *et al.* 2024), breeding for high heat tolerance within (Humanes *et al.* 2022) and between-populations (van Oppen *et al.* 2014; Quigley *et al.* 2019; 2020a), and interspecific hybridisation for novel genomics (Chan *et al.* 2018; 2019).

Interventions that leverage assisted natural recovery using heat resistant, local corals (e.g., Reefs of Hope; Bowden-Kerby 2023) may be particularly well suited to regions with lower intervention infrastructure. In each case, risks of intervention must be carefully measured and weighed against benefits.

Credit: Austin Bowden-Kerby

1.2 Develop guidance, build capacity and provide training on available and emerging interventions, with a focus on ecological risk management

Background / justification

Workshop participants identified a critical need for more project(s) that develop guidance, build capacity and offer training to implement low-risk interventions. Such support is particularly limited in the Western Indian Ocean and helps other regions, such as the Coral Triangle and Pacific Islands (supports the needs for lenses B and D, Table 2). Coverage should encompass existing interventions (e.g., substrate stabilisation, substrate addition, coral gardening) with an initial focus on reduced risk by using local corals for heat tolerance testing, grow-out and use in restoration. These could be followed by further developing interventions using translocations and those with larger infrastructure needs (e.g., managed selection, gamete and larval capture and coral seeding, genetic rescue).

Guidance on how to conduct the interventions, with a clear focus on ecological risk management, help improve conservation outcomes. Examples of recent CORDAP-funded capacity development projects are the Reef Seed Project (www.aims.gov.au/information-centre/news-and-stories/remote-portable-coral-factories-be-developed-reef-restoration) and the Coral Futures Academy (Box 2).

Initially, these projects would conduct a thorough assessment of existing stakeholder capabilities, with particular emphasis on local communities' unique positions and knowledge. The strategy then aims to increase tailored skills and tools so stakeholders can participate effectively in coral reef conservation. These efforts should consider local governance structures and coral reef management goals, and be based on sustainable techniques and technologies.

Linking with recommendations 2.2 and 4.4, to encourage shared understanding of and responsibility to mitigate unintended negative impacts associated with interventions, targeted training programs and materials should be developed that identify, communicate and manage risks in stakeholder groups. This may include workshops, seminars, providing testing equipment, online mentoring and creating collaborative platforms for stakeholders to exchange ideas, concerns and strategies for effective risk management.

In addition to guidance, there is a broader objective to encourage stakeholders to consider risks if they haven't already. This may help encourage a mindset among all parties to actively consider potential impacts of their actions on coral environments, and work to minimise negative outcomes.

This capacity development work should consider ecological and social contexts jointly in intervention implementation and risk management. Projects can help community participants develop and access monitoring systems to ensure the kind of long-term monitoring critical to evaluate intervention efficacy.

Impact

- Knowledge sharing supports local implementation of interventions in more regions and encourages best practices. Directly delivers on the highest priority identified for the Western Indian Ocean, with broader applicability for and beyond the Global South.
- Targeted training programs enable greater engagement on identifying, communicating and managing risks among diverse stakeholder groups.

Box 2. An example of a recent capacity development project.

The **Coral Futures Academy** aims to align local testing of heat-resistant corals of diverse species with local reef restoration projects. It provides a supply of local corals with low transplant risk and high heat resistance to local restoration projects in settings with simple research infrastructure. These would be conducted by reef managers with solid jobs to improve reef value for communities. They would be trained at the Coral Futures Academy in skills to test corals for heat resistance, deliver these corals to restoration projects and monitor success. Trainees in one cycle would become trainers for the next, as a way to scale-up the workforce. A pilot project is underway in Palau and will expand throughout the Marshall Islands, Micronesia and other interested island nations.

Credit: Austin Bowden-Kerby

1.3 Investigate and optimise approaches for translocating corals for conservation and adaptation purposes

Background / justification

Many aspects of interventions can be done with local corals at a regional 1-100 km scale. However, a focus on translocating corals over medium to long distances is based on the idea some areas (such as the Red Sea, northern Great Barrier Reef or equatorial Pacific) have corals that are more heat resistant than those found locally in other places (Quigley and van Oppen 2022).

Interventions involving longer translocations include some restoration techniques to replenish areas from distant source reefs, some assisted evolution methods (e.g., assisted gene flow, assisted migration) and some approaches to rescue coral populations from extinction. Translocation may become a critical tool, particularly considering the need for regional solutions due to the decline of coral reefs and the recurring mass coral bleaching globally. However, these translocated corals increase dangers of disease and invasive species. Corals are also likely to be adapted to other foreign conditions besides high heat. Evaluating the pros and cons of translocation over 100s-1000s km distance is an emerging priority. In general, ecological risks are perceived to increase with the distance corals are moved, but guidelines for safe distances are virtually lacking (NASEM 2019a).

Another type of translocation may involve proactively moving corals from hotspots to protect them from severe heatwaves, securing their survival and value as genetic resources. This could be done in a planned way rather than during an emergency.

While some research indicates that translocating genotypes among distant reefs is unlikely to be problematic from a population genetic perspective and could promote adaptive advantages (Baums *et al.* 2019), it has been previously suggested that assisted gene flow could perhaps cause outbreeding depression (e.g., if source and recipient populations have been long isolated) and may disrupt local adaptation to non-climatic environmental factors (Bartz and Brett 2017).

At present, there is very limited direct experience, and a notable absence of protocols to guide translocating corals and/or their symbionts, or manage associated risks (Bay *et al*. 2019). When considering translocations, it is important to distinguish between translocations to closed-system land-based facilities (without putting corals directly in the marine environment) and translocations into running seawater facilities, or straight to reef or nursery sites. This is because the issues that need to be managed will differ.

Workshop participants considered risk-based decisions especially important, given the potential for invasive and disease risks from translocations, and that translocations over greater distances may carry more inherent ecological risks than those over shorter distances (NASEM 2019b). Participants also recognised (conversely) that larger scale translocations may provide benefits for conservation and adaptation that can't otherwise be realised (e.g., heat-adapted genotypes). There is therefore an urgent need for R&D to focus on risk assessment for coral translocations across various distances and establish optimised protocols and approaches to manage specific risks (e.g., invasive species and disease) of translocating corals.

Creating protocols would weigh the risks and benefits of translocating corals, their symbionts and other co-located species (microbes, algae, etc.) across varied scales, and offer mitigation measures for associated risks. Such protocols should also help weigh action versus inaction.

Attention should be paid to quantify and limit the potential risks of introducing pests, diseases and/or other invasive species, perhaps through genomic comparison of microbes, algae and parasitic species across distances. In situations where there are no unique, potentially harmful species across locations, field trials may collect critical data. Such development and trials could help in defining and managing ecological risks of translocation, and provide evidence for regulatory decision-making.

Impact

- Supports a managed-risk approach to advance interventions involving translocations. This includes assisted evolution methods and triage measures such as moving corals from hotspots to secure genetic resources in a planned, proactive way rather than during an emergency.
- Optimise approaches on how to move corals and/or their symbionts over large scales and manage associated risks. Could also inform rescue of genetic resources and populations in emergencies (as in Priority area 5)

1.4 Global coral genetics centre and global coral genetic management

Background / justification

Workshop participants considered it a high priority to improve global genetic management of coral reef interventions, including all constituents of the coral holobiont. In some parts of the world, there is lack of access to facilities that can sequence whole genomes of corals (including the animal host, symbiotic algae, bacteria and other co-occurring species). This means DNA-based data often isn't available despite it potentially providing answers to fundamental and applied questions of global and local importance.

The methods used by different researchers vary, making it challenging to compare data sets from different parts of the world. Also, data access across species and locations continues to be cumbersome and requisite bioinformatic skills are difficult to develop in every location where genetic data is useful.

A centre which produces DNA-based data to support coral genetic management can be used to provide coral, symbiont, and microbial genome data, which will facilitate comparative studies and unveil answers to fundamental and applied questions about corals. For example (and specific to risk applications), such DNA-based data can construct:

- holobiont metagenomes to identify microbiome, algal and invertebrate co-inhabitants for evaluating translocation risk,
- symbiont genomes to identify scales of symbiont population structure and specialisation between species,
- coral genomes for rapid detection of cryptic species (i.e., species identification and divergence),
- microbial genomes to identify disease prevalence and the presence of beneficial bacteria.

We recommend investing to establish and run a coral genetics centre focused on global coral genetic management. This large initiative would bolster genetic research efforts across spatial and temporal scales, and encourage comprehensive understanding of genetic risks and potential obstacles to advanced intervention activities. The centre would also provide critical support for projects that involve sharing of genetic data across boundaries and jurisdictions. It would also provide key analytical support to reveal patterns of diversity, divergence, disease, holobiont make-up, and other aspects of corals as genetic and ecological communities. These assets will create an unparalleled collaborative effort to address ecological risks on a global scale, particularly among countries in regions like the Caribbean and the Pacific Islands.

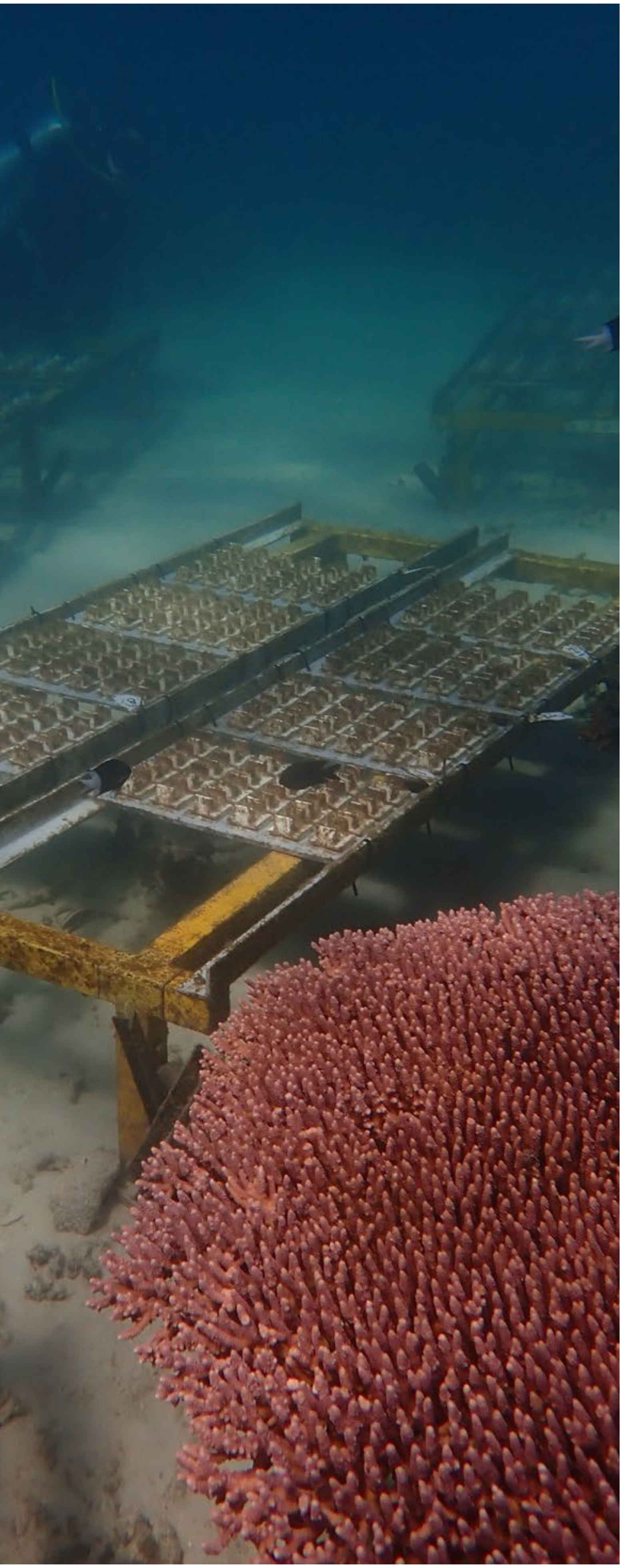
Centralising such a facility is recommended to ensure consistency and high standards in sequencing and analytical methodologies for global coral genetic management. Additionally, the centre could facilitate global studies and genetic monitoring to address key questions. As mentioned above (i.e., recommendation 1.3), for potentially riskier interventions such as translocations across larger scales, the centre could coordinate efforts to characterise holobiont genomes to understand coral, symbiont and microbiome diversity across spatial and temporal scales, therefore identifying potential hurdles to translocation (e.g., population structure or invasive potential).

This central facility would provide a shared genomic core for all projects to address ecological risks of interventions and offer genomic support to projects, as needed. Bioinformatic analyses would be made available to all researchers via intuitive and accessible data interfaces. The centre would therefore benefit all regional perspectives covered during the workshop. By directly tackling genetic hurdles, this initiative also aligns with CORDAP's objective of catalysing step changes, facilitating the testing and adoption of novel R&D projects, as well as scaling up and testing improvements to existing interventions, methods, or technologies. Because this central facility will need coral samples to be transported internationally, we recognise support for this would need to be obtained from all (related) countries.

The initiative could also involve training in bioinformatic analyses for scientists from around the world. This could incorporate access to powerful computing and computational support as well as protocols and platforms for data storage.

Impact

- A central facility that provides whole genome sequencing on all coral holobiont constituents and bioinformatic analyses via intuitive and accessible data interfaces.
- The broad swath of data generated from a global genetic management centre would benefit all regions, regardless of their socio-economic status. The centre would therefore guide and monitor reef interventions and improve global understanding and management of associated genetic, disease and invasive-related risks.
- The centre would also standardise molecular tools for corals (including the animal host, symbiotic algae, bacteria, and other microbes) and make the tools and data accessible to all, including CORDAP projects. By providing coral, symbiont and microbial genome data, the centre could facilitate comparative studies and answer fundamental and applied questions of local and global significance.



1.5 Optimising the generation and use of knowledge on heat tolerance and other traits, filling critical knowledge gaps on field performance of enhanced corals and supporting the advance of existing and new technologies

Background / justification

Our recommendations here align with and reinforce several recommendations in a previous CORDAP Roadmap on understanding natural adaptation and assisted evolution of corals (Bay *et al.* 2023). Specifically, we recommend R&D to identify and fast-track assisted evolution methods that can improve coral heat tolerance as a way to adjust the risk-benefit equation in favour of conservation and help corals adapt. Such knowledge can also help us better understand associated ecological risks.

Our knowledge inventory and the January 2024 workshop identified R&D needs around adaptation, including quantifying heat tolerance and adaptive potential. This could involve exploring biomarkers of heat tolerance, comprehending the contributions of the holobiont to heat tolerance and expediting potentially more effective adaptive intervention solutions (Drury *et al.* 2022). Some associated challenges are discussed in Box 3.

We recommend funding studies to optimise the generation and utilisation of knowledge on heat tolerance and other adaptations, filling critical knowledge gaps on field performance of enhanced corals, and helping advance existing and new technologies. Further research into heat tolerance is necessary to test questions such as the importance of local adaptation to climate and other environmental factors, the maintenance of stress tolerance over time, mechanisms driving natural variability of heat tolerance, and whether heat-tolerant corals sourced from distant locations can survive as well as their local counterparts.

Coral adaptation studies can also benefit from quantitative genetic methods, including studies of wild and captive bred populations, to improve understanding of adaptive potential (Richards *et al.* 2023). This research is a way to improve understanding of associated risks and benefits.

Impact

- Identify those assisted evolution methods that can provide higher impacts in terms of coral heat tolerance enhancement and improve our understanding of associated risks.

Credit: Corinne Allen

Box 3. The challenges of evaluating the adaptive state of corals for enhancing heat tolerance.

Studies demonstrate the potential of assisted evolution strategies, showing enhanced adaptive state through intraspecific selective breeding (Quigley *et al.* 2020a), interspecific hybridization (Chan *et al.* 2018; 2019) and symbiont manipulation (Quigley *et al.* 2020b; 2023; Chan *et al.* 2023; Nitschke *et al.* 2024). However, breeding experiments have demonstrated the issue of how much additive genetic variance there is for heat tolerance (i.e., Quigley *et al.* 2021), and such traits are rarely measured beyond the juvenile stage and potentially decline later in life (Howells *et al.* 2022; Humanes *et al.* 2022).

Furthermore, purebred and hybrid crosses of *Orbicella faveolata* from inshore and offshore reefs in the Caribbean have challenged the current managed selection paradigm (that more tolerant parents will always yield more tolerant offspring). This highlights the challenges of evaluating the adaptive state of corals for enhancing heat tolerance (Zhang *et al.* 2023). Indeed, the phenotype heat tolerance is complex and depends on a multitude of factors such as geography and history, genotypes of the corals and symbionts, and is further influenced by abiotic and biotic environmental variables. The heritability of heat tolerance is therefore likely to vary in space and time.

1.6 Develop guidance on species selection relevant to specific intervention types or combinations of interventions

Background / justification

We recommend developing guidance on species selection for coral and reef interventions. Selecting which species to include is crucial to restoration (Hein *et al.* 2020; Shaver *et al.* 2020; Bay *et al.* 2023), particularly the species combination required to support ecosystem functioning. Sustaining coral reef ecosystems facing ongoing climatic and anthropogenic stressors requires a multispecies approach and considering a suite of biological and ecological processes that support resilience (NASEM 2019b).

Previous models for coral restoration species selection have been proposed (Madin *et al.* 2023), but there continues to be a lack of guidance on species mixes needed for best conservation gains, ecological functioning and climate resilience. For example, guiding interventions that add corals to a reef could consider practical aspects and factors across species such as ease of working on the species, life-history traits, longevity, growth rates, storm resilience, disease resilience, main predators, ecological roles and resource-production value. Various approaches to developing guidance for species selection relevant to specific interventions may include expert elicitation, models, experiments and meta-analyses.

A different issue is the common occurrence of cryptic species among even well-known coral morphotypes (Riginos *et al.* 2024). Correctly identifying corals as to their cryptic species may be important to generate a critical size in a local breeding population. Such identification can't be accomplished easily with morphology or in many cases, simple gene phylogenies. The Coral Genome Centre (discussed previously) could help produce data on these issues across coral genera and reef locations.

Impact

- Better understand how species choices affect ecological outcomes and risks.
- Improves intervention designs and plans, and feeds into genetic management and ecosystem planning (discussed further in recommendation 3.3).

Credit: Alex Mustard

1.7 R&D into additional radical intervention options including evaluation of potential benefits and risks

Background / justification

To date there have been limited investigations into more radical interventions, such as very large-scale translocations (i.e., outside a species' historical range and possibly across ocean basins), novel environmental interventions (e.g., artificial upwelling, regional scale marine and atmospheric shading) and gene editing of coral or their symbionts (applies to lens E; Table 2).

To improve understanding before such interventions may be needed, or to discourage poorly planned or uninformed interventions, we recommend early R&D to explore additional radical intervention options and assess potential benefits and risks. These activities should involve mapping what technology, personnel and infrastructure would be required for the intervention to have the intended consequences, what would be the potential risks and how to measure them, and in some careful cases conducting the experiments necessary to improve quantification of benefits and ecological risks.

Issues about reversibility (i.e., can the intervention be stopped and reversed), benefits to reef value (i.e., not just to single species), and applicability to widespread locations may play a role, especially for radical interventions. It is important to note some well-intentioned radical actions have backfired and still require remediation, such as algal introductions into Kaneohe Bay (Smith *et al.* 2002).

For more radical interventions, it is important to develop methods or targeted studies that evaluate the likelihood of risks associated with the interventions. These may include integrating ecological data, historical precedents and expert insights on risk to predict and evaluate how interventions may affect reef organisms and the environment. Broad ecological implications and the potential for unintended consequences must be considered.

Likewise, interventions aimed at selecting for high levels of enhanced heat tolerance by introducing foreign species or genera may cause large-scale ecosystem and environmental risks, such as altered species interactions, that may have uncertain long-term consequences. It is therefore useful to quantify the relationship between reef state and the impact of introducing foreign heat-tolerant species or genera into the reef system. This requires careful consideration of the roles different species play within coral reefs and an understanding of potential long-term consequences of altering ecosystem dynamics by introducing species.

As the potential for scaling up active coral reef interventions increases, research efforts must also increase to improve understanding of the ecological risks of such scale-ups (temporally and spatially). For example, it may be important to know if risks scale linearly, exponentially or remain flat. With this knowledge, models can be developed to assess how future large-scale interventions may impact local environments. A comprehensive understanding of the spectrum of potential impacts and implications at the targeted scale is essential for effective intervention design and risk management strategies.

Impact

- Builds understanding of benefits and risks before radical interventions may be used.
- Starting R&D now on more radical interventions is preferable to them being used in an uninformed or uncontrolled way.

PRIORITY AREA 2: Investigating the ecological risk of coral reef interventions

2.1 Create and maintain a database of known ecological risk types and studies, and produce a knowledge synthesis on the risks

Background / justification

Integrating rigorous literature reviews with accessible databases is a rapid way to bridge knowledge gaps, streamline conservation efforts and provide insights on risks for various stakeholders. This recommendation involves creating and maintaining a database of known ecological risk types and studies, including outcomes, conclusions, knowledge gaps and guidelines.

Summarising the range of ecological outcomes of active interventions (positive and negative) is vital to steer future research towards methods that maximise ecological benefits. Such a compilation would include assessing the spectrum of interventions (e.g., assisted evolution, reproductive, physiological, environmental, coral gardening, reef structure and stabilisation interventions) and their effects on coral ecosystems during R&D and implementation phases. This would enable informed decisions by practitioners, scientists and policymakers based on existing research (Fidelman *et al.* 2019; Gann *et al.* 2019). A checklist can be produced of which risks should be considered to assess research applications or which ecological risks need further investigation. Such a database will enable novel studies or experiments to be created that may improve our understanding of ecological risks.

Ongoing knowledge development would build on the current knowledge base created by this Roadmap and help practitioners make informed decisions in an environment of rapidly expanding information as interventions are researched, tested and reported in future.

Impact

- Database of known ecological risk types and studies for coral reef interventions.
- Builds on the database created by this Roadmap and foundational for other recommendations and tools.

Credit: Single Fin Photos

2.2 Develop risk assessment method and associated guidance, and apply to novel interventions

Background / justification

Developing and implementing comprehensive risk assessment methods and associated guidance is essential to identify, assess and quantify ecological risks, as well as increase stakeholder understanding. Risk assessment methods and check lists for all current and future coral interventions will facilitate informed decision-making and identify related risks.

While previous detailed manuals were developed for coral restoration (e.g., Goergen *et al.* 2020; Hein *et al.* 2020; McLeod *et al.* 2020; Shaver *et al.* 2020), workshop participants identified a need for easy-to-use risk assessment standards. These could be provided as guidelines, manuals, toolkits or decision trees and applied to established interventions (where gaps in understanding of risks is limiting) as well as emerging interventions.

Developing quantitative risk assessments can help estimate the likelihood of a risk occurring (NASEM 2019b). Intervention modelling can also estimate net benefits of one or more interventions compared to the cost of doing nothing (as in Condie 2022). Comparing action and in-action are further covered in recommendation 4.1.

Risk assessment projects should be tailored to specific countries and regions because the manifestation of ecological risks during research or implementation of an intervention depends on various factors (like 1.2, this recommendation supports the needs of lenses B and D, Table 2). These factors include the type and scale of interventions deployed or tested, details of the intervention design, the socio-economic context or motivations, and regional environmental conditions and biotic composition (NASEM 2019a, b; Fox *et al.* 2019; Bayraktarov *et al.* 2019; Bostrom-Einarsson *et al.* 2020; Razak *et al.* 2022; Banaszak *et al.* 2023).

Impact

- Frameworks (approach) and tools (guidance) for risk assessment and application to novel interventions.

Credit: The Ocean Agency

2.3 Regional studies on genetic risks

Background / justification

Workshop participants highlighted the potential genetic risks from research and implementing active interventions should be made an R&D priority so knowledge gaps do not delay or stop conservation actions.

An inexpensive R&D approach is a desktop study focused on identifying risk mitigation pathways for potential genetic risks, to improve intervention designs and adaptive management of coral reefs. For example, if outbreeding depression is a risk from large scale assisted migration, then this could be addressed directly by changing broodstock or using another Assisted Evolution method. Also see recommendation 3.3 on genetic management plans and principles.

If a high level of investment is available, specific experiments and *in situ* assessments to directly learn about potential genetic risks linked to interventions, could use the following two approaches:

First, conducting population genomic studies on 5-10 species in several coral reefs that span variation in reef conservation status and reef type in major coral region of the world. Where possible, model coral species with different reproductive and growth strategies should be targeted. Such in-depth studies would provide knowledge on genetic diversity, small scale population genetic structure, larval retention and connectivity, cryptic species, patterns of natural selection at the gene level, symbiont population structure, and microbiome makeup. Such large-scale studies on population genomics could be conducted in the proposed Genetics Centre (recommendation 1.4).

Second, by involving multiple research teams, coordinated large scale studies can help determine if genetic risks are already occurring (e.g., inbreeding from small populations of surviving corals), intervention plans are creating additional problems (e.g., outbreeding depression from assisted migration) or genetic differences across populations indicate unforeseen complications (e.g., hidden barriers to connectivity).

We note such studies would require multiple coral generations and many years' investment. Prior knowledge of the genetic risks associated with interventions (e.g., minimum breeding population sizes, small scale connectivity patterns, cryptic species) may make such a multi-generation investment pay off. With this in mind, field sampling and experimental work are to be conducted alongside extensive genetic modelling to monitor coordinated studies that address genetic concerns of active interventions.

Using these approaches, and with careful planning and monitoring, important genetic risk/benefit questions can be collectively and comparatively addressed. These projects should also collect data on variables that may influence risk levels, such as reef health status, environmental extremes and available reef protection mechanisms.

Prioritising coordinated projects on key genetic questions and sharing genetic resources and data to answer them increases collaboration and knowledge exchange among research teams.

Impact

- Accelerates R&D on genetic risks that otherwise prevent implementation using approaches like coordinated projects across multiple locations, and/or an in-depth study of genetic questions at key sites using model species.
- Could combine efforts from multiple teams to collectively address key risk / benefit questions, with the aim that the information is also broadly relevant across regions and intervention types.
- Supports advances in the sharing of genetic resources.

2.4 Studies on other key ecological risk-types

Background / justification

The workshop process and knowledge inventory identified several other key ecological risk-types as priorities for further R&D. For example, trait trade-offs, maladaptation, invasive-potential of corals with 'enhanced' traits such as heat tolerance, unintended effects on microbiome, and pests and disease risks associated with several types of interventions involving corals, aquaculture or moving structures around (as occurs in coral gardening). Examples of these ecological risks are described further in Box 4. We recommend desktop studies and research to better understand these intervention risks, especially if unknowns are preventing implementation of promising solutions, or might cause high residual consequences for environmental protection goals.

Impact

- Speeds up R&D on other key risk types such as trade-offs of attributes (e.g., heat tolerance and growth), maladaptation, invasive potential of 'enhanced' corals, disease or pests and unintended effects on the microbiome.
- Better understand intervention risks, especially if unknowns are preventing implementation or there might be high residual consequences for environmental protection goals.

Credit: Alex Tyrrell

Box 4. Examples of other ecological risks.

There is limited understanding of the extent to which maladaptation may limit the survival of transplanted corals and naturally dispersing larvae (as in Kenkel *et al.* 2015; Matz *et al.* 2018; Barreto *et al.* 2023).

For example, *Porites astreoides* was selected against (maladaptation) in the Florida Keys (Kenkel *et al.* 2015). In the Red Sea, *Porites lobata* had differential outplanting success due to a lack of local adaptations to environmental conditions other than temperature (Barreto *et al.* 2023). Acknowledging that natural selection will likely remove deployed corals that are maladapted, and the associated ecological risks are therefore likely to be negligible (but there will be a waste of resources if deployed stock is lost in this manner), further desktop review into maladaptation is recommended.

Assessing any trade-offs (e.g., growth, skeletal density, fecundity) in selecting for traits that enhance thermal resilience is also important (and also a recommendation from Bay *et al.* 2023). For example, stress-tolerant *Porites* corals in mangrove habitats were assessed for their assisted gene flow potential to cooler, offshore reef sites. The mangrove *Porites* population had reduced genetic diversity, reduced skeletal density and higher skeletal porosity. These are symptoms of metabolic energy redirection to stress response functions, demonstrating caution in their use as stress-tolerant corals in human interventions (Scucchia *et al.* 2023).

Similarly, corals with high bleaching resistance have been suggested as a source for habitat restoration or selective breeding to increase coral reef resilience to climate change. Where these resistant corals can be found, the existence of trade-offs with heat resistance may occur (e.g., low symbiont load, a trait which corresponded to bleaching-resistance, came at the cost of lower growth rates) and in turn this may suggest caution in unilateral use of this one trait in restoration (Cornwell *et al.* 2021). Selecting for high temperature tolerance may therefore have consequences for growth, health, tissue loss, recovery and low-temperature tolerance (Howells *et al.* 2013; Ladd *et al.* 2017, but see Lachs *et al.* 2023), indicating a need for caution when using stress-tolerant corals as interventions (Scucchia *et al.* 2023). Nonetheless, it may be acceptable to have slower growth rates if this means such corals will survive summer heatwaves.

For symbiont manipulations, associating with naturally thermo-tolerant symbionts can cause lower amounts of carbon translocation to the host, slower growth, lower host lipid stores and smaller eggs relative to associating with sensitive symbionts (van Oppen and Nitsche 2022). However, recent work on experimental evolution of common symbionts has shown significantly increased heat tolerance in both the symbiont and coral host, with little evidence of slower growth and other trade-offs in fitness-related traits (Chan *et al.* 2023; Quigley *et al.* 2023).

We recommend further small-scale studies, including desktop reviews, to assess the potential for fitness trait trade-offs from active interventions. Furthermore, if a suite of phenotypes of corals is measured (such as growth, symbiont load, symbiont stability, reproduction, disease and bleaching) in as many intervention experiments and different species as possible, then the trade-off between heat resistance and other phenotypes may be resolved more completely.

Invasiveness (e.g., from 'enhanced' corals and invasive species) and disease risks from translocations were also considered a priority for a desktop study, evaluation or developing predictive tools. Determining what can be learned about invasiveness in other systems and in coral reefs, can help evaluate factors that drive invasive-like risks. By identifying higher-risk scenarios and understanding earlier invasion incidents (e.g., algal introductions into Kaneohe Bay, HI, Lionfish in the Caribbean, *Tubastraea* corals in Brazil), projects can avoid these by better intervention designs/plans or implementing measures to safeguard coral reef ecosystems from invasive species.

Encouraging small scale tests for interventions include antibiotics (but see Connelly *et al.* 2022; Studivan *et al.* 2023), phage therapy (Cohen *et al.* 2013), antioxidants (Contardi *et al.* 2020) and probiotics (i.e., microbiome manipulations such as the application of beneficial microorganisms for corals; Zhang *et al.* 2021; Santoro *et al.* 2021; Peixoto *et al.* 2023). Recent work has even shown that probiotics can be administered to the coral microbiome *in situ* without affecting the surrounding environment (Delgadillo-Ordoñez *et al.* 2024).

Despite the initial success of small-scale tests, the extent to which chemical or biological treatment of corals is effective and scalable is poorly understood and not yet solved (Connelly *et al.* 2022). We recommend further laboratory-based R&D into the unintended and beneficial effects of topical treatments as interventions (reviewed in full by Epstein *et al.* 2019).

PRIORITY AREA 3:
Responding to risk (developing risk treatments)

3.1 Investigate screening tools or other technologies and treatments, which aim to prevent harm from diseases or pests

Background / justification

Investigating screening tools or other technologies and treatments to prevent harm from diseases or pests was covered in the workshop and stakeholder consultations. We recommend further developing such tools, some examples of which include coral dips and treatments as well as quarantining and veterinarian clearance procedures (Box 5). We encourage innovative approaches to screen for and detect diseases or known invasive species. This may include assays for bacterial loads, key pathogenic groups, or other measures of coral health. Coral-trained veterinarians do not attend many coral reef places so measures that need this level of scrutiny are only available in a small subset of places.

Genetic screening tools can also be developed to rapidly identify microbiome, algal, pest and invertebrate co-inhabitants that could potentially cause harm during translocations. This recommendation therefore links to the genetics centre (recommendation 1.4) and genetic/genomic analyses (recommendation 2.3).

Impact

- Database of known ecological risk types and studies for coral reef interventions.
- Builds on the database created by this Roadmap and foundational for other recommendations and tools.

Credit: Corinne Allen

Box 5. Example of screening tools in use.

As an example of how practitioners incorporate screening tools and coral-specific treatments, consultations with Mote Marine Laboratory & Aquarium were conducted about their process of moving corals from their lab-based nurseries to the wild for out-planting. To control pests, diseases and invasive species, veterinarian clearance and quarantining are Florida State mandates, and videos taken by microscopes are often used to evaluate corals exhibiting signs of disease or pest damage (e.g., ciliates). Therapeutic dips are then used to try to rid the corals of micro-pests such as amphipods, copepods and ciliates before being quarantined for a minimum of 30 days after the last symptoms are observed.

Research is on-going regarding the efficacy of these dips and coral treatments, which include essential oils, Lugol's solution, diluted hydrogen peroxide and/or antibiotics. Within their *ex situ* nurseries, they also use ozone to disinfect incoming natural seawater, which is a strong oxidizer and has the potential to oxidize organic materials while posing limited pathogenic stress to the corals themselves. Research leading to standard protocols for both these types of treatments is urgently needed.

If diseases do present themselves during this process, the affected corals and all corals in contact need to be quarantined for at least 30 days beyond the last clinical signs of disease and then undergo re-evaluation by a veterinarian before reallocation to the genebank nursery or the ocean. Similar quarantining procedures were noted from other US-based operations we consulted. This quarantine system presents challenges such as the need for all veterinarian clearance to be in person. This can impede the process of handling corals during emergency response events. However, these federal and state-level regulatory steps help put measures in place to respond to and reduce ecological risks during emergency response, triage, and outplanting phases.

These issues are not limited to large lab-based propagation projects. They also apply to other projects such as translocations of corals from distant reefs.

3.2 Develop intervention risk response plans, including R&D for clean ups of physical damage or removal of leftover structures

Background / justification

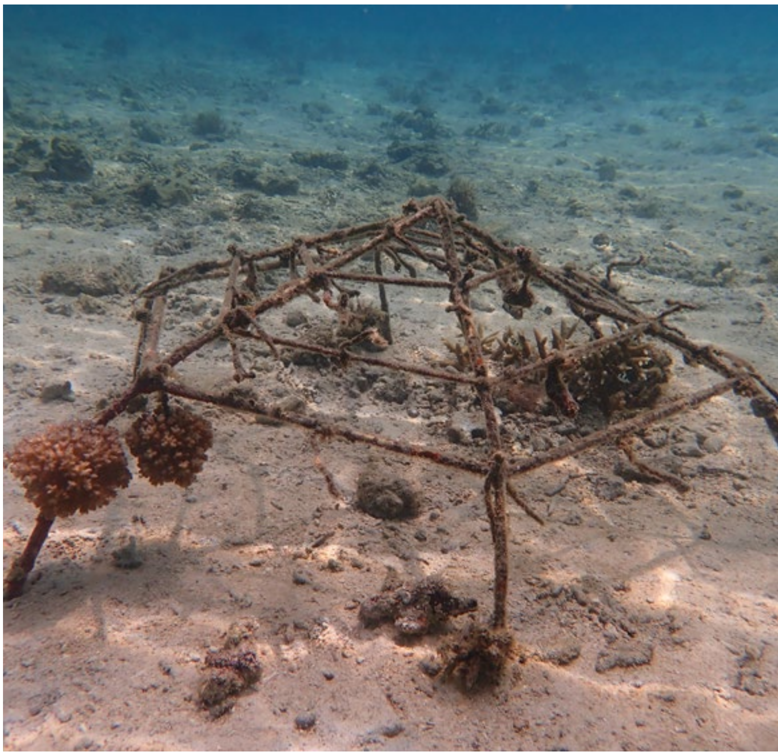
To effectively address certain types of risks during intervention implementation that are amendable to remediation, response options could be investigated, and plans prepared. Such plans would outline predefined steps to mitigate unintended adverse impacts and generate swift and effective action. They would employ adaptive management strategies to enable real-time learning and on-ground adjustments in recognition of the dynamic nature of restoration/intervention work (NASEM 2019b; Shaver *et al.* 2022). This involves continuously monitoring intervention results and a readiness to change direction if necessary (Goergen *et al.* 2020).

Risk response plans may have utility for projects involving physical structures like coral gardening or substrate stabilisation / addition (as in Razak *et al.* 2022). Protocols for clean-ups (e.g., removing leftover structures or addressing physical damage) would help treat risks to local reef habitat, uphold the reputation of the restoration field and prevent environmental littering resulting from some projects.

Impact

- Establishing protocols and contingencies for prompt response to risks such as physical damage during interventions.

Credit: Tries Razak



3.3 Develop regional genetic management plans and principles for more situations and places

Background / justification

Workshop participants noted developing regional genetic management plans and principles as an R&D priority. Science-based management of coral genetic resources and diversity for current and future reef conditions represents a vital way to optimise interventions and reduce associated genetic risks. Genetic management aims to preserve adaptive genetic diversity within species. As a principle, it parallels management for species diversity or species population sizes and is particularly important within degraded coral populations (Box 6) that are vulnerable to severe inbreeding, genetic drift, and local extinction.

As well as overall genetic variation, such plans and principles can detail how adaptive genetic variation is distributed for coral and symbionts, and use this information to inform interventions and deployment. Genetic management must encompass an array of species, locations and environmental conditions to secure genetic resources that preserve adaptive functions. Highlighting genetic variation that is adaptive in different settings is especially important for species facing environmental challenges.

Genetic management plans often start with catalogues of genetic variation at local and regional scales, and since many corals can fragment and regrow, there is a particular emphasis on numbers of genetically distinct coral colonies within an area (genets). Genetic management strategies protect current genetic diversity and aim to restore endangered coral populations to levels conducive to natural selection and adaptation (Baums *et al.* 2019; Hein *et al.* 2020; Shaver *et al.* 2020).

Regions with strong genetic clines (e.g., over depth or distance) can signal the existence of adaptive genes, mark areas with low gene flow or help discover cryptic species. Genetically unique populations (based on host or symbiont genes) can be targets for management protection, particularly if those populations are associated with beneficial coral traits such as heat resistance or high growth. These genetic maps can be a sourcing tool for translocation of corals to other parts of the reef, and can be used to design interventions that don't disrupt this kind of adaptive framework.

A different type of genetic management may be needed for severely depleted populations. In these cases, each colony may represent such a critical genetic resource that strong preservation tools (i.e., cryopreservation), emergency response protocols like bio-banking in aquaria, growth and export of fragments, gamete preservation, and other rapid response tools may be needed.

Specific use of some interventions may require ongoing genetic monitoring, such as mixed-provenance approaches or stepping-stone translocations (as in Bartz and Brett 2017; Baums *et al.* 2019). Such ideas are reviewed in Box 6. These strategies need to be developed in the context of specific reefs, the state of coral populations there and the proposed interventions, and factors like local genetic stock and future environmental changes taken into consideration.

Plans must also account for the varied socio-economic contexts to which they may be applied. This includes considering the local biotic and abiotic environment, and how genetic management plans and principles apply to the goals local people have for their coral reef resources.

These plans would benefit from sound current knowledge of genetic diversity and population structures at small and large spatial scales, as well as projections of how these genetic diversity and structure may evolve in response to ongoing deterioration and climatic disturbances (advocated for in Rinkevich 2019; Vardi *et al.* 2021).

Impact

- Science-based management of coral genetic resources and diversity for current and future reef conditions is a vital way to optimise interventions and reduce associated genetic risks.
- Develop genetic management plans for more regional contexts.

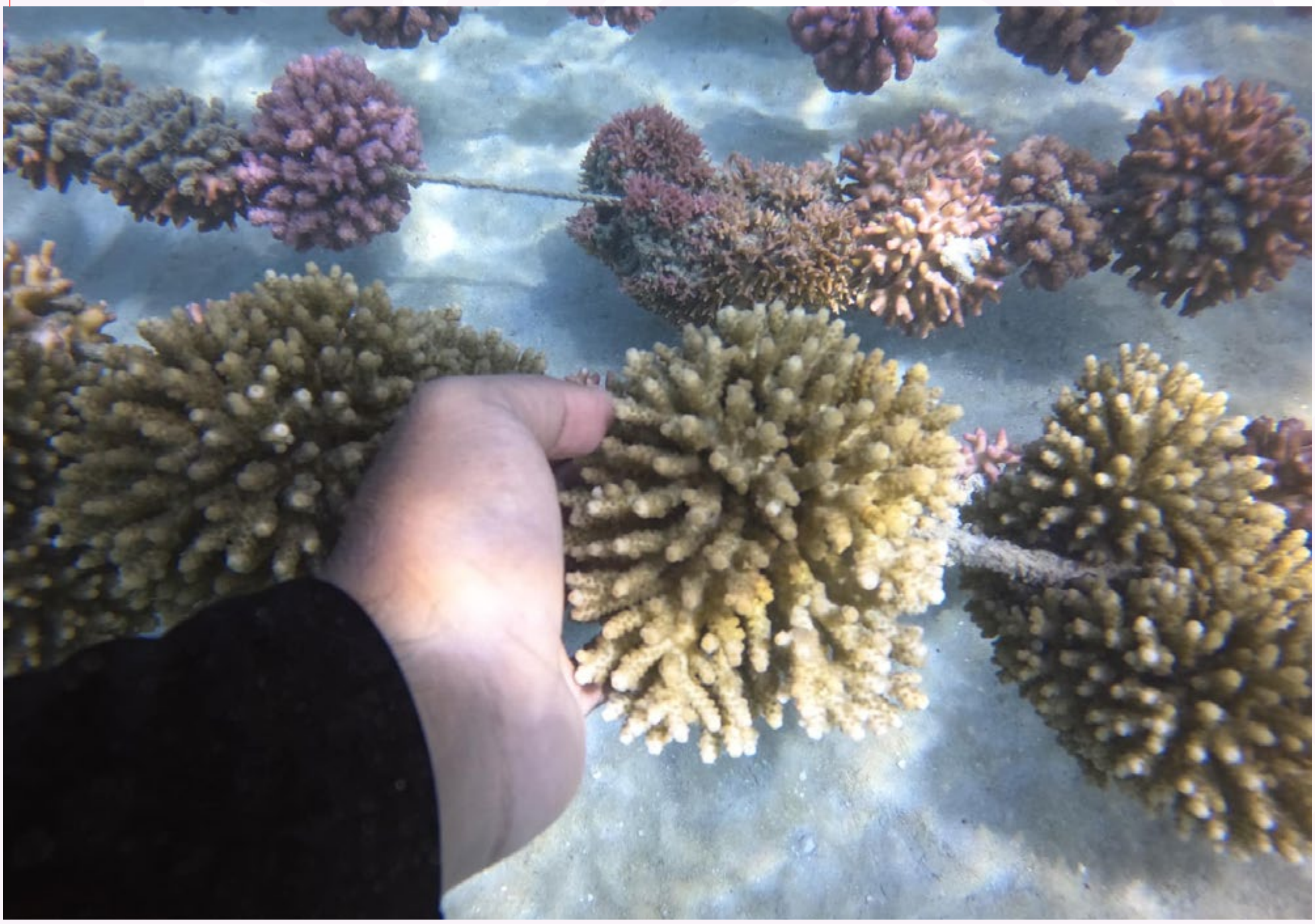
Box 6. Previous genetic management plans.

These plans serve as guides to navigate the complexities of genetic conservation and the intricate dynamics of coral populations and provide essential direction to help maximise benefits and mitigate genetic risks associated with interventions, like coral gardening and translocations (as in Baums *et al*. 2019; 2022).

The plans may guide genetic management issues such as determining the minimal threshold of acceptable genetic diversity for particular coral-centric interventions. They can do this by determining the number of genotypes needed for natural selection and adaptation to bolster climate resilience. Guidance may vary across species, locations and population histories.

Preceding population genetic management principles advocated for a mixed-provenance strategy in the Western Atlantic, sourcing genetically unique colonies locally and from environmentally distinct sites (Baums *et al*. 2019). Intentionally promoting gene flow within a diversified provenancing strategy helps avoid unintended genetic risks such as inbreeding and outbreeding depression (Baums 2008). Such translocations may incur disease and invasive risks, which would need to be tangentially assessed and managed. Limiting the distance between coral translocation sites has also been suggested to mitigate the risk of outbreeding depression (Bartz and Brett 2017).

Credit: Austin Bowden-Kerby



PRIORITY AREA 4: Supporting decision making and communications

4.1 Develop estimates and narratives of 'do nothing' risks for more regions

Background / justification

Anthony *et al.* (2020) suggested that coral reef interventions should be implemented when their long-term benefits outweigh the costs associated with the intervention, taking into account the costs associated with inaction. This is particularly relevant when risks of inaction continue to climb as climate change impacts increase. In such cases, inaction may eventually be more costly than an intervention, even if the intervention has high costs or risks. Essentially, an intervention must be evaluated for its overall value (benefit minus costs) and whether this value is higher than the cost of doing nothing. For instance, interventions like assisted migration have potential risks (e.g., spread of pathogens). But in some cases, these risks might be far lower than the risk of climate-driven extinction and ecosystem loss (McLeod *et al.* 2019).

Developing estimates and narratives of 'do nothing' risks (sometimes using an approach technically called 'counterfactual modelling') is important to gauging which risks are worth taking for intervention implementation (Peterson and Bode 2020; DeFilippo *et al.* 2022).

Counterfactual modelling estimates the outcome without the intervention (i.e., the risk of doing nothing to solve a growing problem). In some countries it informs quality decisions to guide investment and action (Riegl *et al.* 2013; Condie *et al.* 2021; Condie 2022). However, these techniques are often outside the ability of many restoration projects in regions without in-house modelling capabilities (especially applicable to lenses B and D; Table 2).

Providing estimates and narratives of 'do nothing' risks for regions without such capacity would democratise access to crucial information, enabling regions with limited resources to make more informed decisions about coral reef conservation. Such projects could consider cost-benefit analyses of ecological risk in relation to existing socioeconomic factors. Local environmental conditions may be derived from established regional estimates and applied to predictions of reef health (e.g., heatwaves).

Impact

- Provides estimates and narratives for regions with limited in-house modelling capabilities.
- Estimates the costs of inaction or delayed action from a range of perspectives.

Credit: Hannes Klostermann

4.2 Investigations and field trials that generate critical data for decision-makers on intervention performance and ecological risk likelihood

Background / justification

Workshop participants identified the need for investigations and field trials (short and long term) to collect critical data that can't be obtained in the laboratory or within mesocosm settings. Field trials are part of the intervention development pathway and are also part of how risk is managed and quantified (i.e., field trials may be a preferred step before full proposals for implementation at scale).

Mapping the knowledge requirements necessary to understand ecological and genetic risk and intervention performance (to meet environmental protection requirements of decision-makers) can bridge existing gaps in assessing interventions. Investigations and field trials can then be used to obtain this knowledge.

Funding and allowing field trials over extended periods would increase learning about the benefits and risks as a result of more continuous monitoring and data collection across coral generations (see Box 7). For example, longer term funding and field support are likely to improve predictive models of coral adaptation (e.g., Peterson and Bode 2020; Quigley and van Oppen 2022, Bay *et al.* 2023). Predictive models may rely on parameters such as genetic diversity, number of genes coding a particular trait (and resulting genetic variance), connectivity, mutation rate, growth, survival, fecundity and population size (e.g., Matz *et al.* 2020; McManus *et al.* 2021; Torda and Quigley 2022, Bay *et al.* 2023).

Longer and richer time course data would improve estimates of model parameters. For example, longer time-courses would provide more opportunities to collect vital coral traits across various life stages (e.g., larvae, recruits, adults) and generations (parental generation, F1, F2 etc.). This would improve intervention performance assessments. Data and learning also support a managed-risk approach to interventions and a staged approach to intervention research and trials.

Impact

- This data improves predictive models and supports a managed-risk approach to interventions.
- Also informs important traits of corals across life stages and generations to inform intervention performance.

Credit: © AIMS | Jo Hurford

Credit: Mark Gibbs

Box 7. Limitations for long term field trials.

Regarding risk mitigation during the R&D phase, we consulted a researcher who conducted selective breeding and symbiont manipulation studies on the Great Barrier Reef (GBR). They selectively bred corals across the GBR and monitored their survival, as well as other key traits, in the wild (Quigley *et al.* 2021). The permit process required them to assure the regulator that the biological material was safely contained within their research site.

To accomplish this, only juvenile corals were physically secured using a range of methods to the substrate. This substrate had to be a sandy patch some distance away from any adjacent reef. The expectation provided by the manager was that if the young corals were dislodged, they would not survive or be able to settle onto a hard-substrate reef. The corals also had to be removed before reaching reproductive maturity, which meant corals were in place for about a year. Although a risk-reducing option for the early stages of risk management, such a control measure presents a challenge for understanding long-term pros and cons of interventions.

To clarify, removing the 'recruits' after a year reduces invasive and genetic ecological risks (e.g., invasive potential and gene swamping) of the trial but makes it difficult to obtain critical data on risks and benefits (Torda and Quigley 2022) which the selectively-bred corals may have as they grow. It also prevents collection of other key data (e.g., growth, fecundity) that could inform future risk assessments and interventions.

4.3 Synthesise science and illustrate concepts and technologies that support risk communications and target key stakeholders

Background / justification

High quality science communications offer a way to improve the coherence, impact and reach of projects and programs. We are dealing with complex subject matters. Audiences may be unfamiliar with key concepts that underpin the intervention technologies being investigated, the coral holobiont, how coral reef systems work, or how ecological risks arise and the factors influencing risk levels.

An example of a communications challenge is that risk evaluation is often difficult to explain to a lay audience. Nevertheless, it is important researchers communicate clearly about the limits of models and what they suggest, so that local managers can make effective decisions. Another challenge identified by stakeholders is a lack of accessible materials on key concepts.

Workshop participants identified a high need for science communication projects. This will give diverse stakeholders (such as fishers, politicians, regulators, restoration practitioners, users and scientists) accessible information on intervention technologies, key concepts and ecological risk management (applicable across all identified lenses; Table 2).

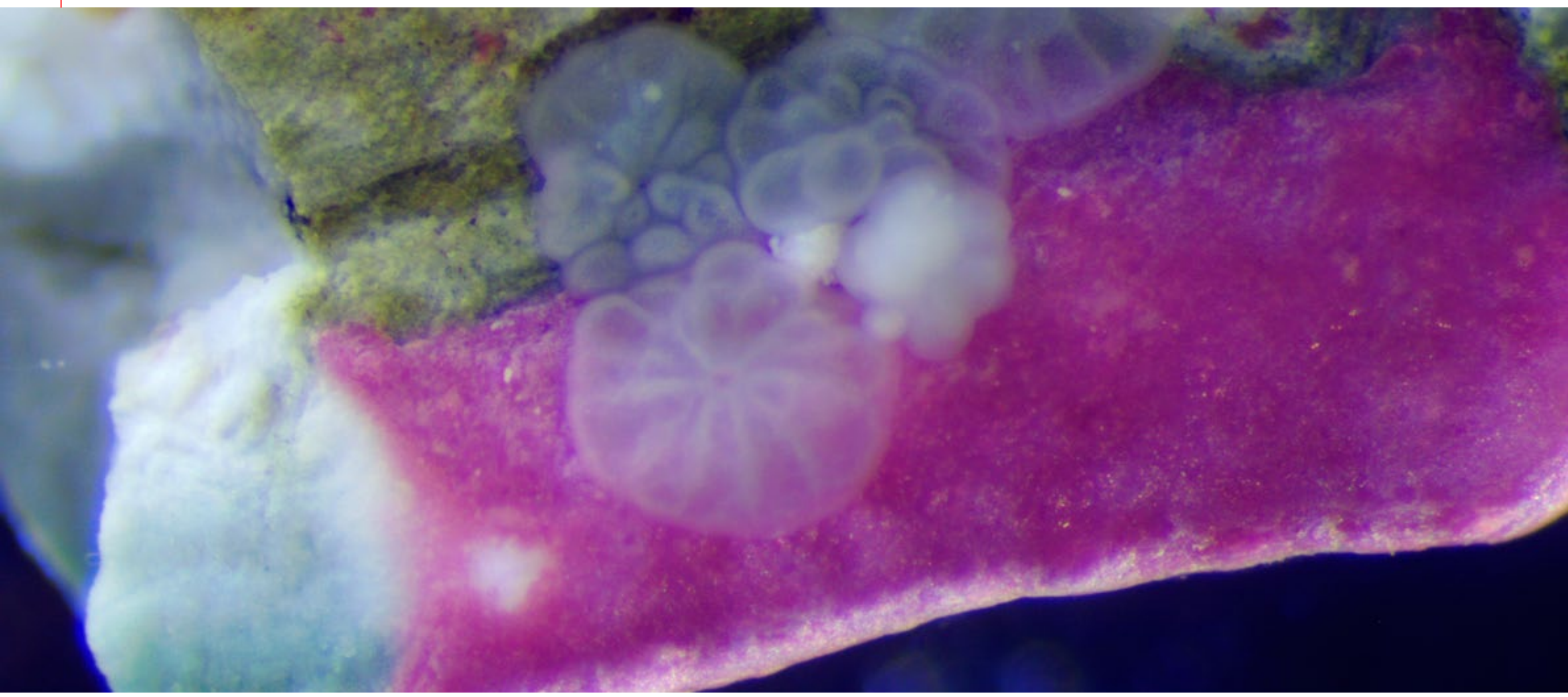
By creating tailored materials and good visuals of key concepts, this initiative promotes a greater understanding of coral and ocean literacy, the intervention techniques and risk concepts within stakeholder groups and supports regulatory processes.

Creation of science communications content and products could illustrate novel coral interventions and support risk communications for better decision-making. By presenting intervention and ecological risk management science in ways that are engaging and easy to understand, stakeholders will be more able to value coral reef restoration efforts. As well as promoting transparency and accountability, this initiative fosters collaboration and engagement among sectors involved in coral reef conservation. It may also stimulate interest in the R&D priorities from other funders and a wide audience of R&D providers (e.g. from outside of reef sciences).

Impact

- Creation of science communications products that provide a broad overview of ecological risk management and active interventions as applied to coral reef settings.
- Promotes improved coral and ocean literacy and may also stimulate broad interest in the R&D priorities.
- Greater coherence, impact and reach of projects and programs.

Credit: © AIMS | Cathie Page



4.4 Perform a knowledge review of conservation genetics and intervention principles from terrestrial or other marine systems that could be applied to corals and coral reefs

Background / justification

Terrestrial and marine systems other than coral reefs (e.g., kelp, seagrass) have long employed genetic tools to understand biodiversity, conserve species, manage genetics, and enhance resilience to climate change. By reviewing these projects, researchers can identify methodologies and strategies that could be adapted for coral reef interventions (see Box 8).

Given the relevance of terrestrial conservation and other marine systems, and the critical lessons which can be learned from these programs, the workshop recommended funding a desktop study or workshop process to review pertinent and applicable conservation projects and principles which may be transferable to coral reef conservation and interventions. This may involve working with conservation planners and reef managers to develop guidance.

Impact

- This knowledge informs conservation genetic principles and intervention guidance for corals and coral reefs.

Credit: Martin Colognoli

Box 8. Some lessons learned from terrestrial restoration.

Terrestrial ecological risk assessment frameworks were previously developed to inform translocations and assisted migration efficacy for conservation managers (Weeks *et al.* 2011). Even though these were developed for terrestrial conservation, the guidance has applicability for marine settings and in the absence of detailed information on the reproductive biology and genetics of the species concerned (see Figure 2 in Weeks *et al.* 2011). Other examples of learning include coral gardening approaches, which were also appropriated from silviculture techniques developed for terrestrial conservation (Rinkevich 2005), and tropical terrestrial restoration principles have been explored to restore coral function and resilience (Bowden-Kerby 2023).

Credit: Corinne Allen

4.5 Convene specialist workshops and working group(s) on intervention risk

Background / justification

There is an ongoing need to foster collaboration between academics, restoration practitioners, NGOs, and government agencies through workshops or working groups to address emerging issues in intervention risk. Including information from traditional ecological knowledge may be important to this process in many settings.

Establishing a community of practice approach, which convenes stakeholders to discuss the field, can facilitate knowledge exchange and improve risk management. The community of practice would exchange knowledge on interventions and the associated risks and benefits, and develop advice and support for intervention management and responsible R&D.

Sustaining such collaborative efforts can also occur through specialist workshop processes or ongoing working groups on intervention risk, even if for a limited duration. Workshop participants recognised the value of processes in Australia and the USA that have advanced the understanding of intervention risks. Continued international engagement on managing intervention risks would improve technologies and solutions and support informed decision-making about intervention implementation.

Impact

- A community of practice approach that exchanges knowledge on intervention risks and develops advice and support for regulating and managing interventions, and responsible R&D.
- Builds on this Scoping Study process and other related activities, including those in Australia and the USA.

Credit: Anderson Mayfield

PRIORITY AREA 5: Developing emergency responses

5.1 R&D to investigate options and trial innovative approaches for *in situ* or *ex situ* securing of genetic resources and species

Background / justification

We recommend supporting projects that investigate and develop guidance for further emergency responses and triage measures for corals. Emergency response and triage projects need to be region-specific and develop risk management protocols as part of these plans.

In developed areas, risk management protocols may include guidance on rapidly moving wild corals to public or private aquaria (i.e., short-term *ex situ* securing of genetic resources; Mayfield *et al.* 2019), managing for health, pest and disease risks and developing triage responses for practitioners (e.g., the *Protect, Rescue, Monitor mode* developed by the Coral Restoration Consortium (CRC) and the International Coral Reef Initiative (ICRI); Box 9).

Like other recommendations in this Roadmap, work must begin by engaging First Nations groups and the local community where appropriate, to obtain social approvals and increase understanding.

Emergency approaches are most likely to be achievable in regions with strong aquaculture resources and clear science infrastructure. For example, there are many regions in the Pacific with existing giant clam nurseries or hatcheries, which could be designated as 'emergency' gathering areas for corals. We also recommend further work to investigate options such as gene banking in lab settings, private aquaria and possibly in freezers, to preserve genetic resources and species.

Advancing and refining *ex situ* gene banking tools like cryopreservation are pivotal for emergency responses. Cryopreservation involves flash-freezing coral reproductive tissues, larvae and even symbionts (from freshly isolated or cultured material) to preserve crucial genotypes in genetic banks (Bay *et al.* 2019; NASEM 2019a; Daly *et al.* 2022). Research on reviving cryopreserved larvae, adult tissues, and algal symbionts is underway, with success varying across species. Nonetheless, this a key area for research that may enable wider use of this tool and help secure genetic resources across a wider geographic scope.

Investigating options and trialling innovative approaches for emergency responses to secure key genetic material held in *in situ* nurseries applies to almost all regional perspectives explored in the workshop. Mote, the Coral Restoration Foundation (CRF) and other practitioners in the Caribbean and Pacific discussed using shade cloths for coral nurseries. They also considered developing systems to move nurseries up or down in the water column to maximise light penetration in winter or avoid excess heat stress in summer.

The ability to create such modifications depends on many factors, including how stratified the water column is, zoning and regulatory requirements, biological constraints of the corals being grown and practical considerations to support diving operations to certain depths. Some are also subject to strong risks of trash production from cloths, wave damage to coral elevators and scalability issues. For example, a square meter of shade cloth weighs about 255 grams (9 ounces), so a reef sized cloth of 10x100m would add a quarter ton of cloth to a reef.

Beyond technical developments, guidance for *in situ* gene bank nurseries can also include ecological considerations. A key question is whether nurseries with larger numbers of species fare better than monocultures. Questions also include the value of using only 'corals of opportunity', responsibly pruning from other intact colonies to avoid damage to the donor, the role of colony spacing, dealing with disease outbreaks and susceptibility, coral predators (e.g., damselfish, CoTS, other invertebrate and vertebrate corallivores), and algal and other organismal overgrowth and competition. Best practices are likely to be highly specific to location so one goal would be to train local coral managers on how to conceive and conduct proper tests so that local restoration is as successful as possible.

Implementing best practices for both *ex situ* and *in situ* gene banking requires research to optimise techniques for coral collection, storage and revival to maximise the survival of genetic resources. This enables a proactive approach to genetic conservation and the securing of high value colonies and broodstock during emergencies, such as extreme marine heatwaves.

Impact

- Reduces loss through region-specific triage and emergency response measures.
- Increases preparedness for genetic rescue.
- Increases preparedness for marine heatwaves and securing high value coral colonies and broodstock, nurseries etc.

Box 9. Emergency response measures.

In Florida and the wider Caribbean, and some other regions, devastating impacts in 2023 of marine heatwaves have pushed restoration practitioners to develop emergency response plans. For example, emerging protocols for risk management during extreme stress events have been developed by the CRC and ICRI. Within this directive, during thermal stress events both organisations encourage coral restoration practitioners to stop restoration activities and shift to 'protect, rescue, monitor mode'.

Other emergency response plans from the CRC include urging practitioners to prepare before the heat wave reaches the location of concern. This involves checking NOAA's Coral Reef Watch, speaking to local authorities in advance to see if permission is required to move corals during extreme thermal events, and lastly, developing or referencing a monitoring plan like the *CRC Coral Reef Restoration Monitoring Guide*.

Emergency response measures and triage for corals during extreme stress events was also discussed among stakeholders in our consultations. Consultation with the CRF noted that during the 2023 marine heatwave, a rapid and coordinated effort occurred with NOAA to move as many remaining important genotypes as possible for priority coral species to *ex situ* gene bank nurseries. Such an effort involved moving corals to multiple aquaria such as Mote Marine Laboratory, the Reef Institute and the Keys Marine Lab.

Triaging corals to public and private aquaria have several risks, including the potential for domestication to aquaria conditions and risks that corals may pick up pests, pathogens or diseases. Examples for how these risks can be handled in such *ex situ* nurseries were described in recommendation 3.1, Box 5). If no action is taken, risks may be more extreme and corals may be unable to survive.

In 2024, in Fiji, over 1,300 whole coral colonies of multiple genera were translocated from shallow stressed reef areas as a precautionary measure as a major marine heat wave approached. The effort was considered successful because the temperature of the shallow hot pockets peaked at 35 °C, with an estimated 90% of corals severely bleached and an estimated 80% mortality rate, while all translocated corals survived in the unshaded nursey with no bleaching observed. The nursery remained below 33 °C. A large collection of diverse corals were therefore secured.

For coral populations located in extreme shallows, a 'hot tub' thermal layer often forms during summer low tides. Lethal temperatures are an increasing threat in these shallowest reef areas during marine heat waves. Corals For Conservation's (C4C) unpublished work has shown that the immediate future of these shallow heat adapted coral populations may be secured in the face of approaching marine heat waves by simply moving them into nearby waters about 1-2 m deeper. Moving jeopardised corals locally is of low or no risk compared to leaving them to die. The potential of using jeopardised heat-adapted coral populations to facilitate coral reef adaptation has generally been overlooked and this opportunity may soon be gone.

Urgent predation-reduction measures were also implemented post-bleaching in Fiji to secure bleaching resistant survivors from CoTS and other predators. This strategy aims to reduce the threat from over-abundant predators to surviving heat adapted corals due to skewed predator-to-prey ratios that can result after mass mortality events (Bowden-Kerby 2023).

5.2 Undertake trials and experiments using disturbance as a natural laboratory to fast-track learning

Background / justification

Natural bleaching events and other disturbances can have devastating impacts on coral health but may offer opportunities to accelerate learning (see Box 10). Workshop participants discussed the potential to undertake trials and experiments using disturbance as a natural laboratory to fast-track learning.

For example, testing interventions (e.g., assisted migration, managed selection, holobiome manipulations, physiological interventions) in this way enables assessment of whether the adaptive intervention confers higher environmental tolerance to the corals during prolonged stress events in real world settings. This critical information helps understand the balance of benefits and risks, and advance technologies for coral reefs.

Tactical, rapid-response funding is needed to facilitate such projects and regulatory processes would need avenues that allow rapid implementation of field trials during stress events (particularly bleaching and disease outbreaks). This may require regional mechanisms for cooperation in coral conservation among agencies (e.g., for assisted migration) and could speed up delivery of new interventions and technologies.

Impact

- Accelerates learning and delivery of new interventions and technologies.
- Builds regional mechanisms for cooperation in coral conservation.

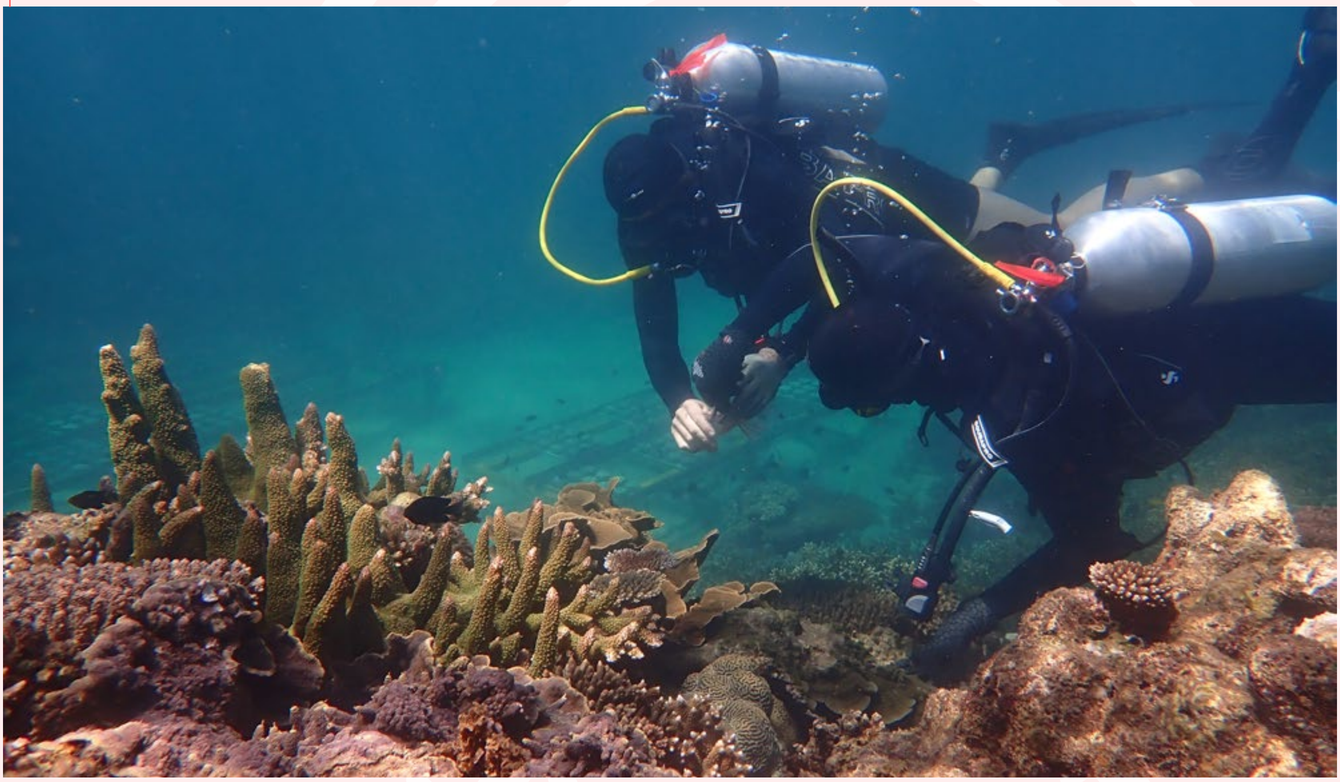
Credit: Austin Bowden-Kerby

Box 10. Using disturbance as a natural laboratory to fast-track learning.

In 2023 and 2024 during mass bleaching events in Fiji, Corals For Conservation (C4C) carried out coral collection and local-scale translocation of corals from highly impacted coral populations before, during, and after the mass bleaching phase. These activities used the disturbance event as a natural laboratory to fast-track learning. Coral populations suffered high levels of bleaching-induced mortality, and the corals used by C4C were subsequently collected before the partially bleached corals had a chance to recover. This approach enabled coral bleaching to become the primary means of selecting corals for their bleaching resistance.

Coral collection began as soon as the water temperatures began to decline, and targeted whole colonies or large sections of colonies to lower the stress of fragmentation, as UV levels remained high. These unbleached heat-adapted survivors were secured within gene bank nurseries in slightly cooler-water and became broodstock for facilitated adaptation work based on patch nucleation. The gene bank nurseries were therefore mostly composed of adult colonies, established on elevated mesh tables in moderately stressed waters 1-2 m deeper and about 2 °C cooler. With C4C's Reefs of Hope strategies, the goal is to keep heat-adapted corals within the natural stress regimes where they evolved, which may now require local scale translocation as thermal conditions shift due to warming oceans. As global warming progresses, the location of the C4C's gene bank nurseries may also need to shift, and opportunities to use disturbance events for fast-tracking learning are anticipated to increase.

Credit: Corinne Allen



Summary tables of the R&D recommendations

A snapshot of the recommendations is provided in Tables 3 to 7.

Table 3.
PRIORITY AREA 1: Responsibly fast-tracking interventions

Impact	Delivery mechanism	Priority
1.1 Responsibly fast-track investigations, development and trials for the most promising interventions while managing risks		
• Risk avoidance for corals and reefs by accelerating all R&D phases (from novel early-phase ideas to final proof-of-concept development and testing) for the most promising interventions. • Conservation benefits obtained by co-applying lower risk interventions as part of integrated approaches. This also includes investigating further applications of promising intervention solutions, while managing ecological risks.	• Develop project proposals based on Roadmap recommendation(s) for open calls.	Medium
1.2 Develop guidance, build capacity and provide training on available and emerging interventions, with a focus on ecological risk management		
• Knowledge sharing supports local implementation of interventions in more regions and encourages best practices. Directly delivers on the highest priority identified for the Western Indian Ocean, with broader applicability for and beyond the Global South. • Targeted training programs enable greater engagement on identifying, communicating and managing risks among diverse stakeholder groups.	• Partner with, or lead by others (e.g., Coral Restoration Consortium, CRC) to develop projects. • Aligned with and informs new CORDAP Capacity Development Scoping Study (March 2024).	High
1.3 Investigate and optimise approaches for translocating corals for conservation and adaptation purposes		
• Supports a managed-risk approach to advance interventions involving translocations. This includes assisted evolution methods and triage measures such as moving corals from hotspots to secure genetic resources in a planned, proactive way rather than during an emergency. • Optimise approaches on how to move corals and/or their symbionts over large scales and manage associated risks. Could also inform rescue of genetic resources and populations in emergencies.	• Develop project proposals based on Roadmap recommendation(s) for open calls.	High

Table 3.
PRIORITY AREA 1: Responsibly fast-tracking interventions

Impact	Delivery mechanism	Priority
1.4 Global coral genetics centre and global coral genetic management		
• A central facility that provides whole genome sequencing on all coral holobiont constituents and bioinformatic analyses via intuitive and accessible data interfaces. • The broad swath of data generated from a global genetic management centre would benefit all regions, regardless of their socio-economic status. The centre would therefore guide and monitor reef interventions and improve global understanding and management of associated genetic, disease and invasive-related risks. • The centre would also standardise molecular tools for corals (including the animal host, symbiotic algae, bacteria, and other microbes) and make the tools and data accessible to all, including CORDAP projects. By providing coral, symbiont and microbial genome data, the centre could facilitate comparative studies and answer fundamental and applied questions of local and global significance.	• Seek to secure new investment in cooperation with key partners to establish and operate a Global Coral Genetics Centre.	High
1.5 Optimising the generation and use of knowledge on heat tolerance and other traits, filling critical knowledge gaps on field performance of enhanced corals and supporting the advance of existing and new technologies		
• Aligns to recommendations relevant to managing ecological risks from Bay *et al*. 2023 • Identify those assisted evolution methods that can provide higher impacts in terms of coral heat tolerance enhancement and improve our understanding of associated risks.	• Develop project proposals based on Roadmap recommendation(s) for open calls.	Medium
1.6 Develop guidance on species selection relevant to specific intervention types or combinations of interventions		
• Better understand how species choices affect ecological outcomes and risks. • Improves intervention designs and plans, and feeds into genetic management and ecosystem planning (discussed further in recommendation 3.3).	• Develop project proposals based on Roadmap recommendation(s) for open calls.	Medium
1.7 R&D into additional radical intervention options including evaluation of potential benefits and risks		
• Builds understanding of benefits and risks before radical interventions may be used. • Starting R&D now on more radical interventions is preferable to them being used in an uninformed or uncontrolled way.	• Develop project proposals based on Roadmap recommendation(s) for open calls.	Medium

Table 4.
PRIORITY AREA 2: Investigating the ecological risk of reef interventions

Impact	Delivery mechanism	Priority
2.1 Create and maintain a database of known ecological risk types and studies, and produce a knowledge synthesis on the risks		
• Database of known ecological risk types and studies for coral reef interventions. • Builds on the database created by this Roadmap and foundational for other recommendations and tools.	• Develop project proposals based on Roadmap recommendation(s) for open calls. • This Scoping Study and the team at AIMS and CEFAS have progressed this by developing an initial database. It is worth keeping the database updated with new knowledge, which is why it is included here. Can be progressed as a desktop activity.	High
2.2 Develop risk assessment method and associated guidance, and apply to novel interventions		
• Frameworks (approach) and tools (guidance) for risk assessment and application to novel interventions.	• Develop project proposals based on Roadmap recommendation(s) for open calls. • Work has progressed under RRAP in Australia, and CRC in the USA, however further R&D is recommended.	High
2.3 Large studies on genetic risks		
• Accelerates R&D on genetic risks that otherwise prevent implementation using approaches like coordinated projects across multiple locations, and/or an in-depth study of genetic questions at key sites using model species. • Could combine efforts from multiple teams to collectively address key risk / benefit questions, with the aim that the information is also broadly relevant across regions and intervention types.	• Develop project proposals based on Roadmap recommendation(s) for open calls. • Desktop studies, and experimental research and investigations to understand these potential risks and develop risk mitigation options.	Medium
2.4 Studies on other key ecological risk-types		
• Speeds up R&D on other key risk types such as trade-offs of attributes (e.g., heat tolerance and growth), maladaptation, invasive potential of 'enhanced' corals, disease or pests and unintended effects on the microbiome. • Better understand intervention risks, especially if unknowns are preventing implementation or there might be high residual consequences for environmental protection goals.	• Develop project proposals based on Roadmap recommendation(s) for open calls. • Desktop studies, and experimental research and investigations to understand these potential risks and develop risk mitigation options.	High

Table 5.
PRIORITY AREA 3: Responding to risk (developing risk treatments)

Impact	Delivery mechanism	Priority
3.1 Investigate screening tools or other technologies and treatments which aim to prevent harm from diseases or pests		
• Reduce the risks of diseases and pests in intervention activities to as low as reasonably practical.	• Develop project proposals based on Roadmap recommendation(s) for open calls. • This also links to Genetics Centre (1.4) above.	Medium
3.2 Develop intervention risk response plans, including R&D for clean ups of physical damage or removal of leftover structures		
• Establishing protocols and contingencies for prompt response to risks such as physical damage during interventions	• Develop project proposals based on Roadmap recommendation(s) for open calls.	Low - Medium
3.3 Develop regional genetic management plans and principles for more situations and places		
• Science-based management of coral genetic resources and diversity for current and future reef conditions is a vital way to optimise interventions and reduce associated genetic risks. • Develop genetic management plans for more regional contexts.	• Develop project proposals based on Roadmap recommendation(s) for open calls. • This also links to Genetics Centre (1.4) above.	High

Table 6.
PRIORITY AREA 4: Supporting decision making and communications

Impact	Delivery mechanism	Priority
4.1 Develop estimates and narratives of 'do nothing' risks for more regions		
• Provides estimates and narratives for regions with limited in-house modelling capabilities. • Estimates the costs of inaction or delayed action from a range of perspectives.	• Develop project proposals based on Roadmap recommendation(s) for open calls. • This also links to synthesis and communications (4.4) below.	Medium
4.2 Investigations and field trials that generate critical data for decision-makers on intervention performance and ecological risk likelihood		
• Aligns to some recommendations relevant to managing ecological risks from Bay *et al.* 2023 • This data improves predictive models and supports a managed-risk approach to interventions. • Also informs important traits of corals across life stages and generations to inform intervention performance.	• Develop project proposals based on Roadmap recommendation(s) for open calls.	Medium
4.3 Synthesise science and illustrate concepts and technologies that support risk communications and target key stakeholders		
• Creation of science communications products that provide a broad overview of ecological risk management and active interventions as applied to coral reef settings. • Promotes improved coral and ocean literacy and may also stimulate broad interest in the R&D priorities. • Greater coherence, impact and reach of projects and programs.	• Develop project proposals based on Roadmap recommendation(s) for open calls.	High
4.4 Perform a knowledge review of conservation genetics and intervention principles from terrestrial or other marine systems that could be applied to corals and coral reefs		
• This knowledge informs conservation genetic principles and intervention guidance for corals and coral reefs.	• Conducted via a small desktop study or workshop process.	Medium
4.5 Convene specialist workshops and working group(s) on intervention risk		
• A community of practice approach that exchanges knowledge on intervention risks and develops advice and support for regulating and managing interventions, and responsible R&D. • Builds on this Scoping Study process and other related activities, including those in Australia and the USA.	• Conducted via a specialist workshop or working group.	High

Table 7.
PRIORITY AREA 5: Developing emergency responses

Impact	Delivery mechanism	Priority
5.1 R&D to investigate options and trial innovative approaches for *in situ* or *ex situ* securing of genetic resources and species		
• Reducing losses through region-specific triage and emergency response measures. • Increases preparedness for genetic rescue. • Increases preparedness for marine heatwaves and securing high value coral colonies and broodstock, nurseries etc.	• Develop project proposals based on Roadmap recommendation(s) for open calls. • Aligns with and informs upcoming CORDAP Scoping Study on emergency responses.	Medium
5.2 Undertake trials and experiments using disturbance as a natural laboratory to fast-track learning		
• Accelerates learning and delivery of new interventions and technologies. • Builds regional mechanisms for cooperation in coral conservation.	• Develop project proposals based on Roadmap recommendation(s) for open calls. • Aligns with and informs upcoming CORDAP Scoping Study on emergency responses.	Medium

Credit: Fabrice Dudenhofer

Credit: Corinne Allen

Broader considerations and conclusions

In summary, our Roadmap advocates to advance coral reef active interventions and highlights the urgency of immediate and innovative approaches to address ongoing challenges facing coral reefs. As coral reefs continue to decline, there is a critical need to research and explore more radical interventions before they may be required. This proactive stance will better prepare us to manage and mitigate the impacts of environmental stressors on coral reefs.

The Roadmap identifies significant regional differences in requirements for effective coral reef interventions, and notes the potential for global applicability. Tailored solutions for adapting corals alongside thorough investigations and trials are essential to address these diverse needs. Understanding regional circumstances will help develop effective, localised strategies that can be scaled or adapted as necessary for broader application.

A comprehensive approach to ecological risk management is vital to achieve the goals of effective and long lasting restoration and conservation of corals. By improving our understanding and control over ecological risks associated with active interventions, we can more effectively navigate the transition from conceptual ideas to proof-of-concept, trials, and full deployment. This progression will be instrumental to ensure interventions are effective and sustainable.

Additionally, the study has advanced discussions on responsible R&D, helping ensure research and development activities are ethical and align with best practices. Integrated management of coral reefs and catchments remains important, emphasising the need to coordinate efforts across different stakeholders for successful implementation and scalable interventions.

Aligning this Roadmap with other CORDAP-funded roadmaps and its broader relevance across various delivery mechanisms, further underscores its importance to CORDAP and beyond. By integrating insights from this Roadmap with existing strategies, we can foster a more unified and effective approach to coral reef conservation and restoration.

Addressing the complex challenges facing coral reefs requires a concerted effort that combines immediate action with innovative research and responsible practices. Through regional and global collaboration, better ecological risk management, and strategic alignment with other roadmaps, we can significantly advance efforts to responsibly fast-track coral reef active interventions.

SECTION 3:

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