UN environment programme

ICRI International Coral Reef Initiative

United Nations Decade on Ecosystem Restoration 2021-2030

CORAL REEF RESTORATION

AS A STRATEGY TO IMPROVE ECOSYSTEM SERVICES

A guide to coral restoration methods

Authors

Margaux Hein, Ian McLeod, Elizabeth Shaver, Tali Vardi, Sylvain Pioch, Lisa Boström-Einarsson, Mohamed Ahmed, Gabriel Grimsditch.

Suggested Citation

Hein MY[1,2], McLeod IM[2], Shaver EC[3], Vardi T[4], Pioch S[5], Boström-Einarsson L[2,6], Ahmed M[7], Grimsditch G[7](2020) Coral Reef Restoration as a strategy to improve ecosystem services – A guide to coral restoration methods. United Nations Environment Program, Nairobi, Kenya.

[1] Marine Ecosystem Restoration (MER) Research and Consulting, Monaco

[2] TropWATER, James Cook University, Australia

[3] The Nature Conservancy, USA

[4] ECS for NOAA Fisheries, USA

[5] University Montpellier 3 Paul Valery, France

[6] Lancaster Environment Centre, Lancaster University, UK

[7] United Nations Environment Programme, Kenya

Advisory Committee

Austin Bowden-Kerby (*Corals for Conservation*), Emily Corcoran (*Independent consultant*), Alasdair Edwards (*Newcastle University*), Jessica Levy (*Coral Restoration Foundation*), Jennifer Loder (*Great Barrier Reef Foundation*), Joanie Kleypas (*National Centre for Atmospheric Research-USA*), Jennifer Koss (*NOAA*), Elizabeth McLeod (*The Nature conservancy*), Phanor Montoya-Maya (*Corales de Paz*), Buki Rinkevich (*National Institute of Oceanography-Israel*), Francis Staub (*ICRI*), David Suggett (*University of Technology Sydney*), Didier Zoccola (*Centre Scientifique Monaco*).

Layout

Johanna Villani Design

Funding

This work was funded by the Swedish International Development Cooperation Agency and the Principality of Monaco.

Additional Support

This project was also supported by the Australian Government's National Environmental Science Program Tropical Water Quality Hub (NESP TWQ) funding to Ian McLeod, Margaux Hein, and Lisa Boström-Einarsson.

Acknowledgement

We would like to express our gratitude to the following experts for supporting this report through the provision of text, case studies, photos, external peer review and guidance: Amanda Brigdale, Anastazia Banaszak, Agnes LePort, Tory Chase, Tom Moore, Tadashi Kimura, members of the ICRI Ad-Hoc Committee on coral reef restoration, and the leadership team of the CRC. We thank them for providing their valuable time, knowledge and expertise, continuous trust and exemplary collaboration and professionalism.

List of Acronyms

CRC – Coral Restoration Consortium

CMP – Conservation Measures Partnership

GBR – Great Barrier Reef

IFRECOR – French Initiative for Coral Reefs

ICRI – International Coral Reef Initiative

IPCC – Intergovernmental Panel on Climate Change

NASEM – National Academies of Sciences, Engineering, and Medicine

NOAA – National Oceanic and Atmospheric Association

RRAP – Reef Restoration and Adaptation Program

RRN – Reef Resilience Network

SER – Society for Ecological Restoration

UNEA – United Nations Environment Assembly

UNEP – United Nations Environment Programme

Cover: Freedivers monitoring corals growing on tables in Pulau Hatamin, Indonesia © Martin Colognoli /Coral Guardian

North Broken Passage GBR
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Contents

EXECUTIVE Summary

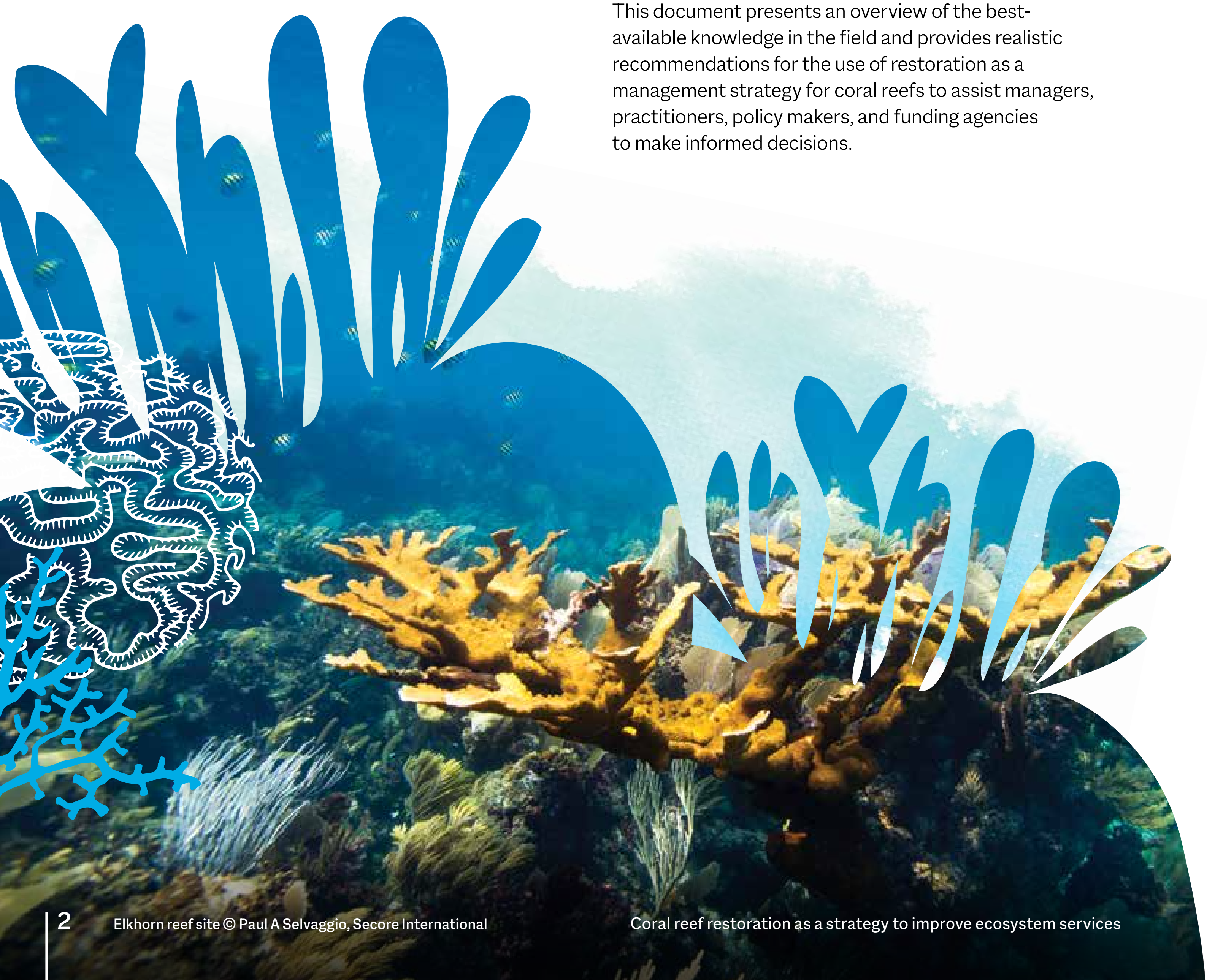
Coral reefs provide billions of dollars in ecosystem services every year globally but are in fast decline in the face of rising climate and anthropogenic disturbances. Urgent climate action is required along with bold local management to halt the declines and support coral reef resilience now and into the future.

Coral reef restoration is increasingly advocated for as a management strategy to combat dramatic declines in coral health and cover globally. It is also increasingly suggested as a mechanism to help countries deliver on national and international commitments under various multilateral environmental agreements.

Yet, there is still a limited understanding of the effectiveness of coral reef restoration efforts, particularly in supporting the maintenance of ecosystem services.

In 2019, the United Nations Environment Assembly (UNEA) adopted Resolution 4/13 requesting the United Nations Environment Programme (UNEP) and the International Coral Reef Initiative (ICRI) to better define best practices for coral restoration for the maintenance of ecosystem services, including for coastal defence and restoration of fish nursery areas. The coming UN Decade on Ecosystem Restoration (2021-2030) and Ocean Science for Sustainable Development (2021-2030), provide an opportunity to highlight the work already underway and set out a path for future actions.

This document presents an overview of the best-available knowledge in the field and provides realistic recommendations for the use of restoration as a management strategy for coral reefs to assist managers, practitioners, policy makers, and funding agencies to make informed decisions.



Elkhorn reef site © Paul A Selvaggio, Secore International

The report is organised in **six** parts.

1

WHAT IS CORAL REEF RESTORATION?

Part 1 defines coral reef restoration in the context of climate change and describes current coral reef restoration goals and methods.

2

CURRENT CHALLENGES AND OPPORTUNITIES

Part 2 presents opportunities and challenges, particularly around scale, standards, ecosystem integrity, and socio-cultural considerations.

3

TO RESTORE OR NOT TO RESTORE – A CALL FOR REALISM

Part 3 calls for realism and advises caution against the unplanned use of coral reef restoration, especially on reefs where local disturbances cannot be mitigated.

4

RECOMMENDATIONS

Part 4 highlights general recommendations on using coral reef restoration as a management strategy, focusing on steps to take prior to restoration in the planning and design phase, as well as in the implementation and monitoring phases. Recommendations that are specific to goals and methods are also highlighted.

5

CONCLUSIONS AND ACTION PLANS

Part 5 draws general conclusions and provides links to trusted sources of information.

6

CASE STUDIES

Part 6 presents six case studies of coral reef restoration efforts in different parts of the world.

Whilst not designed to reduce climate impacts, coral reef restoration can be a useful tool to support resilience, especially at local scales where coral recruitment is limited, and disturbances can be mitigated. Ongoing investment in coral reef restoration research and development globally will improve the scale and cost-efficiency of the methods currently applied.

However, at present, there is limited evidence of long-term, ecologically relevant success of coral reef restoration efforts. Coral reef restoration should not be considered a 'silver bullet' and should be applied appropriately, with due diligence, and in concert with other broad reef resilience management strategies. In the context of climate change, applying coral reef restoration methods effectively and efficiently requires 'climate-smart' designs that account for future uncertainties and changes.

Increased consideration of ecological engineering, beyond just planting corals, that integrate reef-wide and long-term ecological succession processes are also necessary to improve the current scale, cost and effectiveness of coral reef restoration methods.

We suggest coral reef restoration strategies follow four critical principles: 1) planning and assessing around specific goals and objectives, 2) identifying adaptive strategies to mitigate risks, 3) engaging local stakeholders and communities in all stages of the restoration efforts, and 4) developing long-term monitoring plans to allow for adaptive management and to improve the understanding of restoration effectiveness for specific goals.

RECOMMENDATIONS

MANAGEMENT RECOMMENDATIONS

- **Coral reef restoration efforts need to be integrated into broader reef management strategies.**

  Implementing bold action to reduce anthropogenic stressors as part of a broad management strategy is essential to improve the reef conditions necessary for reef restoration to be successful.

- **Future impacts of climate change should be incorporated into the planning and design phase of coral reef restoration efforts.**

  Short and long-term management decisions should be 'climate-smart', accounting for climate change projections and site-specific vulnerabilities to disturbances.

- **Socio-economic considerations need to be considered systematically in all stages of coral reef restoration processes.**

  Engaging various stakeholders in all stages of reef restoration efforts is crucial to build long-term support from the public, empower partnerships with diverse sectors and stakeholders, and link conservation actions to economic goals.

- **Coral reef restoration efforts need to integrate ecological processes beyond planting corals.**

  Meeting goals associated with securing and enhancing the provision of reef ecosystem services, and overall coral reef resilience to climate change requires broader considerations of ecosystem processes associated with reef health, physical integrity, and connectivity principles.

- **Methods' selection should account for cost-effectiveness and scalability, as appropriate for the local context.**

  This report provides an overview of these parameters for current well-established coral reef restoration methods.

- **The field of coral reef restoration is evolving rapidly and needs monitoring and adaptive management strategies.**

  Planning for long-term monitoring should be an integral part of any coral reef restoration efforts to allow for adaptive management and the inclusion of the latest technology and research advances.

- **Coral reef restoration is not a short-term fix for coral reef decline.**

  Ecosystem restoration efforts are interventions that need to be planned and funded as long-term (at least 10 to 20 years) strategies.

Pacific © Hannes Klostermann

POLICY RECOMMENDATIONS

- **Coral reef restoration targets should be included in commitments made to the UN Decade on Ecosystem Restoration.**

  Coral reefs are a critical, valuable and highly threatened global ecosystem, and we recommend that they should be well represented in global, regional and/or national restoration targets associated with the UN Decade on Ecosystem Restoration.

- **Policy, plans, and funding specific to coral reef restoration are needed to assist implementation at local, regional, and global scales.**

  These might include new or refined policies and plans to support on-going investment and collaborations at multiple scales towards intervention strategies for coral reefs. They should reflect the management recommendations above.

INTRODUCTION

Coral reefs are some of the most ecologically and economically valuable ecosystems on our planet. Covering less than 0.1% of the world's ocean, they support over 25% of marine biodiversity and provide a wide range of ecosystem services such as coastal protection, fisheries production, sources of medicine, recreational benefits, and tourism revenues (Burke et al. 2011).

Coral reefs occur in over 100 countries and territories with at least 500 million people directly depending on reefs for their livelihoods. Healthy coral reefs contribute substantially in benefits and services to people, in the order of billions of US dollars. For example, Mesoamerican reefs were recently estimated to provide US$2.6 billion in ecosystem goods and services annually (UNEP 2018), while the Great Barrier Reef is valued at US$56 billion with a yearly economic contribution of US$6.4 billion (Deloitte et al. 2017).

Often referred to as 'sentinel ecosystems', coral reefs are now considered the most vulnerable ecosystems to climate change and local anthropogenic pressures (Bindoff et al. 2019). Some estimates suggest that over 50% of coral cover has already been lost in the last 30 years (NASEM 2019). Disturbances such as declining water quality, destructive fishing practices, coral disease, and predator outbreaks are exacerbated by an increase in the intensity and frequency of storms and mass coral bleaching events (Hughes et al. 2018). Two recent IPCC reports (IPCC 2018; Bindoff et al. 2019) summarize the existing projections of future coral bleaching to state that coral reefs as we know them will all but disappear in a scenario of up to 2°C warming and up to 90% of coral reefs could be lost even with an increase of 1.5°C.

Urgent climate action is essential to combat 'the coral reef crisis' (*sensu*, Bellwood 2004) and ensure a future for coral reefs (Hughes et al. 2017). However, even if greenhouse gas emissions were to be drastically and immediately reduced, global ocean temperatures could still take decades to stabilize (Hansen et al. 2007). Established conservation practices such as marine protected areas and managing land-based pollution are vital for supporting coral reef resilience (Anthony et al. 2017; McLeod et al. 2019a). However, bolder active management actions such as predator control and coral reef restoration are now also needed to protect and re-build reef ecosystems, alongside climate action and conservation and protection measures (Rinkevich 2019; Duarte et al. 2020).

Coral reef restoration could help countries deliver on national commitments linked to Nature-Based Solutions (NBS) and Nationally Determined Contributions (NDCs) to the Paris Agreement on climate change, as well as supporting the UN Decade on Ecosystem Restoration (2021-2030). The UN Decade on Ecosystem Restoration aims to scale-up ecosystem restoration efforts globally to meet Sustainable Development Goals linked to conserving biodiversity, ending poverty, improving livelihoods, ensuring food security, and combating climate change. Coral reef restoration efforts are now implemented in at least 56 countries around the world (Boström-Einarsson et al. 2020), but there is limited guidance on the efficiency and efficacy of various methods, particularly with regards to scale, cost, and regional specificities. The Coral Restoration Consortium (CRC) was formed in 2017 to foster collaborations and technology transfer among experts, managers, and practitioners, and facilitate the adoption of coral reef restoration practices globally. Both the International Coral Reef Initiative (ICRI), a partnership of nations and organisations to preserve coral reefs, and the United Nations Environment Programme (UNEP) have adopted resolutions to better define needs, priorities, and recommendations for implementing coral reef restoration more broadly. In 2019, ICRI formed an Ad-hoc committee to advance a plan of action to promote reef restoration practices by facilitating investment and capacity-building among ICRI members. In the same year, the United Nations Environment Assembly adopted Resolution 4/13 requesting UNEP and ICRI to better define best practices for coral restoration, as appropriate, for the maintenance of ecosystem services, including for coastal defence and restoration of fish nursery areas.

This report is a result of that resolution. The aim is to present an overview of coral reef restoration strategies to assist managers, practitioners, funding agencies, and decision-makers in making informed decisions on the use of restoration as a coral reef management strategy in support of the UN Decade on Ecosystem Restoration.

BOX 1. THE POLICY LANDSCAPE FOR CORAL REEF RESTORATION

There are many levels at which policy can enable and support appropriate reef restoration efforts, as a part of addressing the decline of these ecosystems. For the purpose of this report, policies are considered as a course of actions proposed and adopted by governments, parties, or groups, while initiatives are means by which the policies are implemented. Here we describe some important multilateral environmental agreements as well as some relevant initiatives that support their implementation.

Multilateral environmental agreements

There are a large number of international policy frameworks, instruments and agreements considered to support the conservation and sustainable management of coral reef ecosystems. A 2019 UNEP analysis identified at least 232 global and regional international instruments, and 591 commitments that address the need to protect these ecosystems and manage the key stressors acting on coral reefs such as water quality, chemicals management, and regulation of fisheries (UNEP 2019).

One of the most directly relevant international policy frameworks is the **Convention on Biological Diversity**, whose objectives include the conservation of biodiversity and the sustainable use of its components. Two of the Aichi Biodiversity Targets were related to ecological restoration (14 and 15), whilst Target 10 was specifically about minimizing impacts on coral reefs, and Target 11 set-up a target of effectively protecting at least 10% of coastal and marine areas (CBD 2010). The Aichi Biodiversity Targets expired in 2020 and will be superseded by the Convention on Biological Diversity Post-2020 Global Biodiversity Framework. The negotiation of this new framework provides an important opportunity to ensure that appropriate provision is put in place for the conservation and restoration of coral reef ecosystems.

The **United Nations Environment Assembly** is the world's highest-level decision-making body on the environment. Understanding environmental challenges and preserving and rehabilitating our environment is at the heart of the 2030 Agenda for Sustainable Development and the upcoming UN Decade on Ecosystem Restoration. At its 4th Assembly (UN Environment Assembly), resolution 4/13 on sustainable coral reefs management was adopted. The resolution recognises the role of restoration to achieve biodiversity goals and urges the development of appropriate best-practices and recommendations.

Examples of Initiatives that support policy implementation relevant to coral reef restoration

A number of initiatives are in place to respond to these international bodies and coordinate the implementation of coral reef restoration efforts globally and regionally. **The International Coral Reef Initiative (ICRI)** has adopted resolutions on coral restoration and formed a dedicated Ad-hoc committee on coral restoration with a mission to help coordinate projects and research among international partners (McLeod et al. 2019b). This includes assessing global needs and priorities; advocating best practice in science, policy and legislation; and facilitating the transfer of new knowledge to managers and restoration practitioners.

The Commonwealth Blue Charter, an agreement between the 53 Commonwealth nations to achieve sustainable ocean development and Sustainable Development Goal 14 also has action areas specific to coral reef protection and restoration.

Other examples of initiatives at the **regional level** include the Nairobi Convention Coral Reef Task Force, Caribbean Challenge, Micronesia Challenge, Coral Triangle Initiative, and the Secretariat of the Pacific Regional Environment Programme (SPREP).

At the **national level**, initiatives are also in place with several countries developing action plans for coral reef restoration and 88% of ICRI country members interested in the development of new international commitments and policies specifically dedicated to coral restoration (McLeod et al. 2019b). Examples of national initiatives include a Coral Reef and Restoration Protocol in Costa-Rica, Coral Reef Action Plans in the Netherlands and Thailand, a Coral Reef Conservation Program Strategic Plan in the US, and a Reef Restoration and Adaptation Program in Australia.

1 What is CORAL REEF RESTORATION?

Ecological restoration is defined by the Society for Ecological Restoration as "*the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed*" (SER working group 2004).

In the past, the goal of restoration has been to restore an ecosystem back to a historical baseline. This view also implied that the threat(s) responsible for the degradation, damage or destruction could be removed. However, this may not be possible for coral reefs because the threat of rising ocean temperatures will continue for decades even if greenhouse gas emission targets are met. The goal of coral reef restoration has therefore shifted towards recovering or maintaining key ecosystem processes, functions, and services through the next few decades of climate change, rather than restoring to a historical baseline.

In this report, the term 'coral reef restoration' is used to describe an active intervention that aims to assist the recovery of reef structure, function, and key reef species in the face of rising climate and anthropogenic pressures, therefore promoting reef resilience and the sustainable delivery of reef ecosystem services.

Elkhorn corals as wavebreaker
© Paul A Selvaggio, Secore International

1.1 Motivations, goals, and objectives of coral reef restoration

Understanding the utility of restoration as a coral reef management strategy requires defining specific motivations (WHY we are undertaking restoration), goals (WHAT we want to achieve by undertaking restoration), and objectives (WHAT we want to achieve in order to reach our goal).

Common motivations for coral reef restoration include 1) securing key reef ecosystem services (e.g. coastal protection, fisheries production, tourism), 2) fulfilling legal and political requirements (e.g. reparations for environmental damage following ship groundings), 3) preserving socio-cultural values associated with the reef, 4) preserving biodiversity, and 5) researching restoration techniques and reef ecological processes (Bayraktarov et al. 2019). These rationales are non-exclusive and often complement one another.

In conservation, goals are commonly defined as the ultimate impact you hope to achieve by conducting interventions over the medium to long-term (e.g. 5-20 years; Open Standards for the Practice of Conservation, CMP 2020) and are achieved through a series of smaller, concerted objectives that occur over shorter time intervals (e.g. 1-3 years). The overarching goal of most coral reef restoration projects is to recover a functioning and self-sustaining reef ecosystem, and coral reef restoration efforts should be planned as a long-term intervention. However, there are narrower, but still important goals that motivate managers and practitioners. Below is a list of common goals for coral reef restoration (Table 1).

Table 1. Goals and associated rationales of coral reef restoration.

GOALS	RATIONALES – USE RESTORATION TO....
SOCIO-ECONOMIC GOALS	
a. Sustain or recover coastal protection	Sustain or re-establish the regulating ecosystem services provided by reefs to protect coastal communities and infrastructure by attenuating wave energy and mitigating disturbances such as erosion and coastal flooding
b. Sustain or recover fisheries production	Sustain or re-establish the provisioning services delivered by reefs in providing habitat and nursery areas for commercially important fisheries
c. Sustain or enhance local tourism opportunities	Maintain reef aesthetics to support local reef tourism and/or provide opportunities for eco-tourism experiences
d. Promote local coral reef stewardship	Support local communities and/or Indigenous traditional owners to engage and reconnect with the local reef environment, improve reef custodianship and promote intrinsic value of reefs (spiritual, traditional, worship)
ECOLOGICAL GOALS	
a. Re-establish reef ecosystem function and structure	Rehabilitate the function, structure, diversity and health of degraded coral reef ecosystems
b. Mitigate population declines and preserve biodiversity	Assist the recovery of endangered coral populations, and preserve innate reef biodiversity from genes to phenotypes to ecosystems
CLIMATE CHANGE ADAPTATION AND SUPPORT GOALS	
a. Mitigate impacts and promote reef resilience in the face of climate change	Support resistance and recovery processes to reduce risks of impact and ensure that reefs persist through current and projected changing climate conditions
DISTURBANCE-DRIVEN GOALS	
a. Respond to acute disturbance to accelerate reef recovery	Assist natural recovery process when reefs are affected by acute disturbances such as storms, predator outbreaks, ship groundings, and other structural damages
b. Mitigate anticipated coral loss prior to disturbance	Adopt an effective 'no net loss' mitigation policy whereby if a disturbance (e.g. coastal development) cannot be avoided, it should be minimised and offset for example by relocating anticipated losses prior to disturbance

Different groups of stakeholders may have different primary goals. For example, tourism operators may focus on sustaining local tourism opportunities around 'high value sites' with high coral cover, whereas natural resource managers may instead focus on mitigating population declines and preserving biodiversity. While aiming towards one specific goal, other complementary goals may also be achieved. For example, a local government may initiate reef restoration to reduce coastal erosion, and in doing so, achieve other goals associated with the preservation of biodiversity, and increase in tourism opportunities.

Objectives are formal statements developed to create, track, and accomplish the above-mentioned goals over shorter time periods. To manage ecosystems effectively, both goals and objectives should be crafted using the SMART approach, where they are Specific, Measurable, Achievable, Relevant, and Time-bound. Objectives should be informed by reference ecosystems but should consider future- anticipated environmental change (Gann et al. 2019). Examples of smart objectives specific to coral reef restoration include: *XX genotypes from XX coral species outplanted on XX reefs in the first two to three years, or XX increase in coral cover at XX site within five years resulting in XX% reduced wave action.*

Several objectives should be developed to improve the likelihood of successfully completing overall goals (see Shaver et al. 2020 for guidance on planning coral reef restoration projects).

1.2 Coral reef restoration methods

Coral reef restoration methods were initially developed from methods used in terrestrial ecosystems. For example, the concept of 'coral gardening' developed in the 1990s, adapted silviculture principles to the mariculture of coral fragments (Rinkevich 1995). Other methods stemmed from emergency response interventions following disturbances that affected the structural integrity of the reef substrate such as ship grounding or extreme weather events (Precht 2006). More recently, scientists and conservationists have worked to develop methods to support coral reef resilience in the face of climate change (e.g., McLeod et al. 2019a) and to restore coral reef ecosystem structure and function to ensure the sustainability of reefs and the services that they provide, for example by implementing ecological engineering approaches (Rinkevich 2020). Below is a list of five of the most widely practiced methods currently used globally to restore coral reefs (Table 2).

Table 2. Current methods of coral reef restoration adapted from Boström-Einarsson et al. 2020.

METHOD	DEFINITION
1. DIRECT TRANSPLANTATION	Transplanting coral colonies or fragments without an intermediate nursery phase.
2. CORAL GARDENING	Transplanting coral colonies or fragments with an intermediate nursery phase. Nurseries can be *in situ* (in the ocean) or *ex situ* (flow through aquaria).
3. SUBSTRATE ADDITION (ARTIFICIAL REEF)	Adding artificial structures for purposes of coral reef restoration as a substrate for coral recruitment, coral planting, and/or for fish aggregation.
3.1 Electro-deposition	Adding artificial structures that are connected to an electrical current to accelerate mineral accretion.
3.2 Green engineering	Adding artificial structures designed to mimic natural processes and be integrated into reef landscapes (nature-based solutions, eco-designed structures, living shorelines).
4. SUBSTRATE MANIPULATION	Manipulating reef substrates to facilitate recovery processes.
4.1 Substrate stabilisation	Stabilising substratum or removing unconsolidated rubble to facilitate coral recruitment or recovery.
4.2 Algae removal	Removing macro-algae to facilitate coral recruitment or recovery.
5. LARVAL PROPAGATION	Releasing coral larvae at a restoration site, after an intermediate collection and holding phase, which can be in the ocean or on land in flow through aquaria.
5.1 Deployment of inoculated substrate	Deploying settlement substrates that have been inoculated with coral larvae.
5.2 Larval release	Releasing larvae directly at a restoration site.

While these five methods have been the most widely applied to date, the field of coral reef restoration is rapidly evolving, and future projects may involve approaches that are very different from those described in this report. A number of new emerging interventions are currently being tested experimentally across various scales, from individual corals (e.g. genetics, reproduction, physiology), to coral populations, reef communities, and ecosystems.

For example, field experiments are underway in Fiji and Kiribati to facilitate natural processes of reef recovery by gardening and transplanting coral fragments from colonies that have survived recent episodes of coral bleaching, and encouraging ecological synergies by actively removing coral predators and re-introducing fish and sea urchins to control macro-algae overgrowth (See Coral for Conservation case-study). The US National Academies of Science, Engineering, and Medicine (NASEM) and the Reef Restoration and Adaptation Program (RRAP) have recently provided an extensive review of a number of interventions that could increase the physiological resilience of corals to climate change (NASEM 2019, Bay et al. 2019).

The twenty-three intervention types investigated by NASEM include novel approaches such as cryopreservation, managed relocation of corals to promote assisted gene flow (AGF), or microbiome manipulations (NASEM 2019). Meanwhile, RRAP in Australia is evaluating 'moonshot' solutions that can operate across the entire scale of the Great Barrier Reef, including cloud brightening for cooling and shading reef areas, assisting the evolutionary adaptation of reef species to warmer waters, and mass production and release of coral larvae to seed reefs (Bay et al. 2019).

While the interventions proposed through RRAP and NASEM represent a substantial body of research and future potential for improvement of the field of reef restoration, many are still in the research and development phase and may take years before becoming feasible for implementation. In contrast, many locally-tailored coral gardening approaches are already in various stages of implementation. Coral reef restoration also provides a platform for integrating those interventions to increase coral resilience that are still under development.

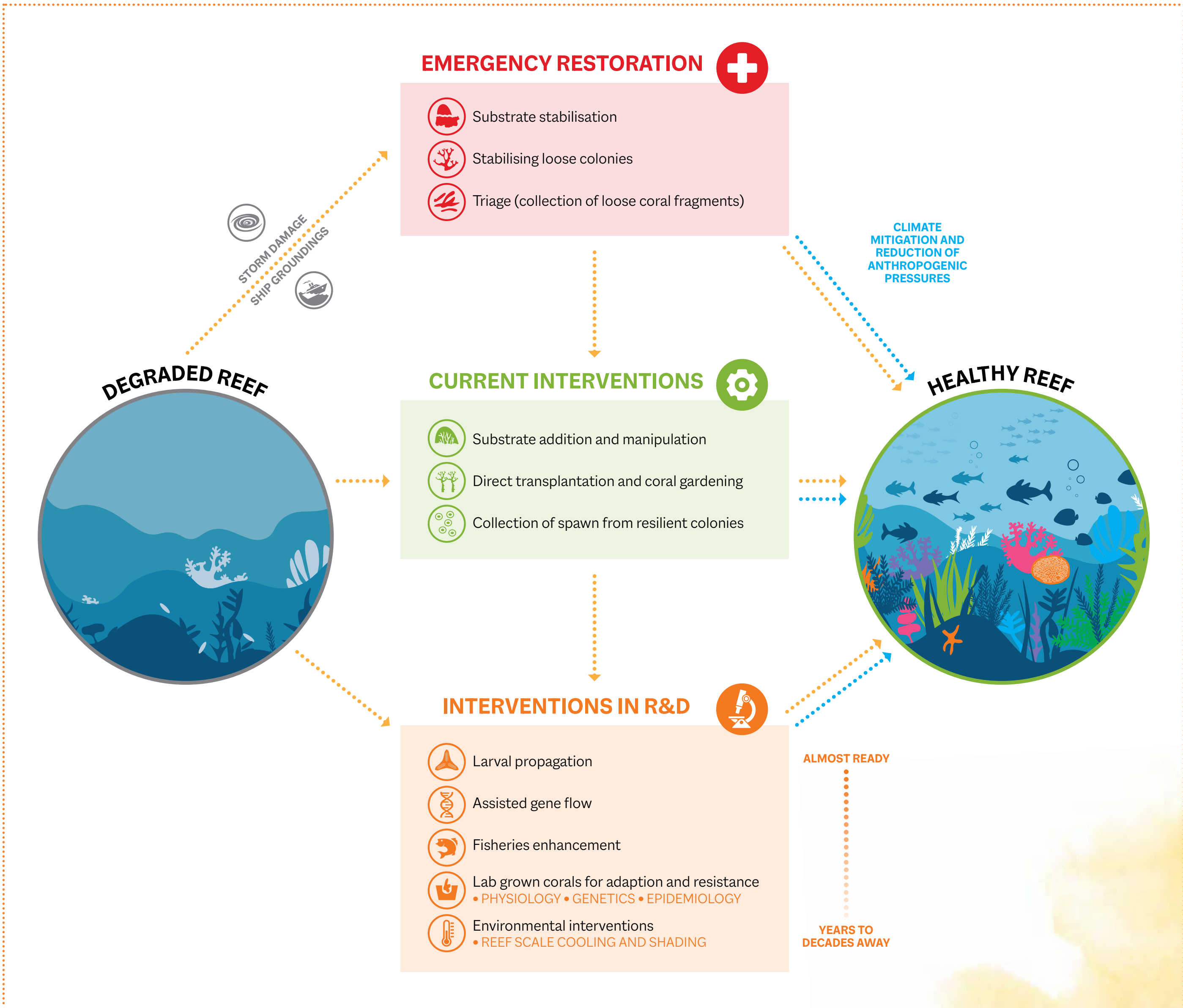


Figure 1. Overview of how current and in-development interventions can be used to assist the recovery of a degraded reef.

2

CORAL REEF RESTORATION: Current challenges and opportunities

A recent study by Boström-Einarsson et al. (2020) surveyed over 360 coral reef restoration efforts by analysing peer-reviewed journal articles and grey literature, as well as through an online survey providing the most extensive overview of the current state of coral reef restoration.

The review revealed that coral reef restoration projects have been implemented in at least 56 countries. Altogether, 229 coral species (about 25% of scleractinian coral species) from 72 coral genera have been used in restoration. A majority (59% of projects), focused on fast-growing branching coral species (that are also the most sensitive to disturbance), and 28% of projects focused on a single species of coral (Boström-Einarsson et al. 2020). The average survival of individual corals post-transplantation was 66%, which is higher than the average 50% survival of individuals transplanted in terrestrial systems (Gann et al. 2019). However, survival rates are likely to be over-estimated given that monitoring rarely continued beyond one year after transplantation. For instance, a recent study in Florida that followed over 2400 outplanted colonies of one species (*Acropora cervicornis*) over eight years found that initial coral survivorship was high but decreased after two years, and projected only 0-10% survivorship after seven years (Ware et al. 2020).

In terms of methods used, Boström-Einarsson et al. (2020) found almost 70% of projects involved coral planting (e.g. direct transplantation, coral gardening). Substrate manipulation methods comprised 10% of all projects, and larval propagation 1% of all projects, making these methods more difficult to assess in terms of feasibility and efficiency. In summary, the field of coral reef restoration is still at an early stage compared to the restoration of other ecosystems, and faces several challenges for successful implementation. We highlight below four critical challenges and associated opportunities.


Freshly settled coral under fluorescence (Reef Patrol) © Secore International

2.1 Limited scales

Increasing the scales at which current projects are being applied, both in time and space, is one of the greatest challenges of coral reef restoration. The spatial scale at which coral reef restoration is currently applied is extremely small when compared to the scale of impacts of disturbances such as mass coral bleaching. While a few projects have been documented to span over 5,000 m^2 (0.5 ha), the median scale of coral reef restoration efforts is ~100 m^2 (Boström-Einarsson et al. 2020). Cost is likely to be a strong limiting factor to scaling-up restoration efforts with median costs estimated at US$400,000 per hectare (e.g. US$40/$m^2$; Bayraktarov et al. 2019). However, many efforts are underway to increase the scale of coral transplantation and site-selection processes (e.g. favouring sites with high larval connectivity) to improve the geographic reach of restoration. Other projects are developing low-cost coral gardening methods, such as the rope nursery, where cost of restoration is under US$1 per coral outplanted (Levi et al. 2010). Whilst scaling-up is one of the most important challenges for coral reef restoration, small-scale projects have value in promoting local, targeted intervention strategies, piloting new techniques, integrating and educating local community groups and stakeholders, and promoting tourism and local economies. If well connected in terms of larval exchange, multiple small-scale projects could also positively impact reefs over larger scales.

Time scales are also an issue. The operational timeframe of coral reef restoration efforts varies depending on project funding, goals, and methods used. In general, positive outcomes at ecologically relevant timescales are likely to take several years to decades to appear, due to the slow growth rate of corals and the slow rate of natural ecosystem recovery. Most coral reef restoration projects monitor for about 12 months (Boström-Einarsson et al. 2020), which is insufficient to understand the ecological response beyond technical characteristics of attachment methods and early-succession patterns. Developing scalable coral reef restoration strategies is the driving force of innovation in the field, and with targeted investment, and increased funding, more cost-effective, scalable solutions should become available to practitioners and managers in the near future.

2.2 Lack of standards

The field of coral reef restoration was initially developed as a haphazard collection of DIY projects aimed at responding to acute disturbance at specific reefs rather than a coordinated effort integrated within broad international standards (such as those developed by SER; McDonald et al. 2016; Gann et al. 2019). Regional contrasts in goals and methods have resulted in very different approaches being used in different regions of the world. For example, the strong focus on restoring endangered *Acropora* species in the Caribbean has generated approaches that are not necessarily relevant for the Asia-Pacific region where the main reef-building species are still abundant. These initial approaches lacked the standardised approaches to monitor restoration projects and report on the cost of various types of interventions, which impeded the ability to compare the efficiency and efficacy of different methods (Bayraktarov et al. 2016, 2020).

In response to these early challenges, coral reef restoration managers and practitioners are increasingly implementing standards developed by SER (SER 2016, 2019; McDonald et al. 2016; Gann et al. 2019). In addition, the Coral Restoration Consortium is developing a list of standard terms and their definitions. For example, the CRC Monitoring Working Group has developed a comprehensive guide to monitoring that recommends universal metrics to be measured by any and all restoration projects (Goergen et al. 2020) and a guide for field-based restoration is currently in preparation. The MERCI_COR method developed by the French Initiative for Coral Reefs (IFRECOR) can be used to assess biodiversity changes throughout different stages of restoration (Pioch et al. 2017). The development of these standards is an important consideration in seeking support and resourcing for future coral reef restoration activities and will ultimately help develop streamlined permitting processes facilitating broader project implementation.

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2.3. Poor ecological integrity

The field of coral reef restoration is still in its infancy compared to restoration efforts in other ecosystems, particularly terrestrial systems. Its scientific maturity is still limited and until recently, primarily focused on elucidating the most cost-effective ways to grow and plant corals (Rinkevich 2014), which explains why the methods of direct transplantation and coral gardening make up over two thirds of all restoration efforts (Boström-Einarsson et al. 2020).

Better integration of keystone reef organisms and ecological processes may also benefit the process and outcomes of coral reef restoration efforts (Shaver and Silliman 2017; Ladd et al. 2018). For example, integrating coral-predator control strategies, connecting fish nursery habitats like mangroves and seagrasses, or protecting and/or re-introducing key herbivores may create positive feedbacks that facilitate recovery of the coral community at the restored site (Mumby et al. 2004). Further, direct transplantation could be combined with larval propagation to enhance genetic diversity over time (Horoszowski-Fridman et al. 2020a). Using mixed-method strategies is also likely to improve the adaptive capacity of the intervention in the face of uncertainties and future climate change conditions (Gardali et al. 2019; Shaver et al. 2020). For example, integrating larval propagation approaches more widely in coral reef restoration efforts necessitates improving the health, growth, and survival of coral recruits. Comprehensive genetic population management strategies also need to be developed to guide the restoration of threatened coral species.

Methods that address the physical restoration of reefs (e.g. substrate addition and manipulation) are often overlooked for being cost and/or permit prohibitive. Yet, physical restoration is often a prerequisite to biological restoration in many ecosystems and can increase the speed of recovery and success of restoration (Gann et al. 2019). Restoring reef structure is also key to restoring some specific ecosystem services such as coastal defence or fisheries production (Zepeda-Centeno et al. 2018; Viehman et al. 2020). Incorporating ecological engineering approaches and interventions that operate at different scales both spatially and temporally might also improve the outcomes of the intervention (Rinkevich 2020). In conclusion, developing broader coral reef restoration strategies that incorporate ecological processes to maintain and restore biodiversity beyond the narrow focus of enhancing populations of a few coral species will have beneficial impacts at more meaningful ecological scales. Although potentially more expensive and technically challenging, coral reef restoration strategies that integrate genetic and ecological considerations are more likely to return greater ecosystem services and lead to self-sustaining ecosystems.

2.4 Insufficient Socio-cultural considerations

Engaging diverse stakeholders and local communities is critical to the success of coral reef restoration efforts (Suding et al. 2015; McDonald et al. 2016; Gann et al. 2019). Coral reef restoration can be a tool for stewardship, a channel for delivering conservation education and calls to action, a way to empower communities, and a platform for evolving reef management approaches. It provides hope and an opportunity for tangible actions against the overwhelming issue of climate change. Past and current coral reef restoration efforts have been driven by scientific research or permitting regulations, and socio-cultural aspects have typically not been well integrated (Hein et al. 2017).

There is an increased recognition of the value of engaging society more widely in the coral reef restoration process, particularly in using traditional local knowledge in planning and design of the efforts (e.g., McLeod et al. 2019b; Shaver et al. 2020). Community engagement has been linked to increase in the long-term success of restoration efforts in general, generating more acceptance, facilitating monitoring through citizen science, and ensuring long-term support (DeAngelis et al. 2020; UNEP 2020). Finding ways to better engage communities first-hand in all stages of the restoration effort is a great challenge for future projects that will necessitate more targeted and effective communication with the public.

Divers from The Nature Conservancy transplanting fragments of *A.cervicornis* in Dry Tortugas © Rachel Hancock Davis, The Nature Conservancy

3

TO RESTORE OR NOT TO RESTORE: A call for realism

BOX 2. Coral reef restoration and global climate change

The main driver of coral reef declines is global climate change, associated mass coral bleaching, and local human pressure (e.g. pollution, overfishing, anchor damage). Even if global targets set by the Paris Agreement are met in the future, current greenhouse gas emissions are still increasing, and the increase in frequency of mass-bleaching events in the last five years suggest that coral reefs globally are very close to their temperature limits (Hughes et al 2018).

In this context, some scientists argue that active interventions, such as reef restoration, are 'band-aid' strategies that do not address the underlying causes of reef declines (Bruno and Valdivia 2016; Hughes et al. 2017; Bellwood et al. 2019). Coral reef restoration has been criticised as an expensive, temporary fix that is not deployable at scales that match the scale of disturbances, and a distraction from other conservation strategies that are more focused on addressing the root causes of disturbances (Bellwood et al. 2019; Morrison et al. 2020). However, it is important to differentiate among the portfolio of actions available to tackle climate change and to ensure coral reefs and their associated services can persist in the future.

Coral reef restoration is not designed to reduce climate impacts, but rather is intended as a complementary tool to support natural recovery following disturbance in key areas. Given the many uncertainties associated with different climate scenarios (Bindoff et al. 2019), the key challenge is to design coral restoration efforts such that the realities of climate change are embedded in the choice of goals, objectives and methods (Shaver et al. 2020). Climate change mitigation does not preclude investment in local management strategies designed to build the resilience and adaptation of the socio-ecological coral reef systems. It is not an 'either or' situation, multiple actions need to be implemented concurrently to provide coral reefs with the greatest hope for the future.

Stocking CRIB with settlement substrates
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Restoration will generally only be successful if the causes of reef degradation are known and have been reduced or removed (Edwards 2010). For example, there is little value in replanting a coral reef where corals have died due to poor water quality if water quality has not been improved prior to planting. It is also not worth the valuable and limited resources of most local reef managers to undertake restoration if the reef can recover without restoration efforts, which is likely to happen on reefs where coral recruitment is not limited and if there is enough time between predicted disturbance events.

Restoration is necessary when there is a barrier to natural recovery that cannot be overcome, to kick start system recovery. The most common barriers to natural recovery are substrate limitations and/or recruitment limitations. Substrate limitation refers to instability and suitability, which both affect the capacity of coral larvae to recruit, settle and grow. For example, unconsolidated coral rubble impedes coral attachment and may create further physical damage (Ceccarelli et al. 2020), while substrate covered in macro-algae impedes coral settlement (Dixon et al. 2014). Recruitment limitation refers to limited supply of coral larvae (or fragments) when reproductive adult populations are too small or when a reef is disconnected from larval supply. Physiological barriers to recovery are also emerging where coral growth and survival are now constrained as corals are pushed to the limits of their thermal tolerance under climate change (Schoepf et al. 2015; Thomas et al. 2018).

There is a growing argument that the risk of doing nothing far outweighs the risks or uncertainties of active interventions (Anthony et al. 2017, 2020). The rapid increase in implementation of coral reef restoration strategies globally is driven by a sense of urgency following catastrophic losses in coral cover in the last decade. This sense of urgency creates unique scientific uncertainties as there is not enough time to wait for climate action to be enacted, for pressures to stop, or for repeated experimental methods to be published in scientific journals before action is taken.

Even in the context of continued coral declines attributed to climate change, coral reef restoration can provide benefits at local scales such as: 1) promoting genetic diversity and maintaining the potential for coral species to adapt to change, 2) helping to prevent the extinction of some species, 3) assisting species migration to new locations, 4) continuing to provide critical ecosystem services, and 5) providing tangible mechanisms for people to combat ecological grief. Importantly, coral reef restoration should not be considered as a solution on its own but rather as part of an integrated resilience-based management framework (e.g. McLeod et al. 2019a) that includes a hierarchical portfolio of actions from threat reduction (i.e. climate change mitigation, water quality controls, fishing regulations), to actions that support the recovery and resistance of ecosystem processes such as marine protected areas or coral predator removal (e.g. crown-of-thorns starfish).

Within that framework, the different strategies integrate both social and ecological adaptive capacity to manage uncertainty and change (McLeod et al. 2019) a. Coral reef restoration can be a useful tool to support resilience, and if well integrated into a resilience-based management framework, can play a key role in meeting Sustainable Development Goals associated with the UN Decade on Ecosystem Restoration (Claudet et al. 2019). Implementation of coral reef restoration actions should be carefully planned and should not divert resources away from other reef management strategies that actively control stressors.

4

RECOMMENDATIONS

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4.1 Prior to restoration

Following the standards developed by SER (Gann et al. 2019), restoration is the last part of a continuum of activities including reducing impacts, remediation, and rehabilitating ecosystem function (Figure 2). Actions aimed at protecting and enabling recovery can be broadly categorised as 'proactive' and they support other 'reactive' actions, commonly referred to as 'restoration'. 'Reactive' actions are aimed at repairing ecosystem function and assisting the recovery of a degraded reef system, should it not be able to recover on its own (Figure 2). This continuum highlights that restoring corals should not be the first point of action in a reef management strategy, but rather a last resort strategy in a carefully planned ecosystem management framework (Edwards 2010). Avoiding and mitigating local impacts to reefs should always be the priority, and restoration should never be used as an offset approach to justify degradation in another area.

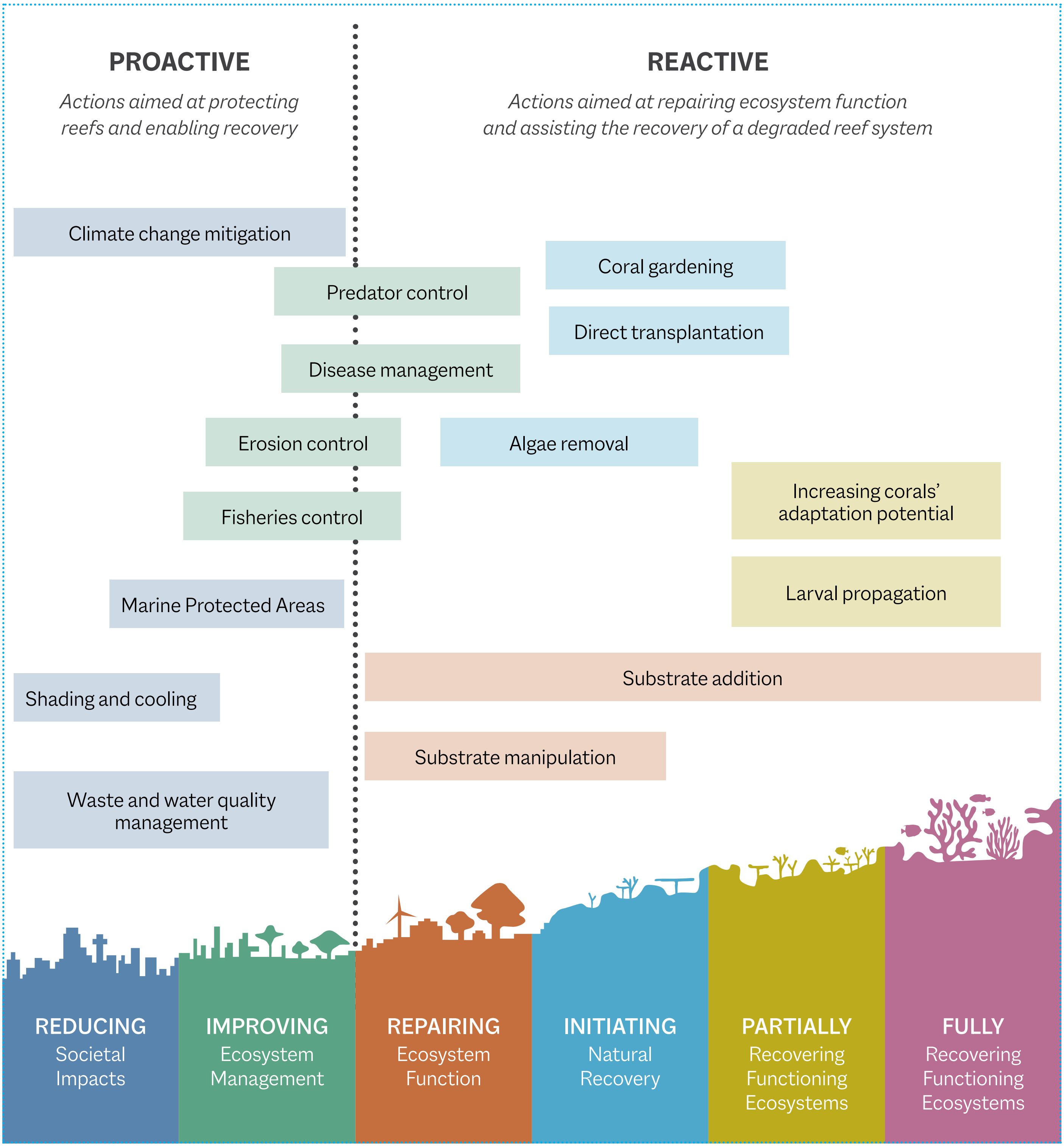

Figure 2. Continuum of actions for coral reef conservation and restoration with examples of 'proactive' and 'reactive' interventions. Adapted from SER guidelines (Gann et al. 2019).

When applied to coral reef management, several key questions should be considered prior to implementing restoration actions, in order to identify if restoration is feasible and necessary (Edwards 2010).

1. WHY DID CORAL MORTALITY OR REEF DEGRADATION HAPPEN IN THE FIRST PLACE?

This question requires an assessment, as thorough as possible, of the cause(s) of coral decline (e.g. pollution, human activities, overfishing or destructive fishing, thermally induced bleaching). It is critical to assess whether threats have been identified and are currently being sufficiently addressed through effective management strategies, and whether restoration is necessary to supplement existing approaches.

2. WHAT ARE THE BARRIERS/IMPEDIMENTS TO NATURAL RECOVERY?

This question requires a careful review of the factors affecting the natural recovery potential of corals (e.g. spawning capacity, barriers to coral recruitment, limits to coral growth). It is critical to assess whether natural recovery can happen on its own, over time, or whether restoration strategies are necessary to assist the recovery of the system.

3. WHAT TYPE OF REPAIR OR INTERVENTION IS NECESSARY TO RECOVER ECOSYSTEM FUNCTION?

In some instances, repairing the physical integrity of the reef (e.g. securing loose rubble), or recovering key ecological processes (e.g. herbivory) should be a prerequisite to coral restoration as these will greatly impact coral survivorship and resilience, and ultimately the efficacy and efficiency of the restoration effort. This step may be informed by designating a reference ecosystem, and an assessment of whether the site supported a coral community prior to the disturbance.

4.2 Planning and design

BOX 3. A MANAGER'S GUIDE TO CORAL REEF RESTORATION PLANNING AND DESIGN

A Manager's Guide to Coral Reef Restoration Planning and Design (Shaver et al. 2020) has been developed to assist managers in developing restoration plans based on global standards that are consistent with these recommendations for restoration planning and design. This guide provides instructions on how managers can lead a process for identifying and developing SMART goals and objectives for their location, use local data and criteria to select restoration sites considering current and future impacts, apply an evaluation tool for selecting and designing appropriate and climate-smart restoration interventions, and develop a local Restoration Action Plan using a template.

PLANNING A SMART APPROACH

Restoration is not a 'one size fits all' approach, and each aspect of a restoration program, from goals to methods used, should be tailored to the specific needs and abilities of each location. If coral reef restoration is deemed appropriate, it is critical that goals and objectives be clearly defined. Goals and objectives should be crafted that follow the SMART approach, meaning they are Specific, Measurable, Achievable, Relevant, and Timebound. Applying SMART objectives for specific goals will help define the scope of the restoration efforts in terms of both space and time, and guide operations in terms of specific resources needed for each objective.

From this information, restoration sites can be selected where restoration is most relevant to your goal (e.g. on windward sides of the island or valuable coastlines if your goal is to improve coastal protection services), coral survivorship is likely in the near and long-term (e.g. according to local management and climate change model predictions), and restoration is required to improve condition (e.g. natural recovery processes will not occur without intervention). Well-defined objectives will also allow for targeted monitoring programs, beyond 12 months, that should improve understanding and reporting of long-term recovery patterns and adaptive management needs through time.

BUILDING AN ADAPTIVE DESIGN

Methods of interventions should be chosen and designed specifically to achieve your goal. For example, outplanting corals can be done through direct transplantation, asexual fragmentation with a nursery, or corals reared from gamete collection or a combination of the above. We provide guidance below on the suitability of methods to different restoration goals (Figure 3). However, managers are advised to stay up-to-date as technologies used in coral reef restoration are evolving rapidly (see links to resources). Overall, the selection of interventions should include careful considerations of scale, cost-efficiency, and feasibility (see Figure 4). Pilot studies should be included to refine the choices of sites and methods and the Action Plan prior to full implementation. In addition, climate change considerations should be applied to the design of interventions to ensure the restoration project has the best possible chance of success under future climate conditions (see Van Hooidonk et al. 2016; West et al. 2017,2018).

ENGAGING STAKEHOLDERS AT ALL STAGES

Engagement with stakeholders, local communities, Indigenous communities, and traditional owners in all stages of restoration planning and implementation is critical to reduce potential conflicts associated with the use of reef resources and maximise collaborations and investment opportunities. Incorporating traditional or local knowledge of the specific reef system of concern will improve the chances of restoration success. Appropriate engagement and communication are critical to maximise the flow of socio-cultural and economic benefits beyond the people directly involved in the restoration effort, therefore securing longer-term support. Coral reef restoration can be a useful educational tool that encourages tangible behavioural changes and improves the social resilience of local communities, the economic resilience of local reef-reliant industries, as well as the ecological resilience of the reef (Hein et al. 2019).

4.3 Monitoring and communication

MEASURING EFFICACY AND HAVING AN EXIT PLAN

Improving the efficacy and efficiency of coral reef restoration efforts does not stop with careful planning and design but should also incorporate a long-term plan specifically around monitoring and communication, and an Operational Plan with an exit strategy detailing long-term sustainability of the project (see the *Open Standards for the Practice of Conservation,* CMP 2020). Monitoring is crucial to inform decision-making and help redefine goals and methods as the field evolves, i.e. adaptive management. Monitoring is also essential to increase transparency and accountability. In some instances, scoring methods (e.g. MERCI_COR, Pioch et al. 2017) can help assess gains and losses associated with the interventions. Ideally, restoration efforts should be set up in a way that allows for an assessment of effectiveness (with control sites and/or following a before/after/control/impact (BACI) design , see Falk et al. 2006; Gann et al. 2019), and monitored and evaluated consistently, so improvements can be made as the project evolves and environmental conditions change.

To date, monitoring has strongly focused on assessing the efficacy of methods used by tracking the fate of transplanted corals in the first months following transplantation (Hein et al. 2017; Boström-Einarsson et al. 2020). Including long-term monitoring of ecological, social, and economic outcomes tailored to specific goals and objectives is integral to furthering the understanding of the effectiveness of coral reef restoration to assist the recovery of degraded reefs. Such long-term monitoring plans will require a longer-term vision (5 to 10 years) for planning and investment. While monitoring plans may vary across regions and the goals of specific projects, they should follow international standards highlighted in the CRC's *Coral Reef Restoration Monitoring Guide: Methods to Evaluate Success from Local to Ecosystem Scales* (Goergen et al. 2020) as closely as possible. Improving the standardisation of monitoring plans will advance our understanding of the effectiveness of restoration in meeting socio-ecological goals and the return on investments.


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COMMUNICATING PROJECT OUTCOMES

Communication of both successes and failures is critical to improve collaboration and outreach (DeAngelis et al. 2020). Improved communication on the role and effectiveness of coral reef restoration as a tool for coral reef management is instrumental for supporting decisions and policies on coral reef protection. It will also assist policy makers in delivering on national, regional and international commitments. Communicating monitoring results (e.g. hectares restored, number of people involved, etc.) and stakeholder engagement should provide the basis for improving research and implementation of coral reef restoration efforts globally. It is important to communicate often to keep the public engaged and to use non-scientific language that is easily understandable and relevant to your audiences. Managers and practitioners should strive to join local, regional, and international restoration groups such as the CRC and the RRN to maximise the potential for sharing and communicating lessons learned.

4.4 Recommendations on restoration goals

The recommendations outlined above are relevant for any coral reef restoration effort. However, for projects that have been designed to achieve a specific goal, it is important to consider some additional information. The following table (Table 3) was developed to highlight expert recommendations for each restoration goal listed in Table 1. These recommendations were developed to align with guidelines from SER (McDonald et al. 2016; Gann et al. 2019), as well as other recent seminal pieces (Suding et al. 2015; Gardali et al. 2019).

For example, Suding et al. (2015) highlight four key principles to ensure goals align with resilience and sustainability principles:

1. Having restoration efforts planned to enhance ecological integrity, focusing on functional groups and redundancy,
2. Having long-term goals and objectives to ensure long-term sustainability,
3. Ensuring restoration efforts are informed by the past and the future, and
4. Having the restoration effort benefit and engage society.

These principles also align with Gardali et al. 's (2019) call to design 'climate-smart' restoration efforts, in which programs account for future uncertainties associated with climate change. Timeframes for the realisation of any of the goals will be a minimum of three years, and efforts must be designed to account for how reef systems will be affected by changing conditions during and after that time. Engaging the public to foster long-term stewardship, integrating climate-change models, having a long-term monitoring plan, and building resilience through ecological integrity and redundancy are all critical considerations for the success of any restoration project in today's changing climate (Gardali et al. 2019).

This report provides an index for the suitability of each method for each of the coral reef restoration goals (Figure 4). Coral reef restoration methods currently applied in the field have been qualitatively ranked from least to most appropriate in fulfilling specific goals, based on current knowledge. This index is meant to assist managers, practitioners and decision-makers in choosing methods depending on their initial goals. Note that for most projects, multiple methods may be used to satisfy specific goals and associated objectives. Note also that given the fast pace at which the field of coral reef restoration is moving and the high level of regional and global investments, new methods that may be more appropriate are in development. The cost, scales, and efficiencies of current methods are also likely to improve in the near future.

Reefscapers coral propagation, Maldives © Reefscapers

GOALS	SOCIO-ECONOMIC GOALS			
SUB GOALS	**a. Recover and sustain coastal protection**	**b. Recover and sustain fisheries production**	**c. Sustain local tourism opportunities**	**d. Promote local coral reef stewardship**
TIMEFRAME	**Medium (3-5 years)**	**Long (> 5 years)**	**Short (< 3 years)**	**Short (<3 years)**
KEY CONSIDERATIONS	• Use nature-based solutions (green engineering, eco-design, biomimetics) as much as possible • Careful consideration of hydrology in site selection • Functional design should include ecological and physical function (habitat, species) • Consult with engineers so designs are robust (durable) against future disturbances and ecofriendly • Embed with coastal protection policies	• Site selection should consider fisheries protection and connectivity to healthy fish population • Design should maximise complexity and diversity of substrates • Design should consider potential for recruitment of desirable species • Engage fishermen and local communities as early as possible	• Engage the tourism industry in the project as early as possible • Develop effective communication plan • Design should incorporate aesthetics considerations • Develop specific training to reduce risks of doing more harm than good • Follow sustainable funding models	• Engage local stakeholders in the project as early as possible • Incorporate Indigenous knowledge in site selection and project design • Target young people • Develop effective communication plan • Embed within Resilience Based Management frameworks

GOALS	ECOLOGICAL GOALS		CLIMATE ADAPTATION AND SUPPORT GOALS
SUB GOALS	**a. Re-establish reef ecosystem function and structure**	**b. Mitigate population declines and preserve biodiversity**	**a. Mitigate impacts and promote reef resilience through climate change**
TIMEFRAME	**Long (> 5 years)**	**Medium (3-5 years)**	**Medium (3-5 years)**
KEY CONSIDERATIONS	• Long-term process • Integrate within Resilience-Based Management frameworks • Maximise diversity and functional redundancy from genotypes, to species, and growth forms • Consider positive ecological feedbacks beyond coral transplantation	• Careful site selection where disturbances have been mitigated • In-situ and ex-situ nurseries can be used as gene banks for endangered species • Maximise genetic diversity especially when target specific species	• Site selection and project design based on climate smart models • Species selection based on local knowledge of resilient coral assemblages and functional redundancy • Integrate research on coral adaptation mechanisms

GOALS	DISTURBANCE-DRIVEN GOALS	
SUB GOALS	**a. Respond to acute disturbance to accelerate reef-recovery**	**b. Mitigate anticipated coral loss prior to disturbance**
TIMEFRAME	**Short (< 3 years)**	**Short (< 3 years)**
KEY CONSIDERATIONS	• Consider substrate stabilisation and triage of live corals early on • Mitigate source of disturbance prior to restoring • Have an emergency response plan in place ahead of time (similar to oil spill response planning) • Might be constrained by insurance and permitting rules	• If possible, move corals to in-situ or ex-situ nurseries prior to disturbance • Relocation site should have similar environmental parameters to donor site • Mitigating the disturbance to avoid relocation is always the favoured solution • Aim for 'no-net loss' to offset ecological losses

Table 3. Key considerations and timeframe for restoration goals.

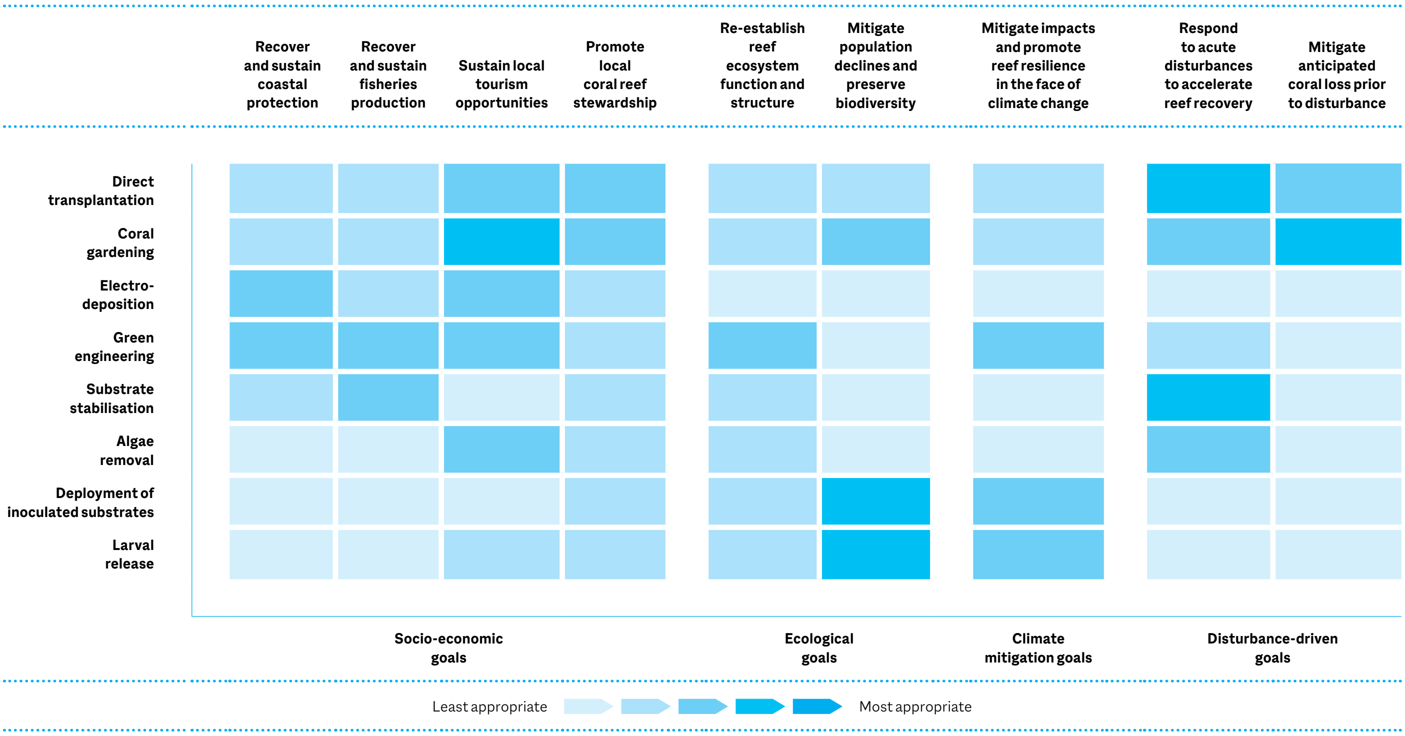


Figure 3. Method suitability index matrix for each coral reef restoration goal. The darker the colour, the more appropriate a method is to each specific goal.

Monitoring in St Thomas, US Virgin Islands © Colin Howe

4.5 Recommendations on methods

To assist practical implementation, we also drew specific challenges and recommendations for each of the methods described (Table 4). Challenges represent obstacles currently experienced in the field, while recommendations align with key principles described above to ensure methods are aligned with goals and objectives.

Each of the methods was scored from 0 to 10, where 0 is low and 10 is high, by eleven coral reef restoration experts for cost, efficiency and scalability providing a qualitative comparison among methods for these three parameters (Figure 3).

High variability in the scores reflect some uncertainty among experts given the youth of the field. Estimates of cost, scales, and efficiencies of current methods are likely to improve in the near future given the high level of regional and global investment.

Table 4. Challenges and recommendations for current methods of coral reef restoration.

METHOD	CHALLENGES	RECOMMENDATIONS
1. DIRECT TRANSPLANTATION		
	• Can be expensive • Availability of diverse coral fragments as donor material • Limited to small scale projects	• Planting sites should be as similar to donor site as possible • Avoid planting during storm and bleaching season • Maximise diversity of fragments as much as possible • Attachment methods: invest time, use non-toxic materials and/or chemicals • Use citizen science to reduce cost and increase engagement • Have a plan to monitor and maintain outplanting site
2. CORAL GARDENING		
	• Cost and labour intensive • Limited to small scale projects • Materials used are often not eco-friendly or not resistant to damage or degradation over time • Health of corals can be compromised due to algae overgrowth and spread of disease in high density nurseries • Requires sustained maintenance that can be expensive	• Requires careful consideration of depth and other environmental factors at nursery sites (e.g. water quality, wave action) • Have a plan for extreme weather events • Plan to maximise diversity of fragments in nursery: growth forms, sources, species, and genetic diversity • It is a two-step process: see recommendations for direct transplantation • Have a long-term plan for maintenance and removal of the nursery once restoration project is complete
3. SUBSTRATE ADDITION (ARTIFICIAL REEFS)		
3.1 Electro-deposition	• Very expensive and difficult to deploy • Limited evidence of success • Needs a reliable power source	• Develop more research to justify its usefulness compared to simpler structures • Consider alternative local sources of energy (solar, wind)
3.2 Green engineering (Nature Base Solution, eco-design)	• Expensive to design and deploy • Limited to small scale projects • Limited evidence of success linked to structures being overgrown by corals • Failure can have lasting detrimental effect on reef aesthetics	• Consult engineers for optimal design depending on goals • Materials used should integrate potential to become living structure (recruitment potential on the structure following bio-mimetic principles of green engineering) • Consider impact of structure(s) on the site hydrodynamics • Mostly relevant when reef structure and stability has been compromised
4. SUBSTRATE MANIPULATION		
4.1 Substrate stabilisation	• Can be very expensive to deploy • Can have poor aesthetics • Limited evidence of success, approaches not very well documented • Difficult to assess when it's appropriate to use (natural recovery versus intervention)	• More research into natural ways to stabilise substrate (e.g. natural binding by sponges or crustose coralline algae) • Apply careful consideration of hydrodynamics
4.2 Algae removal	• Algae can grow back quickly • Very labour intensive • Risk of removing natural, non-invasive algae species and disrupt positive ecological processes	• Use in conjunction with other intervention that increase herbivory and control water quality • Time removal around coral recruitment • Use citizen science and volunteers to maximise engagement
5. LARVAL PROPAGATION		
5.1 Deployment of inoculated substrate	• Expensive, labour intensive, and requires expert knowledge • Limited evidence of long-term success due to the novelty of the method • Substrates can become overgrown by algae, sponges, and other sessile invertebrates compromising recruits' health and survival	• Need to improve coral recruits' growth and survival substrates • Invest in technology development and training to scale-up current efforts • Optimise outplanting strategy to promote self-sustaining populations of sexual recruits
5.2 Larvae release	• Expensive: requires a lot of equipment and involvement of experts • Difficult to engage the public and community members • Evidence of success currently limited by high post-settlement mortality • Timing of action dictated by coral spawning • Long time scale for meaningful ecological outcomes	• Consider mixing genets from different regions (Assisted Gene Flow) • Potentially one of the most scalable methods for coral reef restoration, and a research priority for making this method more accessible and improving coral recruits health, growth, and survival

PLOT KEY

Violin plots illustrate the full range of answers – here scores of cost, efficiency and scalability from 0 to 10.

Lines indicate a lack of consensus

Bulges indicate some consensus

Dotted lines represent average scores

ALGAE REMOVAL

COST — Average

EFIICIENCY — Average

SCALABILITY — Average

CORAL GARDENING

COST — Medium to High

EFIICIENCY — Average

SCALABILITY — Medium to High

DIRECT TRANSPLANTION

COST — Average

EFIICIENCY — Average

SCALABILITY — Medium to Low

ELECTRO-DEPOSITION

COST — High

EFIICIENCY — Low

SCALABILITY — Low

LARVAL PROPAGATION

COST — High

EFIICIENCY — Average

SCALABILITY — Medium to High

SUBSTRATE ADDITION

COST — High

EFIICIENCY — Medium to Low

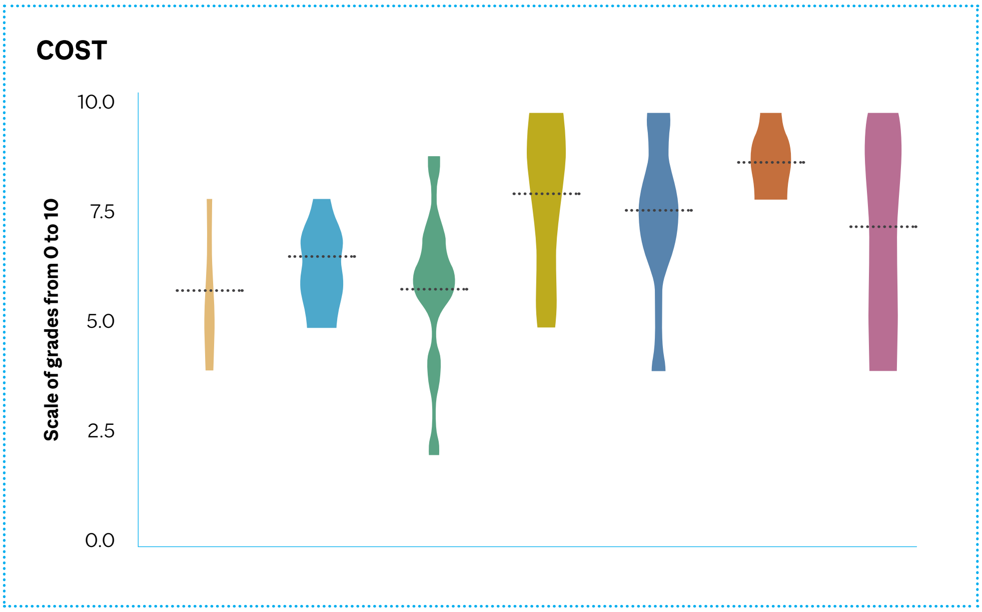
SCALABILITY — Average

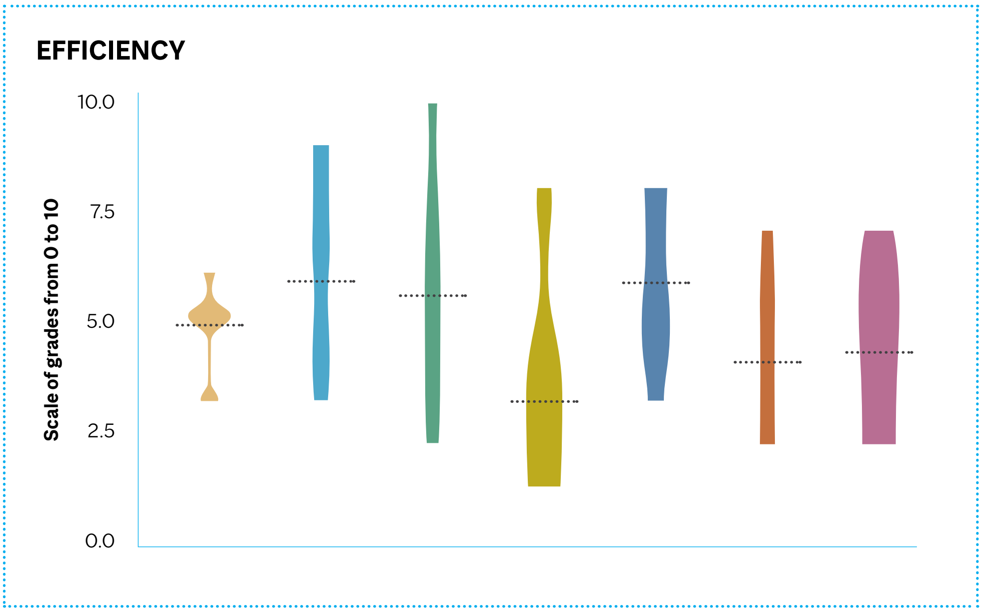
SUBSTRATE STABILISATION

COST — Medium to High

EFIICIENCY — Medium to Low

SCALABILITY — Average





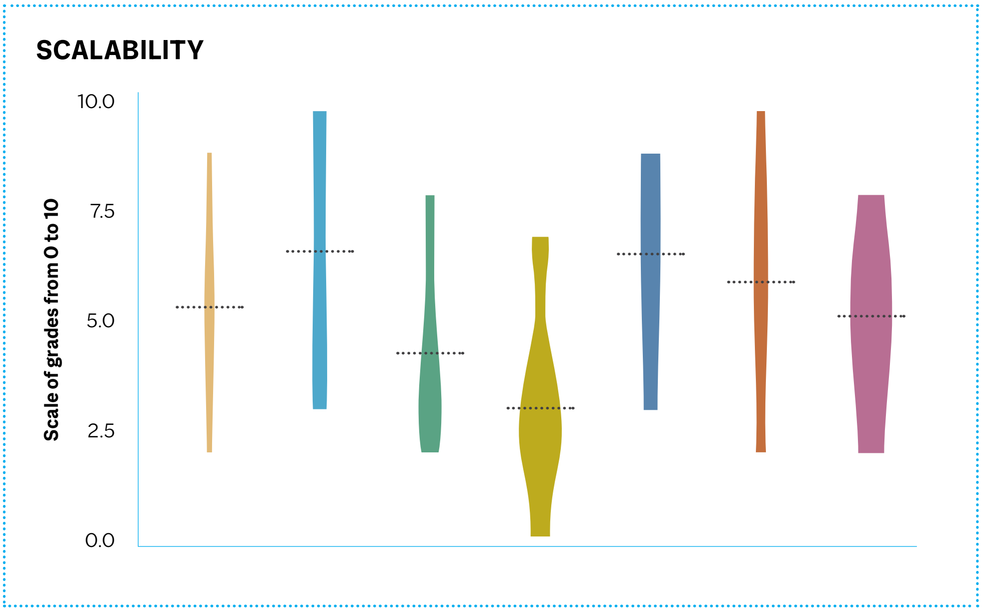
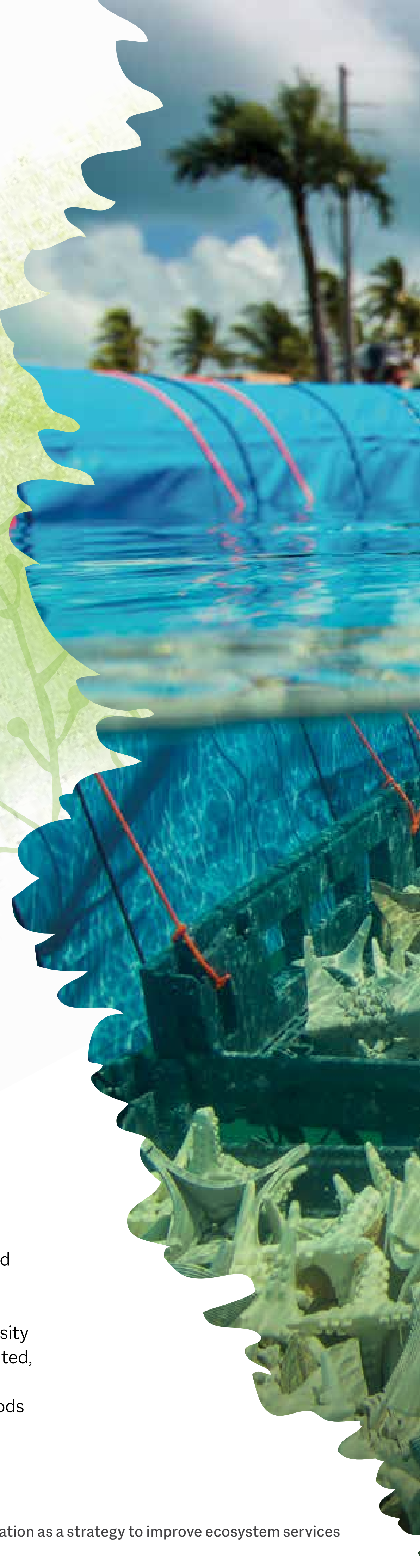


Figure 4. Violin plots representing cost, effectiveness, and scalability of seven common coral reef restoration methods, graded on a scale of 0 to 10 by 11 global experts.

5

CONCLUSIONS



The goal of this report is to assist practitioners, managers, and decision-makers to decide whether and how to use coral reef restoration as a strategy to protect coral reefs locally, regionally, and globally. As coral reefs have experienced catastrophic losses in health and cover during the last few years, the need for coral reef restoration efforts is accelerating.

Whilst not designed to reduce climate impacts, coral reef restoration can be a useful tool to support resilience, especially at local scales where coral recruitment is limited, and disturbances can be mitigated. With ongoing and further investment in research and development, cost-effectiveness of established and new methods should improve the scalability and effectiveness of coral reef restoration interventions. However, at present, given the limited spatial scale, high costs, and limited evidence for long-term, ecologically relevant success, the necessity of applying coral reef restoration should be carefully thought through. If implemented, it should be integrated within an overarching reef resilience-based management framework. In the context of climate change, applying coral reef restoration methods effectively and efficiently requires 'climate-smart' designs that account for future uncertainties and changes (Parker et al. 2017).

Settlement substrates in the CRIB
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Diver performing coral tree maintenance
© Zach Ransom, Coral Restoration Foundation™

Current information and projections on the specific vulnerability of a reef site to climate change should be incorporated in initial planning to ensure the chosen intervention(s) have a chance to withstand future conditions (West et al. 2017, 2018; Shaver et al. 2020). Increased consideration of ecological engineering, beyond just planting corals, that integrate reef-wide and long-term ecological succession processes are necessary to improve on the current scale, cost and effectiveness of coral reef restoration methods (Shaver and Silliman 2017; Rinkevich 2020).

Following recommendations from SER, we suggest coral reef restoration strategies follow four critical steps: 1) planning and assessing around specific goals and objectives, 2) identifying adaptive strategies to balance risks and trade-offs, 3) engaging communities in all stages of the restoration efforts, 4) developing long-term monitoring plans to allow for adaptive management and improving the understanding of methods' effectiveness for specific goals.

Source of trusted information to follow up:

- A Manager's guide to coral restoration planning and design: https://www.coris.noaa.gov/activities/restoration_guide/welcome.html

- Online database for Boström-Einarsson et al. 2020's "Coral restoration- a systematic review of current methods, successes, failures and future directions: https://doi.org/10.1371/journal.pone.0226631.g003

- IFRECOR's ecological engineering guide by Léocadie et al. 2019: http://www.ifrecor-doc.fr/items/show/1877

- ICRI's report mapping current and future priorities for coral restoration and adaptation programs: https://www.icriforum.org/wp-content uploads/2020/05/ICRI_MappingPriorities_lowres_DEC19-1.pdf

- NASEM report on interventions to increase the resilience of coral reefs: https://www.nationalacademies.org/our-work/interventions-to-increase-the-resilience-of-coral-reefs

- NOAA Corals and climate adaptation planning design tool: https://www.coris.noaa.gov/activities/CCAP_design/

- RRAP website https://www.gbrrestoration.org

- CRC website http://crc.reefresilience.org

- RRN website https://reefresilience.org

6

CASE STUDIES

Collecting elkhorn coral gametes
© Paul A Selvaggio, Secore International

6.1 CORAL NURTURE PROGRAM

by David Suggett

GOALS

Promote local reef stewardship and build more sustainable tourism economies

LOCATION

Great Barrier Reef, Australia

THE CHALLENGE

Australia's iconic Great Barrier Reef (GBR) has experienced catastrophic loss of coral (>30%) from mass bleaching via back-to-back marine heatwaves (2016–17), with a third event underway in 2020. These unprecedented impacts solidified concerns that conventional GBR management – largely marine area protection and mitigating deteriorating water quality – was no longer sufficient to secure the GBR's future. This prompted government investment into national intervention – and dynamic adaptive-management options. The tour operator industry largely sustains the GBR's $6.5B per year asset value and has an overwhelming desire to maintain and restore the quality of their 'high value' reef sites (Suggett et al. 2019). Whilst the desire was in place to specifically adopt established coral propagation practices for site-tailored reef rehabilitation (e.g. from the Caribbean, and rapidly developing elsewhere), capacity was limited by fundamental legislative, governance and operational barriers designed for reef protection.

The objective was to develop low cost approaches that could dovetail into existing operations and thus be cost effective, but also easily adopted into existing tour operator business models.

ACTION TAKEN

Initial activities, 'Phase one' (February 2018-February 2019), were designed in partnership with the government's Great Barrier Reef Marine Park Authority (GBRMPA) to design the workflow for, and in turn implement, coral propagation practices. Detailed site ecological surveys, alongside assessments of historical site knowledge, were conducted to help guide the first nursery and propagation and outplanting permits. A novel physical attachment device consisting of a nail and a strap, the Coralclip® (Photo 1), was invented, which sped-up planting by one or two orders of magnitude faster (and hence more cost-effectively) than was previously possible via conventional chemical fixatives used to date (Suggett et al. 2020). From this first phase, over 2500 corals were maintained in the new nurseries and nearly 5,000 corals outplanted to Opal Reef in the space of a few weeks (Suggett et al. 2020), largely during routine vessel operations and using operator staff to outplant.

Photo 1. Examples of Coralclip® deployment: Top, new Coralclip® attachment, securing branching Acropora; Bottom is aged Coralclip® (3 months) where device is largely non-visible and coral has cemented in place. Bottom left shows example of securing *Acropora hyacinthus* in place to the sides of substrate © John Edmondson (Wavelength Reef Cruises).

Subsequent ‘Phase Two’ CNP activities (April 2019-April 2020) examined how the approach developed for the test site and tourism operator via ‘Phase One’, applied to multiple reefs with different environments and coral conditions, and among multiple tourism operators with different business models. Efforts focused on ensuring standardised workflows for establishing nurseries and outplanting across operators and sites – including training, site evaluations and data reporting (in part for ecological trajectory assessments as well as permit compliance; Photo 2).

Photo 2. Coral Nurture Program at work. Top: Operators tending to nurseries and outplanting using Coralclip®. Bottom: surveying outplant success as part of the ‘Phase two’ kick-off workshop amongst multiple GBR tourism operators, staff, researchers and GBRMPA.

HOW SUCCESSFUL HAS IT BEEN?

As of May 2020, over 50 nursery platforms have been established and over 17,000 corals planted across six major high-value tourism sites, as a result of the Coral Nurture Program tourism-research partnership. Operators were equipped with the knowledge and tools to 'pivot' and redeploy efforts and resources from tourism to site rehabilitation during the COVID19-induced tourism downturns.

Planning has begun towards 'Phase three', which includes broader (regional) adoption amongst the tourism industry – as well as other key GBR stakeholders, notably traditional owners – and fully tracking ecological responses of the outplanting sites, to ensure these initial efforts inform 'what works best, where and when' in deciding future scaling of activities.

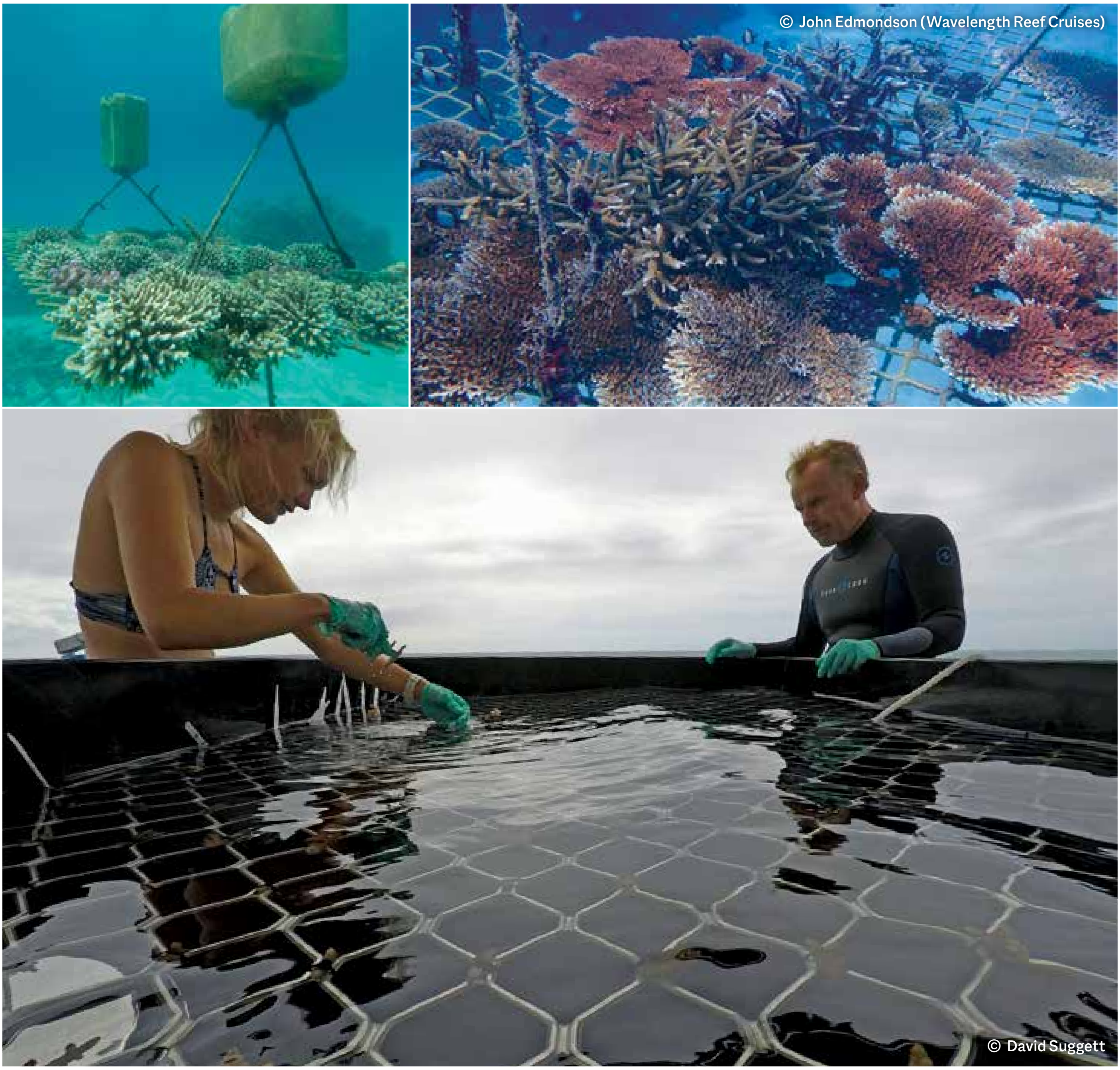

Photo 3. Application of the floating coral propagation nursery platforms, Opal Reef, GBR. Top shows growth of coral after 12-18 months propagation from fragments. Bottom is 'on-deck' seeding tray initially trialled to sow frames with fragments during the early phases of deployment.

LESSONS LEARNED

1. Adapting nursery and outplanting design to fit location-specific requirements

Tools were conceived specifically for the conditions that had driven the need for restoration. For example, numerous coral species (across all growth morphologies) had been impacted at GBR sites, and therefore floating platforms were designed in favour of existing 'coral tree' structures to consistently accommodate any taxa, but also within often physically dynamic outer reef sites (Suggett et al. 2019; Photo 3).

2. Monitoring and implementation

Based on the extent of outplanting achieved in 'Phase One' for the test site, it was clear that attempting to 'fate track' 1,000s of outplants was impossible, and instead the outplant 'success' evaluations were established around ecological approaches using marked replicate plots of reef (and un-amended controls). Initial installation of nursery platforms at all sites provided very visible demonstrations relatively quickly to the operators and their tourist customer base of active site rehabilitation practices. Active outplanting was slower to adopt, and ultimately was best executed in targeted 'campaigns' when staff were available without impacting on regular operations.

3. Empowerment and capacity building is key

Empowerment and capacity building are at the core of the approach and philosophy of CNP. Stakeholders want to save the reef, and researchers want to help support robust methods to do this. Therefore, the partnership we built between researchers and tourism operators (or any other stakeholder) capitalised on the passion and drive of all involved to make positive change. The desire to optimise effective practice(s) tailored to the GBR has been critical in ensuring key lessons are learnt prior to initiating projects purely for commercial gain, in particular where the ecological impacts are yet to be fully resolved. Importantly, scientific rigour has been central in driving increased social licencing, learning through implementation, but under well controlled environmental and social conditions. This has been central in building trust amongst researchers, stakeholders and the wider public to better define when restoration is (and isn't) appropriate for the GBR.

FUNDING SUMMARY

Australian & QLD Government ('Boosting Coral Abundance' Challenge. AMP Foundation)

LEAD ORGANISATIONS

University of Technology Sydney
Wavelength Reef Charters

PARTNERS

Ocean Freedom
Passions of Paradise
Quicksilver/Great Adventures
Sailaway
TropWATER James Cook University
Great Barrier Reef Marine Park Authority

RESOURCES

www.coralnurtureprogram.org

Suggett, D. J., Camp, E.F., Edmondson, J., Boström-Einarsson, L., Ramler, V., Lohr, K., Patterson, J.T. (2019). Optimizing return-on-effort for coral nursery and outplanting practices to aid restoration of the Great Barrier Reef. Restoration Ecology 27, 683-693.

Suggett, D.J., Edmonson, J., Howlett, L., Camp, E.F. (2020). Coralclip®: a low-cost solution for rapid and targeted out-planting of coral at scale. Restoration Ecology 28, 289-296.

6.2 ECO-DESIGNED MOORING PROJECT

by Sylvain Pioch

GOALS

Nature based solution to stop anchoring damage and develop new substratum for coral implantation

LOCATION

Deshaies bay, Guadeloupe

THE CHALLENGE

Our challenge was to design a new mooring system that would 'kill two birds with one stone' by reducing the impacts, from boat anchors in coral reef and seagrass areas, and to enhance coral colonisation and associated fauna. The new mooring system was to integrate an eco-design approach as a Nature-Based Solution (NBS) which mimicked coral habitats and their ecological functions using methods of green engineering.

ACTION TAKEN

First, protection actions were taken by prohibiting anchoring in the bay of Deshaies, and then eco-mooring devices were designed and implemented. A total of 40 mooring blocks were designed to attract coral larvae settlement. The blocks mimicked natural roughness, pits and the shape of small caves that could be found in surrounding coral reefs (Photo 4). As an NBS approach and eco-design construction (Pioch et al., 2017), the size, orientation and aesthetic parameters were considered to enhance the ecosystem integration of this eco-mooring project.

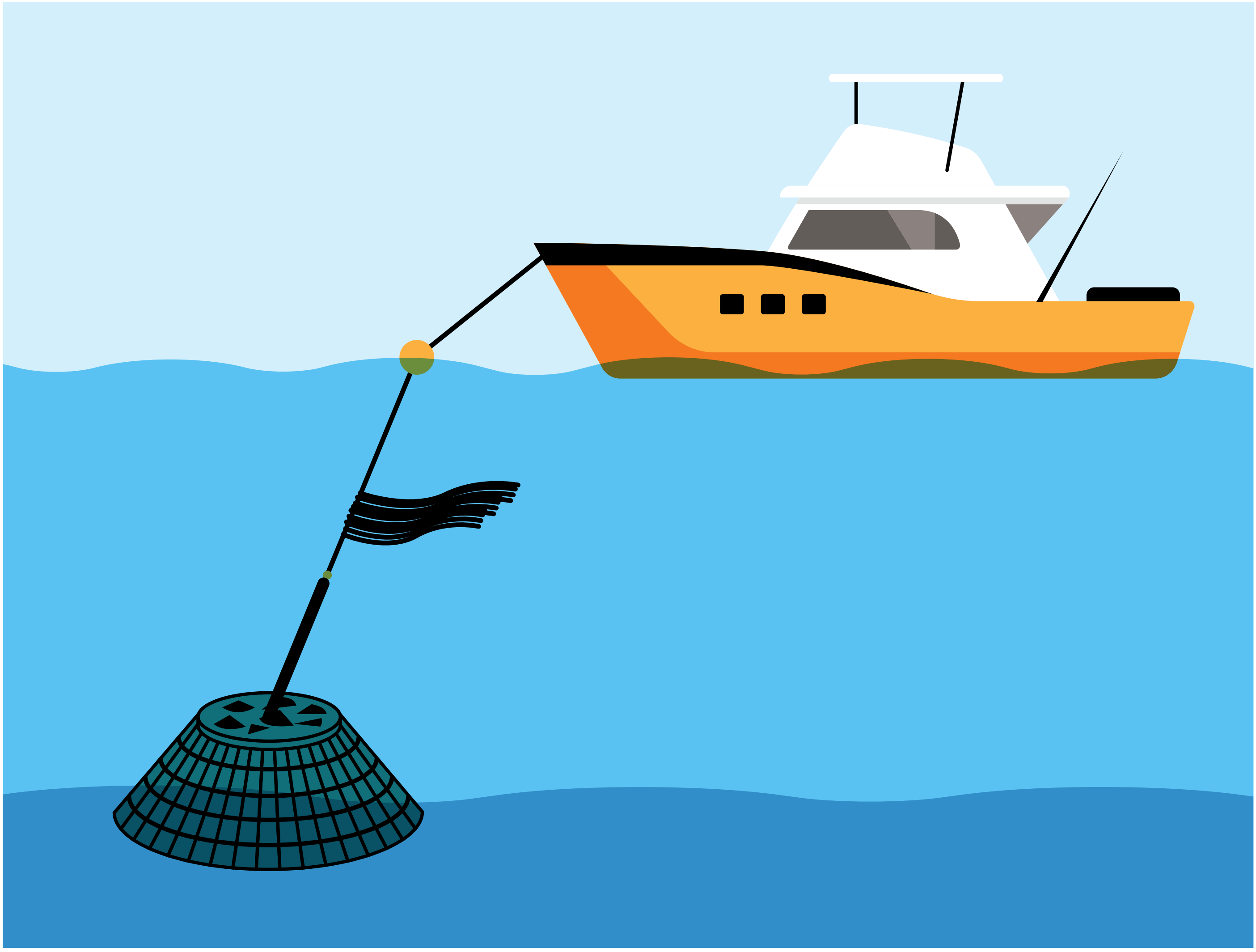

Photo 4. The concept of eco-mooring to maintain safe boating or yachting tourism and effective coral substratum (adapted from Pioch S.).

HOW SUCCESSFUL HAS IT BEEN?

The six years of ecological monitoring showed a return of normal growth of coral and seagrasses in the bay of Deshaies, after boating anchoring prohibition and installations of the eco-moorings. After six years, 52% of local coral species had settled on the eco-moorings, even though the total surface of the 40 mooring blocks only covered 300 m^2 in the bay.

Altogether, nine species of coral (*Agaricia agaricites, Porites astreoides, Porites divaricata, Diploria labyrinthiformis, Pseudodiploria strigosa, Colpophyllia natans, Meandrina meandrites, Siderastrea radians and Favia fragum*) and 43 species of fish were recorded on and around the mooring blocks (Photo 5). In comparison, 17 species of corals and 25 species of fish were recorded in adjacent natural coral areas.

Photo 5. Mooring system with coral recruitment on a mangrove 'skirt' (Bouchon, C.).

LESSONS LEARNED

1. Design

Three different models were tested to assess the capacity of different concrete treatments and surface roughness to attract coral recruits. The 'mangroves roots' design was by far the best for coral recruitment (Photo 4).

2. Storm resistance

Corals settled on the eco-mooring resisted and survived the passage of the super hurricane Irma in 2017, and its 17m high waves.

FUNDING SUMMARY

Regional environmental and development agency (SEMSAMAR; 50%), local community (city and county; 30%), European funding (20%). The cost of one eco-mooring was €4,000 (US$4,320) with an expected durability of 50 years.

LEAD ORGANISATION

Regional environmental and development agency (SEMSAMAR). The monitoring was done by the University of Antilles, Borea (Prof. Claude Bouchon) and Caraïbes Aqua Conseil consulting (CAC).

PARTNERS

National Natural Park of Guadeloupe, fishermen, local diver's shops, diving clubs and French Water Agency.

RESOURCES

Pioch, S., Léocadie, A. (2017). Overview on Eco-moorings facilities: Commented bibliography. International Coral. Reef Initiative (ICRI), Foundation for the Research on Biodiversity (FRB) report. https://www.icriforum.org/sites/default/files/OVERVIEW%20of%20eco-mooring-light.pdf

6.3 LONG-TERM OUTCOMES OF REPEATED RESTORATION EFFORTS

by Buki Rinkevich

GOALS

1. Evaluate long-term outcomes of coral outplanting;
2. Reveal the ecological engineering outcomes of successive restoration acts in a specific site.

LOCATION

Eilat, Gulf of Eilat, Israel

THE CHALLENGE

Our challenge was three-fold: 1) A conceptual challenge – to restore a denuded reef that has been degraded by intensive anthropogenic activities, and is still impacted by unremitting human impacts; (2) An ecological engineering challenge – to significantly enhance long-term survivorship of transplanted coral colonies; (3) A technical challenge – to securely attach transplanted corals on hard bottom three-dimensional reef structures, including vertical substrates.

ACTION TAKEN

1. Nursery phase

Eight locally common coral species were selected for the project: seven branching species (*Stylophora pistillata, Pocillopora damicornis, Acropora variabilis, A. humilis, A. pharaonis, A. valida, Millepora dichotoma*) and a massive species (*Dipsastraea favus*). Coral nubbins were pruned from donor colonies and were maricultured until they reached sizes of fully developed colonies in an underwater floating reef nursery installed in the northern Gulf of Eilat (Photo 6A).

2. Permitting phase

Another major challenge included getting permits for the transplantation site, the transplantation methodologies and procedures, and the number of transplanted coral colonies per site.

3. The transplantation phase

The approved transplantation site was a reef off Dekel Beach, about 3 km southwest of the nursery. This area is heavily impacted by various anthropogenic activities due to its proximity to the navy, the commercial ports, and a popular diving centre. The shallow reef at Dekel Beach (6-13 m depth) consists of scattered knolls on a sandy slope, mostly denuded of corals. We randomly selected 11 knolls that were divided into either 'transplanted' or 'reference' groups. A total of 1,400 coral colonies were transplanted during three transplantation sessions. The first session was started in 2005, and the following sessions occurred in 1.5 year intervals, which allowed us, for the first time, to repeat transplantation (i.e. add transplants onto knolls transplanted in former outplanting sessions). The transplants were secured to the knolls using an underwater drilling methodology that enabled the transplantation on vertical facets for maximum coverage of the target area. Monitoring was performed every 2-3 months over the first six years and sporadically for the next 9 years (now 15 years since first transplantation event). The overall transplantation plan is described in Horoszowski-Fridman et al. (2015, 2020b).

HOW SUCCESSFUL HAS IT BEEN?

This study revealed encouraging and surprising results.

1. Coral outplanting was not associated with any recorded stress to the coral colony, and over the long-term, the nursery-bred transplants had slightly lower survival rates than the highly adapted colonies naturally growing at the experimental site (Horoszowski-Fridman et al. 2015, 2020b).
2. Despite challenging environmental conditions at Dekel Beach reef site, the farmed transplants continued growing at enhanced rates, equivalent to those recorded in the coral nursery.
3. The drilling methodology employed increased transplantation efficiency compared to gluing/ cementing approaches and enabled transplantation on vertical facets (Horoszowski-Fridman et al. 2015).
4. Repeated transplantation dramatically improved the survival of transplants. After 15 years, only the knolls that were repeatedly transplanted are still flourishing (Photo 6B).

5. *Stylophora pistillata* had improved reproductive outputs, releasing ten times more larvae than the colonies naturally growing at Dekel Beach for the 8 years following transplantation.
6. Transplants provided new habitats for coral-associated organisms (fish and invertebrates) that recruited to the restored site in high numbers.

Photo 6. Long-term outcomes of repeated restoration efforts in the Gulf of Eilat, Israel. A. Coral mariculture at the Eilat's mid-water floating nursery (10 m depth): new colonies are generated from small fragments (left in the photo) and reared until developed to large colonies ready for transplantation (right). Photo: Y. Horoszowski-Fridman; B. A transplanted knoll at Dekel Beach, 11 years after it was restored by the 'marine silviculture' repeated methodology. Transplant colonies created complex spatial structures supporting a diverse reef-associated fauna. This knoll remained the same even 15 years post- transplantation. Photo © S. Shafir.

LESSONS LEARNED

(a) Coral reefs can be restored even in sites where anthropogenic impacts are not relieved

(b) Nursery-farmed transplants can have enhanced and improved growth rates and reproductive outputs compared to local colonies

(c) Nursery conditions (Photo 6A) can 'equip' transplants with improved biological traits

(d) Improved attachment methodologies to the substrate enhance restoration efficiency

(e) Repeated transplantation emerged as an important ecological engineering tool in reef restoration

(f) Long-term outcomes attest to the restoration of reef associated fauna in addition to the restoration of coral communities (Photo 6B)

FUNDING SUMMARY

Funding sources: AID-MERC program (no M33-001) and the North American Friends of IOLR (NAF/IOLR).

LEAD ORGANISATION

National Institute of Oceanography, Haifa, Israel

PARTNERS

Dr Yael Horoszowski-Fridman, Dr. Shai Shafir, Oranim College, Israel; graduate students and volunteers.

RESOURCES

Horoszowski-Fridman, Y. B., Rinkevich, B. 2020b. Active coral reef restoration in Eilat, Israel: Reconnoitering the long-term prospectus. In: D. Vaughan (ed.) Active Coral Restoration. J. Ross Publishing (in press).

Horoszowski-Fridman, Y.B., Brêthes, J.C., Rahmani, N., Rinkevich, B. 2015. Marine silviculture: Incorporating ecosystem engineering properties into reef restoration acts. Ecological Engineering 82, 201-213.

6.4 DEVELOPING THE *MISSION: ICONIC REEFS*

by Tom Moore

GOALS

Mitigate population declines and preserve biodiversity

LOCATION

The Florida Keys, Florida, USA

THE CHALLENGE

Reefs in the Florida Keys have suffered dramatic declines in the last 40 years and are not recovering on their own. Current management and local, independent reef restoration efforts are not enough to stop decline, particularly after recent impacts from hurricane Irma and outbreaks of the fast-spreading stony coral tissue loss disease (SCTLD). Urgent emergency action is required – one that involves collaboration among many local, national and international partners. The challenge involves finding actions to intervene on causes of decline, scale up current restoration efforts, and develop new and lasting collaboration with key partners.

ACTION TAKEN

Development of the *Mission: Iconic Reefs* project. The process started in 2019 and lasted over 6 months involving 25 local researchers, restoration practitioners, and members of several state and federal agencies. The plan was to use the best available restoration science and allow for research and development to occur concurrently with phases of active construction. Two in-person meetings and numerous conference calls were organised to plan restoration around specific goals:

1. *Site selection:* the aim was to select sites spread out throughout the upper, middle, and lower Keys, and representative of multiple reef types across a wide geographic range to help spread the risk of large-scale impacts. The site selection process involved in-depth habitat mapping and measuring efforts.

2. *Specific restoration objectives* were developed for each reef site in consecutive phases to meet 10-year and 20-year goals (Figure 5). Defining objectives involved developing target percent cover for each habitat zone and translating these targets to an estimate of number of planted corals required. It also involved consideration of the capacity to achieve these targets from production to outplanting, and monitoring capacity (Figure 5).

*This figure represents the generalized % cover at the 7 Iconic Reef Sites based on preliminary data and observations from 2019, post-disease event. **Within the appropriate reef sites and zones for species targeted in Phase 1A (Elkhorn Coral). All percent cover values are generalized estimates across the sites and zones. Exact values are available on a per reef and zone basis.

2019

STATUS QUO

2% CORAL COVER*

(Based on 2019 observations from Iconic Reef sites only)

No action leaves the reef precipitously close to functional collapse and at significant risk with major economic implications.

- Trending Down
- Ecological Catastrophe
- Widespread Economic Implications
- Very Little Time

2020 – 2025

PHASE 1A

10% CORAL COVER**

Elkhorn Restoration –focuses on quickly restoring reef structure with rapidly growing framework building corals that are not affected by the current disease event.

- Immediate Start
- No R&D Required
- No Special Permitting
- Rapid Results

2021 – 2028

PHASE 1B

15% CORAL COVER

Balances the reef with a more diverse group of corals and the addition of other non-coral species such as grazers.

- Infrastructure Buildout
- Some R&D Needs
- 1-2 Year Ramp Up
- 7 Year Construction Period

2025 – 2035

PHASE 2

25% CORAL COVER

Focuses on slower growing corals that give the reef its full diversity and cover. Completion of Phase 2 should result in a resilient and regenerative reef.

- Utilizes Phase 1 Infrastructure + New
- Achievable R&D
- 10 Year Construction Period

Figure 5. Generalized coral cover targets and associated restoration actions for the three consecutive phases of the *Mission: Iconic Reefs* project.

3. *Novelty actions considered:* based on lessons learned from past projects, new actions were added to the restoration plan (Figure 6). First, active site preparation will be considered prior to the beginning of the restoration effort, and not only where corals are being planted but rather as large-scale removals of invasive and nuisance species across a site before restoration begins.

Second, active supplementation of herbivores back to the sites including *diadema* sea urchins and king crabs will be considered in Phase 1B.

Third, a stewardship and maintenance program will be incorporated throughout the process to ensure that sites are checked on a more frequent basis and that issues are addressed while they are still minor.

4. *Source funding and build collaboration:* public and private funding streams will be sourced by multiple organisations using a partnership approach. This public-private partnership should be coordinated by a collection of stakeholders, managers, and citizens and be known as the Florida Keys Restoration Council.

1 **SITE PREPARATION**
Prior to restoration, nuisance and invasive species will be removed and substrate cleaned and prepared for corals.

2 **CORAL PROPAGATION AND PLANNING**
Coral fragments will be grown in ocean and shoreside farms for ~1 year prior to being planted on the reef in clusters that will form a larger coral.

3 **SUPPLEMENT WITH GRAZERS**
To restore ecological balance and prevent future algae overgrowth the site will be supplemented with sea urchins and crabs.

4 **STEWARDSHIP AND MAINTENANCE**
Sites will receive regular professional and volunteer maintenance to fix broken corals, remove debris, and ensure coral health.

5 **MONITORING AND ADAPTIVE MANAGEMENT**
Performance monitoring will ensure that project success and failures can be incorporated onto ongoing work and future projects.

Figure 6. Suite of actions considered to achieve the restoration objectives for the *Mission: Iconic Reefs* project.

HOW SUCCESSFUL HAS IT BEEN?

1. *Site selection:* Seven iconic reefs narrowed down from a list of 37 initial reef sites. Reef sites were chosen based upon characteristics such as likelihood of success, biodiversity and habitat composition, connectivity to other habitat types, allowable and compatible human uses, and current enforcement and compliance activities. The final seven reef sites are spread out along the stretch of the Florida Keys (Figure 7).

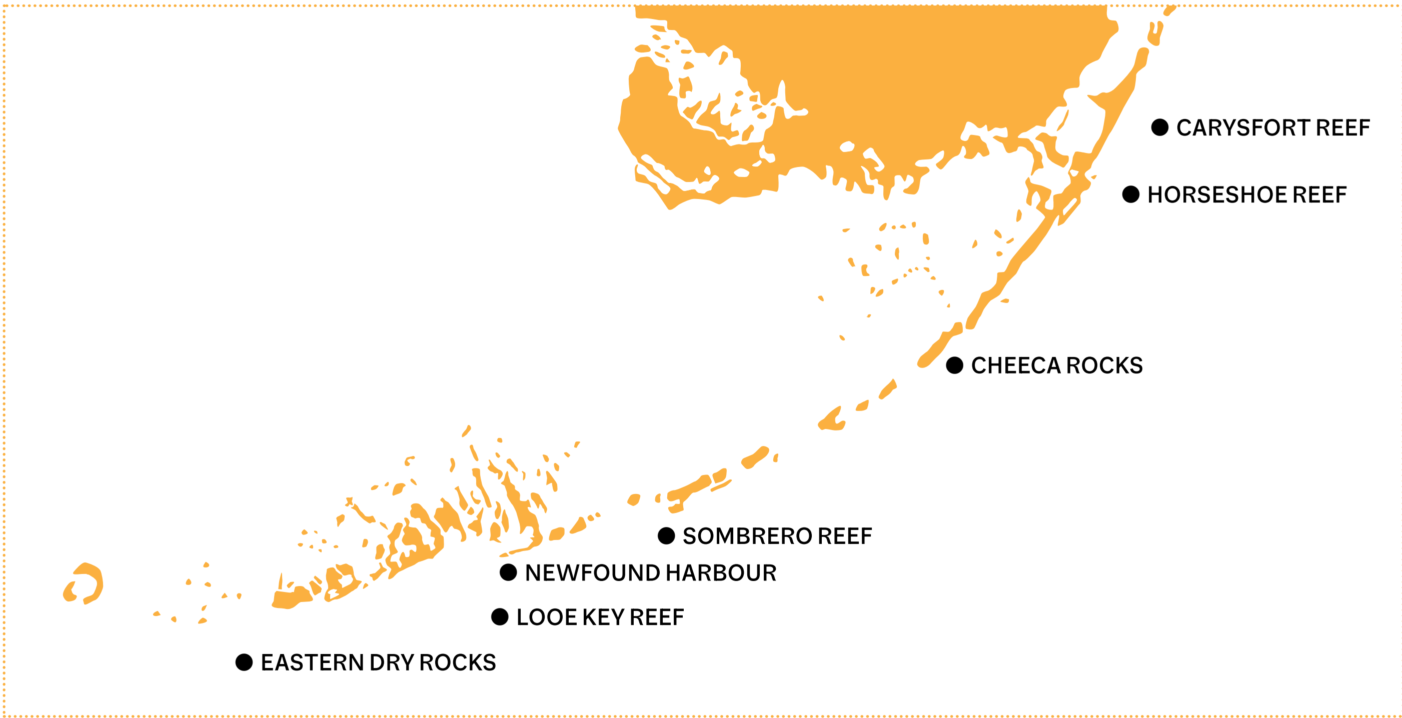

Figure 7. Map of the 7 iconic reefs chosen along the Florida Keys for the *Mission: Iconic Reefs* project.

2. *Restoration plan:* Specific objectives were laid out in percent cover of corals as well as number of corals outplanted in distinct implementation phases. Targets to achieve these objectives were differentiated among reef zones and coral species (Figure 8, Table 5) and developed for each of the seven selected reef sites (Figure 8). These targets were broken down among the different phases of the project, including specific monitoring plan and flexibility for adaptive management. Objectives were budgeted to provide a cost estimate of necessary funding required for completion.

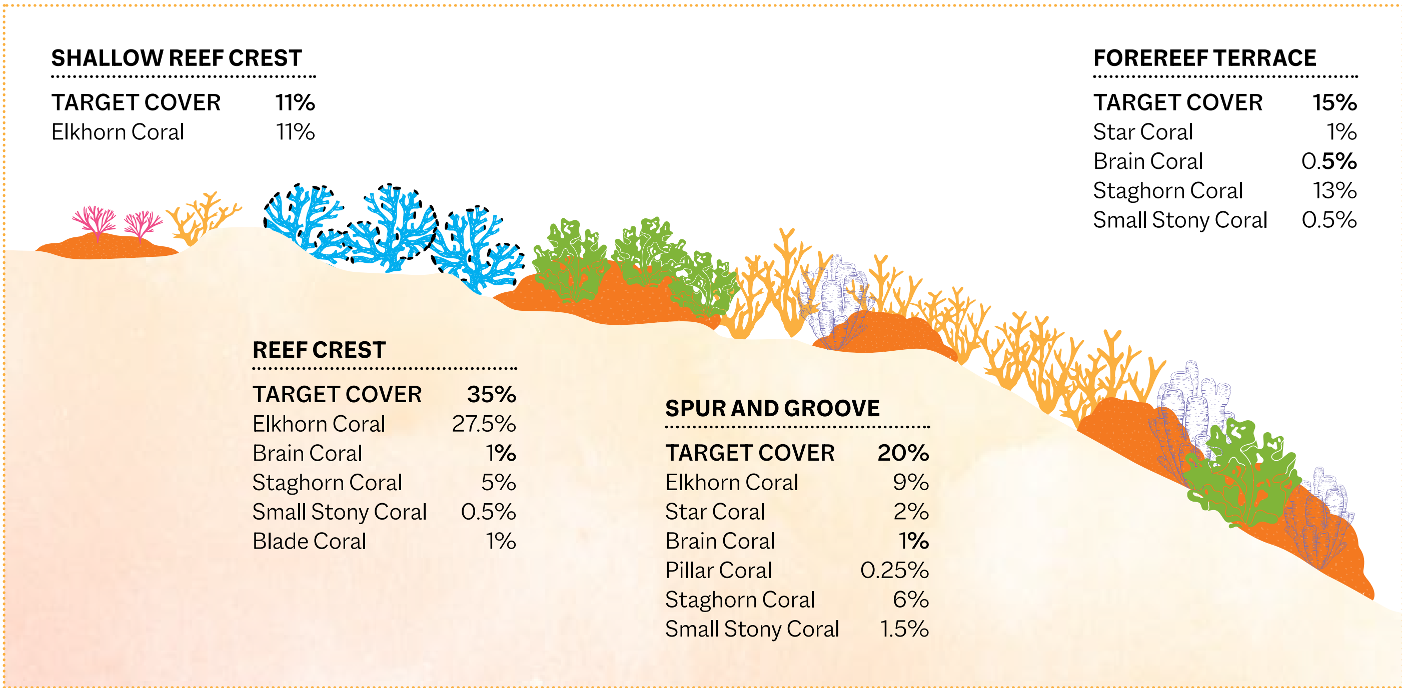

Figure 8. Target percent cover among coral species and reef zones to achieve restoration objectives for the *Mission: Iconic Reefs* project by 2035.

Table 5. Example of targets for restoration actions associated with the spur and groove reef area for the Eastern Dry Rocks reef site.

ZONE	**3 - EASTERN DRY ROCKS - SPUR AND GROOVE - TOP**						
Restorable Area of Zone	10,794	Coral Restoration Component					
	Completion Target	**Phase 1 (10 Years)**			**Phase 2 (20 Years)**		
Target % Cover	**20.25%**	**13.60%**	**Area of Restored Coral (sq m)**	**Restoration Requirement (clusters/ heads)**	**6.65%**	**Area of Restored Coral (sq m)**	**Restoration Requirement (clusters/ heads)**
Elkhorn Coral	10.00%	8.00%	864	4,179	2.00%	216	847
Star Coral	2.00%	1.00%	108	3,792	1.00%	108	2,922
Brain Coral	1.00%	0.50%	54	1,896	0.50%	54	1,461
Pillar Coral	0.25%	0.10%	11	323	0.15%	16	337
Staghorn Coral	6.00%	4.00%	432	2,090	2.00%	216	847
Other Small Stony Coral	1.00%	0.00%	0	0	1.00%	108	4,567
Other	0.00%	0.00%	0		0.00%	0	

Other Components					
Site Preparation			**Sea Urchins**		
Site Condition Score	5	Significant	% of Restorable Area to Target	50%	
Restoration Area (sq m)	10,794		Area (sq m)	5,397	
Site Prep (sq m/day)	100		# per sq m	3.0	
			Phase 1/2 Allocation	50%	50%
Preparation Days Required	**108**		**# Sea Urchins**	**8,096**	**8,096**
Monitoring			**Caribbean King Crab**		
% of Zone	20%		% of Restorable Area to Target	0%	
Area (sq m)	2,159		Area (sq m)	0	
Plots per Zone	21.6		# per sq m	1.0	
Plots/day | Events/10 Years	6	20	Phase 1/2 Allocation	50%	50%
Monitoring Days Required	**72**		**# Crabs**	**0**	**0**

3. *Secured funding:* The funding plan was approached as a vision for investment strategy, with initial funding secured to allow for developing a bigger vision and argument for investment. NOAA Restoration Center and the NOAA Coral Reef Conservation Program have awarded US$5.3 million in grants to two primary restoration practitioners in the Keys. In addition, NOAA will work with outside partners to secure additional public and private funds up to US$100 million.

4. *Plan for implementation:* We are hiring an implementation coordinator, segmenting each reef into work zones, and beginning to develop site by site implementation strategies.

5. *Secure community support and engagement:* Community engagement informed the thinking on this project and the plan development throughout the process thanks to other existing related efforts in the region. The plan is to engage the community in the efforts throughout the duration of the project.

LESSONS LEARNED

As this effort is just launching it is too soon for a comprehensive consideration of lessons learned. However, a few pertinent particulars from the planning process that might help others when considering a similar effort are noted below:

- While the use of resilience predictions and data were considered as part of the site selection process, the spatial resolution and associated trends/ differentials were not sufficient to make these datasets particularly useful.
- High resolution mapping of the reef area and the ability to differentiate habitat zones was critical to making accurate predictions of restoration requirements within a site.
- Previous experience with restoration in the region and the specific sites was key to informed site selection and planning. Conducting a pilot restoration study prior to embarking on a major planning effort should be given serious consideration.

FUNDING SUMMARY

- NOAA Restoration Center and the NOAA Coral Reef Conservation Program have awarded US$5.3 million in grants to two primary restoration practitioners in the Keys.
- Call for additional investment for up to US$100 million.

LEAD ORGANISATIONS

NOAA
Coral Restoration Foundation
Mote Marine Laboratory and Aquarium
Reef Renewal
The Florida Aquarium

PARTNERS

The Nature Conservancy
Mote Marine Laboratory & Aquarium
SECORE
University of Florida
University of Miami
Nova Southeastern University
Florida Department of Environmental Protection
Florida Fish and Wildlife Conservation Commission
National Marine Sanctuary Foundation

RESOURCES

https://www.fisheries.noaa.gov/southeast/habitat-conservation/restoring-seven-iconic-reefs-mission-recover-coral-reefs-florida-keys

6.5 A TRIAL OF CORAL REEF RESTORATION AT A LARGE SPATIAL SCALE BY OKINAWA PREFECTURAL GOVERNMENT IN JAPAN

by Tadashi Kimura, Tomofumi Nagata and Nakamura Akihiro

GOALS

Re-establish reef ecosystem function and mitigate population declines from climate change and enhance sustainable initiatives of local communities.

LOCATION

Okinawa prefecture, Japan

THE CHALLENGE

Coral reefs in the Okinawa prefecture, Japan, are important habitats supporting high biological diversity and high value fisheries and tourism industries. However, in the early 2000s, coral cover around the Okinawan islands had dropped below 10% due to a range of disturbances including bleaching, predation by *Acanthaster* cf. *solaris*, soil erosion and eutrophication. In 2010, The Okinawan prefectural government declared a '21st century vision for Okinawa' that aimed to review economic and public values of coral reefs and natural coastlines and develop a new system/framework for its conservation and restoration.

ACTION TAKEN

The prefectural government conducted a 7-year project (2010-2016) for the technical development and research on coral reef restoration accompanied by various other projects on reef conservation including public awareness and education. The project contained 2 major programs; 1) pilot study of coral outplanting at a large spatial scale, and 2) research on coral reef restoration.

1. The pilot study of coral outplanting at a large spatial scale was conducted at three locations: Onna, Yomitan and Zamami villages (Figure 9). Activities included:
   - 1-1) Seed (Juvenile) colony production
   - 1-2) Nursing culture
   - 1-3) Outplanting (at 3 ha)
2. Research on coral restoration included:
   - 2-1) Reviewing the literature on coral culture and outplanting
   - 2-2) Conducting genetic analysis of coral populations for genetic diversity
   - 2-3) Assessing the appropriate density of seed colony for coral outplanting

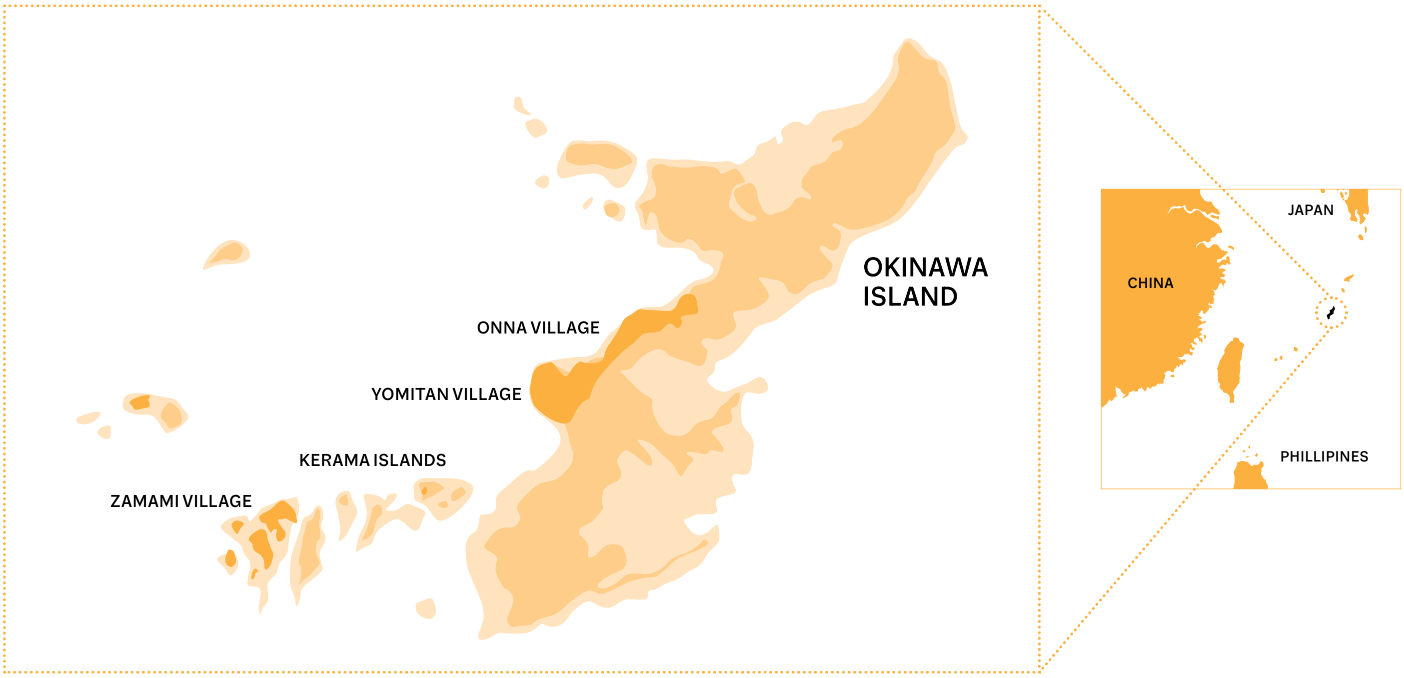

Figure 9. Map of the Okinawan Islands and locations of the restoration trials.

HOW SUCCESSFUL HAS IT BEEN?

1. A systematic cycle of seed production and nursery processes (Figure 9) was developed for large scale restoration to provide coral seeds across 3 hectares.
   - 1-1) At Onna village, all coral seeds for outplanting were produced from asexual reproduction from nursed colonies which consisted of 20 *Acropora* species and 30 other coral species. Coral seeds were also produced by sexual reproduction at private research institutes in Aka Island and Kume Island for outplanting.
   - 1-2) At Yomitan village, coral seeds were produced at the local facility with asexual reproduction for outplanting.
   - 1-3) At Zamami village, coral seeds were collected from the natural recruitments on the ropes of the aquaculture facility in the village. The seeds were also produced from the natural larvae during the mass spawning for outplanting.
   - 1-4) Total area and number of seed colonies for the outplanting pilot study are shown in Table 6. The outplanting area using seeds by asexual reproduction was highest in Onna village with an area of 2.74 ha. The number of seeds were also the highest at Onna village with 104,687 colonies.

Table 6. Total area and number of seed colonies of outplanting pilot study at 3 different villages for 7-year project.

VILLAGE AREA	ONNA VILLAGE		YOMITAN VILLAGE	ZAMAMI VILLAGE	
Type of seed production	**Asexual reproduction**	**Sexual reproduction**	**Asexual reproduction**	**Asexual reproduction**	**Sexual reproduction**
Area (ha)	2.74	0.38	0.18	0.08	0.04
	3.42 (total)				
No. of colonies for outplanting	104,687	15,306	23,935	1,885	5,501
	151,314 (total)				

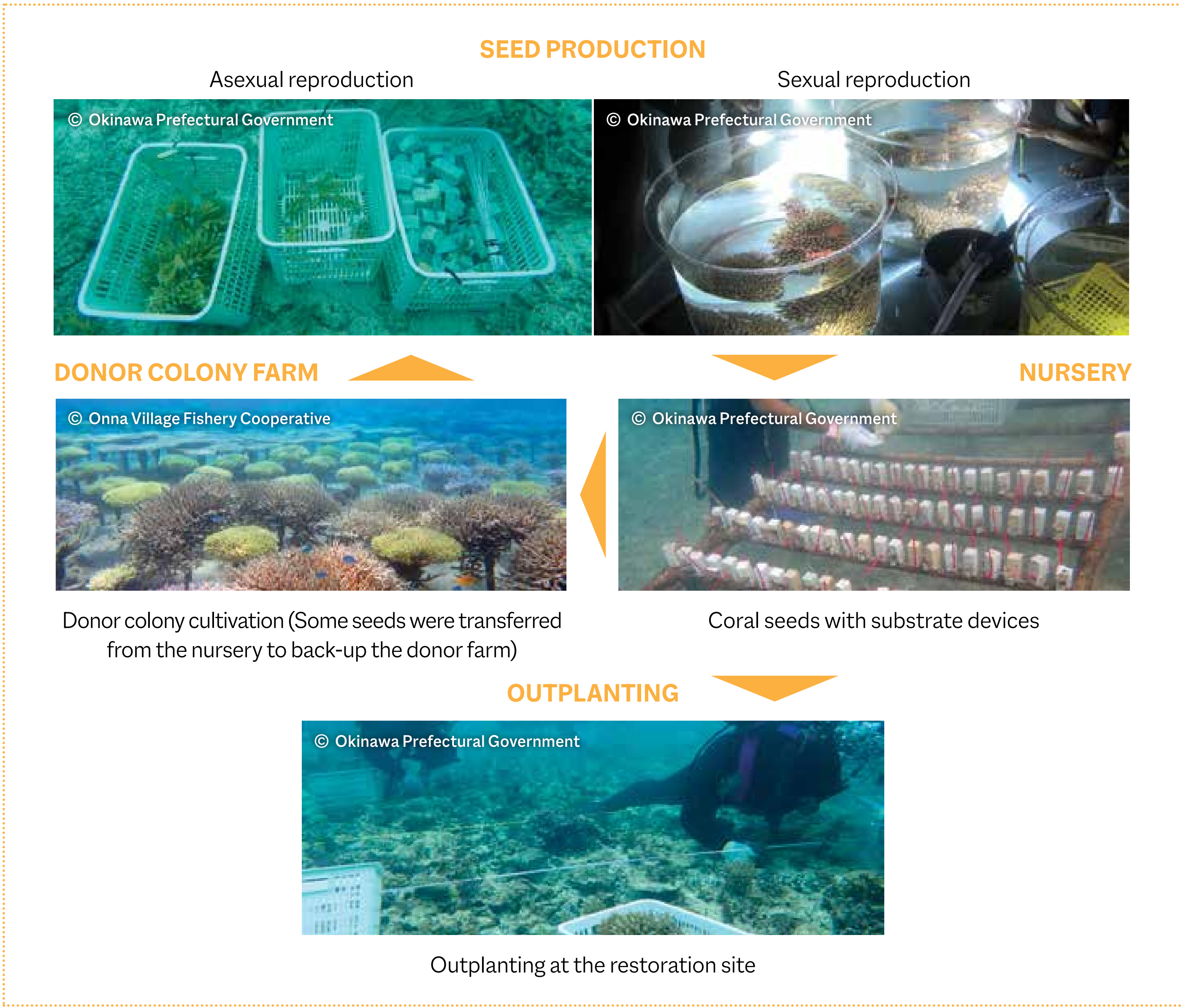

Figure 10. Cycle of seed production and nursery processes for large scale restoration.

2. For the research phase, current and past information on coral transplantation and restoration were collected to summarize and develop recommendations for future restoration efforts. The genetic analysis of coral populations was also conducted in this project for examining genetic diversity of cultured seed colonies. Finally, the population density of outplanted colonies was assessed to identify appropriate density for successful reproduction.

   2-1) A genomic analysis of the coral *Acropora digitifera* (Dana, 1846) showed that the species did not have a single gene population in Nansei islands including Okinawa, but there were specific markers at the DNA level for different areas and island localities.

   2-2) *Acropora tenuis* (Dana, 1846), a popular species for coral restoration, had at least 2 genetic populations in Okinawan waters. However, these 2 populations were not clearly identified, but had different population genetic structures depending on the site.

   2-3) The genetic analysis revealed that the genetic structure of the coral population was complex around Okinawa prefecture and seed colonies and donor colonies for outplanting should be collected from the site near the outplanting to prevent destruction and disturbance of genetic structure of the population.

   2-1) As *Acropora tenuis* (Dana, 1846) didn't show any population cloned at natural habitat, seed colony for restoration should be produced by sexual reproduction. Even when seeds from asexual reproduction were used for outplanting, the donor colonies should be identified on genotypes and seed colonies should be outplanted at the different locations for successful fertilization with different genotypes when they are matured.

LESSONS LEARNED

The project found 3 major lessons learned.

1. The cost of seed production is still high and should be reduced for sustainable restoration.
    - Seed production by asexual reproduction cost JPY2,000 (US$18.39) per seed colony compared with JPY2,700 (US$24.82) – 3,500 (32.18) for seed produced by sexual reproduction.
    - Improving the cost-effectiveness of seed production would require simplifying and optimizing the techniques for both sexual and asexual reproduction, and improving survival after outplanting.
2. Importance of sustainable system on reef management at the local level.
    - Onna village showed successful restoration led by the Fishery Cooperatives during the project. That village has had strong enthusiasm and policy for sustainable development since coral conservation efforts started in 1998 after they experienced mass coral bleaching. The Fisheries cooperative from the village has had many projects to prevent soil erosion, eutrophication and predation by *Acanthaster* cf. *solaris*, and protect not only their fisheries resources but also tourist resources. In 2018, the village was declared a 'coral village' to respond to another mass coral bleaching event that occurred in 2016, and continue to address challenges on reef conservation for sustainable development. These experiences have accelerated their conservation policy and activities on sustainable use of natural resources and led to long-term actions on reef restoration.
    - Local community development for sustainable resource management should be emphasized in the context of the reef restoration.
    - Public awareness and education for the community would support long-term and sustainable actions on reef restoration and integrated management along the coast.
3. Need countermeasures against coral bleaching induced by high water temperatures.
    - Both outplanted and natural coral colonies had severe damages from the mass bleaching in 2016.
    - More research on vulnerable sites, genetic strain of resistance for high water temperature and technical development of shading of natural sunlight would provide possible countermeasures against coral bleaching.

To follow-up on these lessons, a new project is underway until 2022 to tackle the challenges of enhancing seeds' survival and growth, increasing research on larval dispersal and population dynamics of the outplanted colony, and the effectiveness of ecological, economic and social values of reef restoration for local communities.

FUNDING SUMMARY

Annual budget for the project from 2010 to 2016

2010:	JPY	5,900,000 (US$ 56,000)
2011:	JPY	98,500,000 (US$ 940,000)
2012:	JPY	192,900,000 (US$ 1,841,000)
2013:	JPY	216,600,000 (US$ 2,067,000)
2014:	JPY	217,900,000 (US$ 2,080,000)
2015:	JPY	224,800,000 (US$ 2,146,000)
2016:	JPY	228,900,000 (US$ 2,185,000)

*This budget included support for various coral reef conservation projects conducted around the prefecture and for holding some events for public awareness.

LEAD ORGANISATIONS

Nature Conservation Division, Department of Environmental Affairs, Okinawa Prefectural Government

PARTNERS

Onna Village municipal office
https://www.vill.onna.okinawa.jp

Onna Village Fishery Cooperatives
http://www.onnagyokyou.com

Okinawa Institute of Science and Technology Graduate University https://www.oist.jp

Zamami Village municipal office
https://www.vill.zamami.okinawa.jp

Zamami Village Fishery Cooperatives

RESOURCES

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6.6 CORAL RESTORATION FOR CLIMATE CHANGE ADAPTATION IN THE SOUTH PACIFIC

by Austin Bowden-Kerby

LOCATION

Fiji, Kiribati, Tuvalu, Samoa, Vanuatu, and French Polynesia

THE CHALLENGE

Climate change is increasingly becoming the major stressor on coral reefs of the South Pacific region, replacing overfishing, water quality issues, and physical destruction of reefs as the major cause of reef decline on many reefs. Warming oceans is resulting in mass coral bleaching and coral death, which threatens to undermine much of the progress made in coral reef conservation over the past decades. Well-managed, and even pristine coral reefs have proven no more resilient than overfished and degraded reefs in the face of mass bleaching. Strategies to increase bleaching resistance and post-bleaching recovery are needed in order to address climate change as the greatest emerging challenge. For the South Pacific, where funding for coral reef restoration has been very difficult, these strategies need to be mainstreamed into the tourism industry and community-based efforts.

ACTIONS TAKEN

Coral-focused climate change adaptation measures have for the most part been nested within existing coral reef management strategies and MPAs, through capacity building and the establishment of coral nurseries and restoration sites composed of bleaching resistant corals. Unbleached corals are sampled during mass-bleaching events and from populations proven resistant to bleaching within natural hot pockets in the wider reef system – shallow closed lagoons and reef flat tide pools. Special emphasis is placed on sampling *Acropora* species, which have proven particularly vulnerable to bleaching and to post-bleaching mortality, and which we have found to become rare or locally extinct on reefs severely impacted by bleaching. It is often a race against time, as our sites have clearly shown that predation can kill most of what survives mass bleaching within only months. Fragments are taken from these bleaching resistant corals and established within gene bank nurseries located in less stressful/cooler water conditions secure from predators. The second phase of the work involves trimming fragments from colonies grown in the nurseries, for outplanting into restoration patches located on degraded reefs within established no-take reserves where other stressors are minimized.

HOW SUCCESSFUL HAS IT BEEN?

We have established a restoration strategy that builds bleaching resistance on coral reefs in seven South Pacific island nations, helping coral reefs adapt to increasing water temperatures. We have taught the strategy to a sizable group of trainees in the region. National and local partnerships have been established, and the restoration work has been linked to ongoing coral conservation work. Twenty-two gene bank coral nurseries have thus far been established: Fiji (8), Kiribati (1), Tuvalu (5), Samoa (4), Vanuatu (3), and French Polynesia (1), each with dozens of species and multiple coral genotypes of each species (Photo 7).

In Fiji, our major resort partnership site is located at Plantation Island Resort in the Mamanuca Islands. The resort has sponsored the training of 15 Fijians as professional coral gardeners to serve in the tourism industry. The resort hired two of the coral gardeners as full- time staff in 2018, to maintain and advance the coral restoration work. Three highly successful international restoration workshops were carried out at the resort in 2019-20, training 75 people from thirteen nations. A foundation has also been laid with the Indigenous community and other resorts for establishment of a permanent marine park in the wider area. With the COVID-19 crisis, the resort is closed and all training is cancelled, however the resort continues to employ the two coral gardeners, and to provide boats and accommodation for Corals for Conservation (C4C) in order to maintain and advance the coral restoration and bleaching resistance work.

In Kiribati, where mass coral bleaching in 2015-16 lasted for 14 months, and where bleaching temperatures have continued for 30 months out of the past 60 months, very few corals have survived, and many species have become locally extinct. At our Kiritimati (Christmas Atoll) site, virtually all branching corals were killed in the mass bleaching, however we have been able to locate and to propagate a few 'super coral' survivors, with more than one genotype of at least seven *Acropora* species and two *Pocillopora* species collected and propagated within our field nursery. Two outplanting sites have thus far been established for two of the *Acropora* species and for one of the *Pocillopora* species (Photo 8).

The COVID-19 crisis has prevented international travel and follow up, limiting C4C's work to the Fiji sites for now. Local partners are continuing with site maintenance, although reporting is erratic.

Photo 7. Gene bank nursery with mother corals, and coral gardeners, and the fish which help keep the corals healthy. Mamanuca Islands, Fiji.

Photo 8. Kiribati's super corals on ropes in a nursery.

LESSONS LEARNED

- Post bleaching predation and subsequent mortality of the few survivors of mass bleaching can be an important factor preventing coral reefs from adapting to increasing temperatures over time.
- The collection of corals from heat stressed hot pockets can be time-sensitive, as thermal stress is increasing year by year, and some hot pockets formerly filled with resistant corals have already over-reached the maximum temperature for any corals to survive. The most bleaching-tolerant populations had already died out on Kiritimati Atoll by the time the work began in 2016. On Funafuti Atoll, Tuvalu, >90% of the corals of the shallow southern lagoon were dead and standing, apparently dying in mass bleaching before the work began in 2018. Where possible, remaining hot pocket corals should be sampled and established within gene bank nurseries located in cooler waters.
- It is impossible to replant entire coral reefs, however it may be possible to jump-start natural recovery processes, and to spread bleaching resistance among coral populations. We have seen strong larval recruitment around our nurseries, with nurseries apparently becoming a strong settlement signal for incoming larvae. Reefs without corals may have delayed recovery via recruitment due to a lack of settlement cues, therefore scaling up does not require that corals be replanted to entire reef systems, rather dense patches of corals widely spaced might serve to reboot natural processes of coral recruitment, as long as a source of larvae exists up-current. There is also hope that widely spaced outplanting might reap a much bigger result, as coral larvae settle in 'naked'- without symbiotic algae, and acquire their algae from what leaks out of nearby corals- so patches of bleaching resistant corals might spread their resistant algae to newly settled corals. Lastly, if the outplanted patches are composed of multiple genotypes of each coral species, sexual reproduction will be re-established among populations of rare and resistant corals, and so a third source of natural recovery and resistance is secured.
- The tourism sector and communities can become major resources for action and progress, but training and long-term guidance is required for effectiveness. Coral Gardener as a profession is operational, and the diverse methods employed do not rely on SCUBA and are thus less expensive and more accessible (Photo 9).

FUNDING SUMMARY

Funding has mostly been crowd sourced through Global Giving, with Fiji site expenses supported by Plantation Island Resort, sites in Kiribati and Tuvalu were also supported by the Conservation Food and Health Foundation, Line Islands Fisheries (Kiribati), Southern Cross Cable and the Ministry of Environment (Tuvalu). Other support was UNFAO (Samoa), Island Reach (Vanuatu), and the World Surf League (Mo'orea).

LEAD ORGANISATION

Corals for Conservation, a Fiji-registered NGO

PARTNERS

Plantation Island Resort, Malolo Community, Naidiri Community, Line Islands Fisheries, Samoa Fisheries, FAO South Pacific, Coral Gardeners Moorea, World Surf League and Tuvalu Reef to Ridge Program.

RESOURCES

C4C has developed an ecologically based coral restoration field training course and text draft with international significance. Training sessions will again be offered twice annually, once travel is restored.

Photo 9. First international coral gardening workshop for the tourism industry at Plantation Island Resort, Mamanuca Islands Fiji, in February 2019.

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