Rebuilding Coral Reefs

A Decadal Grand Challenge

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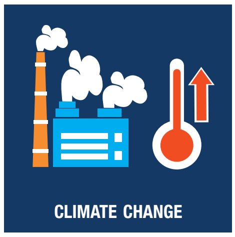

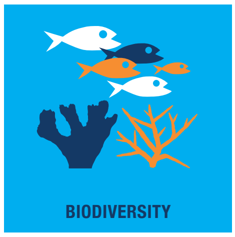

REBUILDING CORAL REEFS

A Decadal Grand Challenge

ICRS Science to Policy Paper 2021

ICRS International Coral Reef Society

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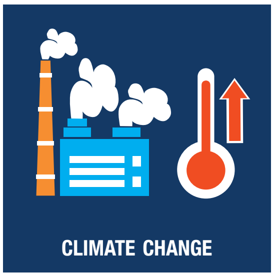
REBUILDING CORAL REEFS

A Decadal Grand Challenge



ICRS Science to Policy Paper 2021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Contents


Alex Mustard / *The Ocean Agency*

Executive Summary

THIS DOCUMENT IS THE WORK OF A TEAM assembled by the *International Coral Reef Society* (ICRS). The mission of ICRS is to promote the acquisition and dissemination of scientific knowledge to secure the future of coral reefs, including via relevant policy frameworks and decision-making processes. This document seeks to highlight the urgency of taking action to conserve and restore reefs through protection and management measures, to provide a summary of the most relevant and recent natural and social science that provides guidance on these tasks, and to highlight implications of these findings for the numerous discussions and negotiations taking place at the global level.

Coral reefs provide direct economic benefits and other contributions to human wellbeing for 100s of millions of people across more than 100 coral reef countries worldwide. Reefs are, however, highly threatened by human activities, with their very future hanging in the balance. This is due to ubiquitous threats associated with human activities, whose effects are felt both locally (e.g., overfishing and pollution) and globally (i.e., ocean warming and acidification due to rising greenhouse gas emissions).

The coming year and decade likely offer the last chance for international, regional, national, and local entities, working synergistically, to change the trajectory of coral reefs from one heading towards world-wide collapse to one heading towards slow but steady recovery.

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Executive Summary

Recovery depends on three interdependent pillars of action:

- Reduce global climate threats by lowering greenhouse gas emissions and increasing carbon sequestration, preferably through nature-based solutions.
- Improve local conditions by increasing protection and improving management for coral reef resilience.
- Invest in restoration science and active coral reef restoration to enhance recovery and adaptation rates, maintain or restore biodiversity, and explore new restoration technologies.

Meeting the challenge of ensuring a future for functional coral reefs is daunting but doable, as successful efforts in reef conservation, management, and restoration, as well as proven and developing climate mitigating technologies and approaches, can be found around the world. Moreover, promising new technologies and approaches are emerging, which we have summarised herein. However, efforts need to be dramatically scaled up.

> Meeting the challenge of ensuring a future for functional coral reefs is daunting but doable. However, efforts in conservation, management, and restoration need to be dramatically scaled up.

Our Asks of the international policy community are threefold:

ASK 1: Establish Commitment—Ensure ambitions are enough to halt dangerous climate change and coral reef biodiversity loss, and that they are implemented.

Both climate change and biodiversity loss are at an inflection point, and the time for action is now. Key decision points, including during 2021, at the *Conference of Parties* to the *Convention on Biological Diversity* (i.e., COP15) and the *Conference of Parties* to the *UN Framework Convention on Climate Change* (UNFCCC) (i.e., COP26) will provide vital opportunities for making commitments and developing mechanisms for their implementation. Ensuring that decisions at these COPs are ambitious enough to halt dangerous climate change and biodiversity loss, and that they are implemented, is critical to securing a positive outcome for coral reefs, as for almost all other ecosystems on the planet.

ASK 2: Promote Coherence—Build strong coordinated and synergistic actions across related policy fields at all levels of governance.

Effective action at local and national levels is hindered by persistent geographic, sectoral, policy, and disciplinary fragmentation. Efforts across the Three Pillars of action—on climate, local conditions, and coral restoration—must be appropriately resourced and brought into coherence across sectors and at all

scales. Climate change, biodiversity, and sustainable development are closely linked and highly relevant to coral reefs, and this needs to be reflected in streamlined, coherent policies and actions across these fields.

ASK 3: Drive Innovation—Develop new approaches where current solutions are insufficient to tackle the emergency facing coral reefs.

Although many tools in the current tool box for reef conservation, management, and restoration remain essential (fisheries management, water quality control, capacity building, long-term monitoring, assessment metrics, etc.), a future with coral reefs will also require new technologies to ensure that reef ecosystems will continue to support human health, nutrition, wellbeing, and employment. Innovation should build on efforts of existing organizations and programs, such as the *International Coral Reef Initiative* (ICRI), the *Global Fund for Coral Reefs*, the *Reef Restoration and Adaptation Program*, and the *G20 Global Coral Reef R&D Accelerator Platform*, and capitalise on the *UN Decade of Ocean Science for Sustainable Development* and the *UN Decade of Ecosystem Restoration*.

For each of these Asks, options for actions that could be taken in the immediate future and looking ahead over the coming decade are presented.

Examples of healthy, well-managed, and recovering coral reefs exist, upon which additional successes can be built. New technologies are also being developed at a rapid pace that have the potential to accelerate progress. We cannot repair all past damage in the next ten years. However, by preventing irreversible damage we can lay the groundwork for future progress and begin to repair the degradation of these extremely valuable ecosystems.

Steps must be taken now to slow and reverse climate change, improve local reef conditions, jump-start recovery through restoration, and accelerate innovation towards adaptation. These urgently needed actions must be designed so that they can respond to both changing conditions and changing scientific understanding and capabilities. They must also take advantage of and increase the synergies between steps taken at the international, national, and regional scales and implementation at the local level. Approaches that rely on co-management and local and Indigenous knowledge stand to be the most successful. There is no time to spare.

Steps must be taken now to slow and reverse climate change, improve local reef conditions, jump-start recovery through restoration, and accelerate innovation towards adaptation.

HOW TO USE THIS DOCUMENT

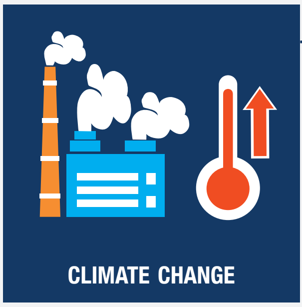
THE PURPOSE OF THIS DOCUMENT is to present the most important messages from scientists regarding the conservation, management, and restoration of coral reefs as related to three critical and interlinked areas of international policy—Climate Change, Biodiversity, and Sustainable Development. This year is a critical decision moment for the coming decade: a raft of biodiversity and sustainable development targets expired in 2020, a new framework for biodiversity under the *Convention on Biological Diversity* is being negotiated, and there is a drive to increase ambitions for addressing climate change with submission of revised *Nationally Determined Contributions* under the next *UN Climate Change Conference* (COP26). In addition, the newly launched *UN Decade of Ocean Science for Sustainable Development* and *UN Decade on Ecosystem Restoration* provide the opportunity to galvanise the science and policies needed to reverse reef decline.

THE INTENDED AUDIENCE includes government negotiators and technical advisors responsible for climate change, biodiversity, and sustainable development policy portfolios. This document provides the latest scientific evidence regarding coral reef ecosystems and provides signposts to help negotiators identify opportunities to build coherence across policy areas—something that is vital to stimulate and prioritise effective actions that are needed to conserve and rebuild our coral reefs.

THE STRUCTURE AND DESIGN OF THE DOCUMENT aim to help the user navigate and identify relevant information depending on their principal entry point. A bibliography is provided at the end (see page 38) to provide access to the underlying evidence.

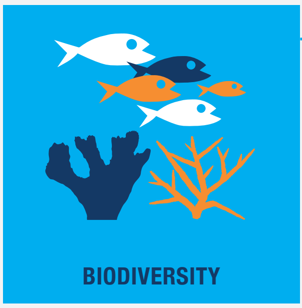
Readers are encouraged to use and share the graphics, which have been designed to be extracted as stand-alone elements, shared on social media, or made into presentation slides. No explicit permission is required for doing so, but you are asked to kindly cite this report (see inside cover for full citation).

The boxes below set out the three critical areas of international policy—Climate Change, Biodiversity, and Sustainable Development—that form the focus of this document. Many of the messages are relevant to more than one policy area.



CLIMATE CHANGE

The principal framework for discussion of issues relating to climate change is the *United Nations Framework Convention on Climate Change* and membership of 197 Parties. Of particular relevance to coral reefs is the *2015 Paris Agreement* to keep global average temperature from rising above 1.5 degrees Celsius above pre-industrial levels this century. This would allow for nature to adapt and enable sustainable development, and is to be achieved through *Nationally Determined Contributions*, which are revised every five years and due to be updated at the *26th Conference of the Parties.*

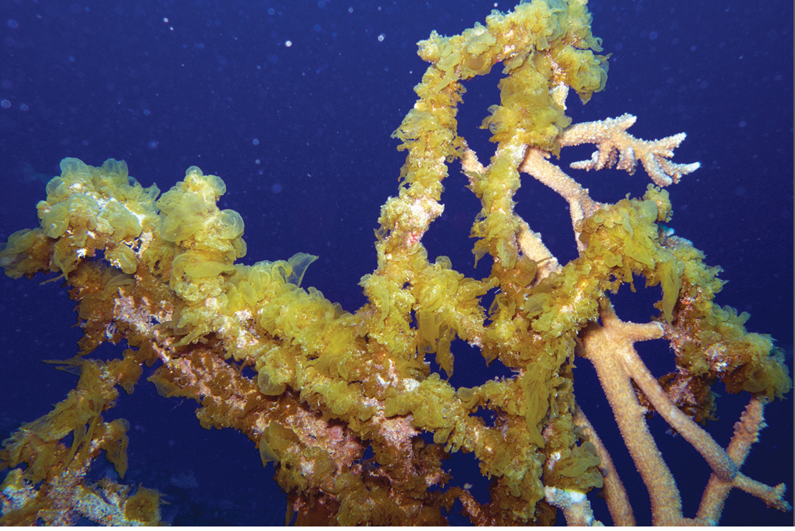


BIODIVERSITY

The *UN Convention on Biological Diversity* has three objectives: to conserve biological diversity, ensure the sustainable use of components of biodiversity, and ensure the fair and equitable sharing of the benefits arising from the use of genetic resources. The Convention has 196 Parties and is implemented through decadal strategies. The last strategic action plan expired in 2020, with a new *Global Biodiversity Framework* in negotiation and due to be adopted at the next *Conference of Parties*, setting a pathway for living in harmony with nature by 2050.

SUSTAINABLE DEVELOPMENT

The *2030 Agenda for Sustainable Development* sets out a 15-year plan to achieve the 17 *Sustainable Development Goals* adopted by UN Member States in 2015. To accelerate the progress needed to meet the goals, 2020 marked the start of a Decade of Action to enhance implementation by 2030 across all sectors.



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Introduction

CORAL REEFS ARE PLANETARY FLAGSHIP ECOSYSTEMS due to their unique, high, and geographically restricted biodiversity and their enormous value to people [1,2,3,4]. However, coral reefs and the ecosystem services they provide have been severely degraded over past decades and even centuries by a variety of human activities [5,6,7]. These negative impacts continue to increase due to unsustainable growth in human population and consumption, resulting in worsening habitat conditions and climate change. Thus, steps taken during upcoming global negotiation and decision-making events, followed by the implementation of policies shaped by existing and new goals and targets, will have enormous importance for the future of coral reefs.

Specifically, the expiration of a raft of global biodiversity and sustainable development targets in 2020 necessitates the establishment of new goals and targets, as well as the reinforcement of existing *UN Sustainable Development Goals*. A new 'post-2020 *Global Biodiversity Framework*' (GBF) is being negotiated by governments under the auspices of the *Convention on Biological Diversity* (CBD) for adoption at the 15th meeting of the *Conference of Parties* to the CBD (CBD COP15). Efforts to increase collective ambition for addressing climate change will be discussed at the *UN Climate Change Conference* (COP26). The *UN Food Systems Summit*, which will include discussions related to aquatic-based food production or "blue foods", provides an opportunity to focus on the critical role of coral reefs in providing sustenance for coastal communities.

Efforts are needed to increase collective ambition for implementing international commitments.

1 Costanza et al. 2014
2 Fisher et al. 2015
3 UN Environment Programme et al. 2018
4 Morrison et al. 2019
5 Knowlton 2001
6 Pandolfi et al. 2003
7 Hoegh-Guldberg et al. 2019

Introduction

In addition, the newly launched UN "*Decade of Ocean Science for Sustainable Development*" and UN "*Decade on Ecosystem Restoration*" are highly relevant to the science and management needed to reverse coral reef decline.

For these reasons, the leadership of the *International Coral Reef Society* (ICRS), the world's foremost association of coral reef scientists, brought together a team of experts to clearly and succinctly present the science-based information needed to inform policy-makers on the actions required to sustain coral reefs. The primary audiences for this document are those involved in negotiating and setting policy agendas for the coming decade and beyond at national, regional, and global levels. This effort is in accordance with the mission of the ICRS to 1) promote the acquisition and dissemination of scientific knowledge to secure the future of coral reefs and 2) use this knowledge to inform relevant policy.

Now, more than ever, coral reef ecosystems are a global environmental priority, requiring immediate attention given the threats of unsustainable development and climate change. This document therefore sets out the evidence-based imperatives for policy and action that are needed to ensure the success of the two UN decadal grand challenges of ocean sustainability and ecosystem restoration and relevant global initiatives so that coral reefs are protected, managed, and rebuilt.

We provide a brief summary of the most up-to-date and policy-relevant knowledge on coral reefs: their value, the threats they face, and their current and projected status. We then outline three priority actions (see Chapter 2: The Three Pillars) that are needed to restore and protect coral reefs: (1) reduce global climate change threats, (2) improve local conditions to build resilience, and (3) invest in active restoration to enhance recovery. We also emphasise the key role that rapidly developing science and technology will play in these efforts. Examples are provided of technologies, interventions, and approaches that will assist with scaling-up efforts and ensuring success [8,9]. We conclude that action must begin immediately, as the coming decade will determine the future of coral reefs. In formulating three Asks (see Chapter 6: The Three Asks) from the international policy community, we link the required actions to upcoming global policy and decision-making agendas, thereby setting coral reef policy options for this decade and beyond.

> For this document, the leadership of the *International Coral Reef Society*—the world's foremost association of coral reef scientists—brought together a team of experts to clearly and succinctly present the science-based information needed to inform policy-makers on the actions required to sustain coral reefs.

8 Duarte et al. 2020
9 Knowlton 2021


Matt Curnock / *The Ocean Agency*

1 Coral Reefs: What We Know

Indigenous and traditional knowledge of coral reefs, including their sustainable use, management, and conservation, builds on millennia of experience in tropical coastal societies and remains highly relevant today (e.g., [10,11]). Western coral reef science, in contrast, is a relatively new discipline [12]. In the 1970s and 1980s, as it became clear that reefs were coming under environmental stress worldwide, research into the geological and biological processes that underpin reef formation expanded to include the nature and causes of reef decline. Now, the emphasis has shifted again to research aimed at identifying solutions and supporting decision-making to inform protection, conservation, sustainable use, and restoration of coral reefs, which requires social science and its integration with natural science [13,14,15,16].

10 Johannes 1982
11 Aswani et al. 2007
12 Knowlton 2006
13 Kittinger et al. 2012
14 Hughes et al. 2017
15 Hoegh-Guldberg et al. 2019
16 Anthony et al. 2020

1 Coral Reefs: What We Know

1.1 The Value of Coral Reefs

Coral reefs are found within the waters of over 100 countries, many of which are lower-income nations [17]. These reefs are essential for human wellbeing, providing value through food, employment, recreational opportunities, coastline protection, medical products, and culture [18]. For atolls, they even form the entire structure upon which people live. Reefs provide critical nutritional value to tropical coastal communities; at least six million people fish or glean on coral reefs, which is over a quarter of all small-scale fishers worldwide [19]. Reef-related tourism globally generates nearly US$36 billion per year [20]. Many reef organisms produce potent biochemical compounds. A number of antiviral and anticancer drugs, including the very first marine-derived drug Cytarabine, are derived from coral reefs [21,22]. The estimated global economic value of coral reefs approaches US$10 trillion per year [23] —the same order of magnitude as the US$16 trillion governments have had to mobilize globally in multi-year fiscal actions to address the impacts of the COVID-19 pandemic from its beginning until March 2021 [24].

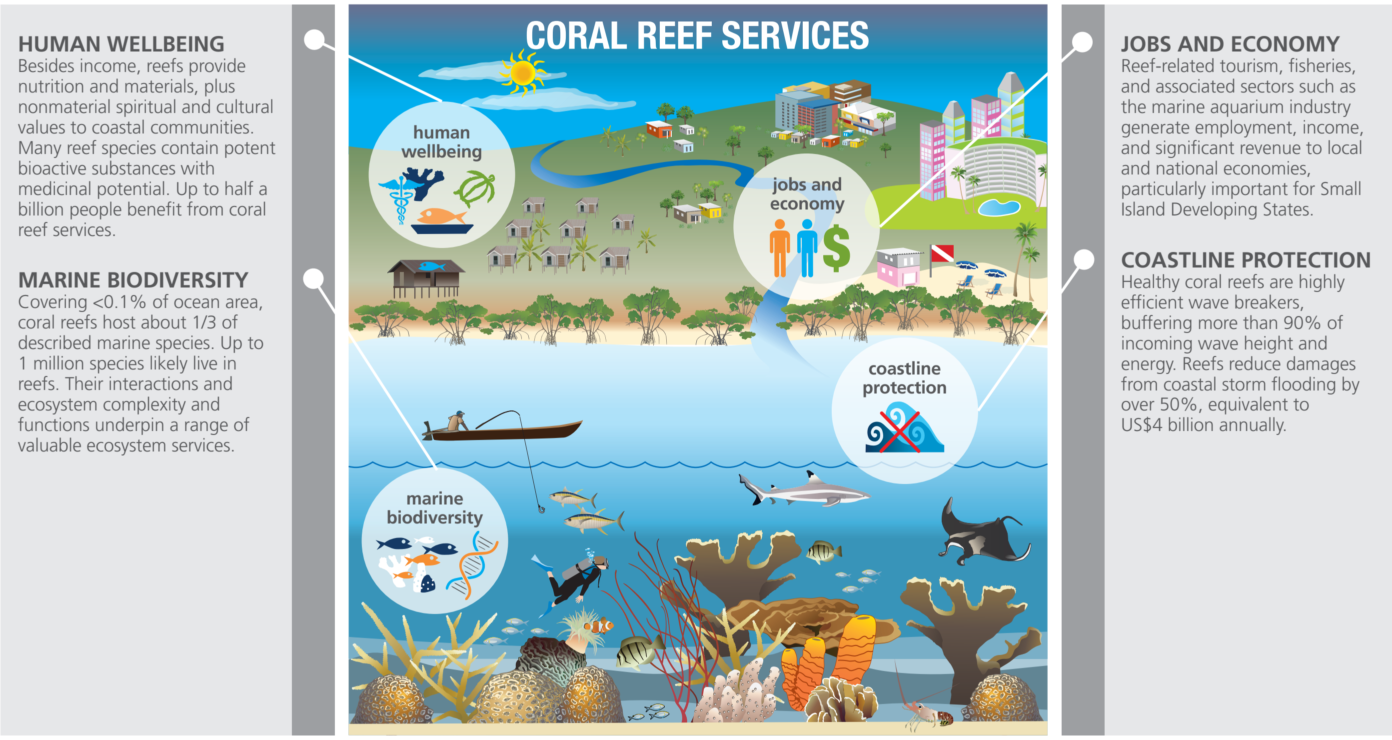


Figure 1. Coral Reef Services. Healthy and intact coral reefs provide critical ecosystem services that amount to an equivalent of nearly US$10 trillion per year. They often occur in close proximity to other coastal ecosystems such as mangroves and seagrasses, with mutual interdependence, and provide effective nature-based solutions, for example in coastal protection.

17 UN Environment Programme et al. 2018
18 Kittinger et al. 2012
19 Teh et al. 2013
20 Spalding et al. 2017
21 Molinski et al. 2009
22 Dyshlovoy and Honecker 2020
23 Costanza et al. 2014
24 IMF 2021

Coral reefs are also exceptionally important to ocean life. The over 800 species of reef-building corals [25] create habitats that harbour an estimated 32% of all named marine species (excluding microbes and fungi)[26]. For some groups, such as fishes, the percentage is even higher: of the ~16,800 named marine fish species [27], ~6,300 (over 37%) are associated with tropical reef environments[28]. However, recent estimates suggest that more than 90% of coral reef species have not been named and that total reef species numbers exceed 800,000[29]. This level of diversity is particularly impressive given that reefs only cover about 285,000 km^2, which is less than 0.1% of the surface area of the ocean[30]. Coral reefs are also rich with symbiotic relationships among species, honed by millions of years of evolution. The disruption of these symbioses by climate change threatens reef biodiversity and the function of the entire reef system[31].

Management of coral reefs is a prime example of a nature-based solution in that, as well as safeguarding the ecosystem, it provides societal benefits through mitigation of risks posed by climate change and natural hazards. For example, most reefs provide a highly effective physical barrier that protects homes, businesses, and infrastructure against storm waves and tsunamis. A healthy reef can reduce coastal wave energy by up to 97%[32]. Across more than 70,000 km of coral reef coastlines, living reefs reduce 1) the annual expected damages from storms by more than US$4 billion and 2) the number of people affected by flooding by 45%[33]. In the United States and its territories alone, the annual value of flood risk reduction provided by coral reefs is more than 18,000 lives affected and US$1.8 billion[34]. Without reefs, it has been estimated that annual damage would more than double, and that flooding of land would increase by 69%[35].

25 Carpenter et al. 2008
26 Fisher et al. 2015
27 Eschmeyer et al. 2010
28 Kulbicki et al. 2013
29 Fisher et al. 2015
30 Spalding et al. 2001
31 Goulet and Goulet 2021
32 Ferrario et al. 2014
33 Beck et al. 2018
34 Storlazzi et al. 2019
35 Beck et al. 2018

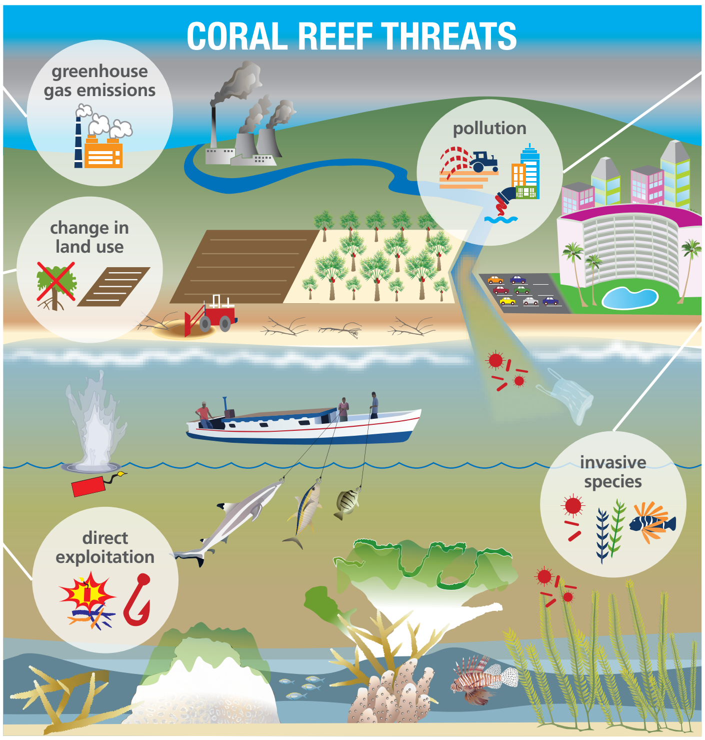
1.2 Local and Global Threats to Coral Reefs

Coral reefs are among the most threatened of all marine ecosystems[36,37]. Their vulnerability is due to their sensitivity to multiple human actions at both local scales (e.g., overfishing, pollution) and global scales (e.g., release of CO_2 into the atmosphere causing ocean warming and acidification). Thus, reefs must be managed using joint approaches and shared local, national, and regional resources supported by national, regional, and global policies. This is particularly important since some types of threats, from local to global, may interact synergistically, increasing their negative impacts[38]. Regardless of the source, both local and global threats can elicit widespread coral mortality and prolong reef recovery for decades due to 1) the slow growth of many coral species and 2) the disruption of key ecological processes needed to sustain healthy reef ecosystem function. When severe, this mortality can result in the collapse of the reef ecosystem and a shift to an alternative state in which corals are not the main benthic organisms, preventing reef recovery.

GREENHOUSE GAS EMISSIONS
Increasing marine heatwaves and ocean acidification resulting from greenhouse gases in the atmosphere and dissolution of carbon dioxide in the oceans lead to coral bleaching and impaired calcification of corals and other reef organisms.

CHANGE IN LAND USE
Intensifying agriculture, coastal development, and loss of coastal and riparian vegetation lead to increased pollutants and sediments from land, resulting in loss of reef, mangrove, and seagrass habitats that serve as nurseries and natural filters.

DIRECT EXPLOITATION
Reefs are highly susceptible to illegal, unreported, and unregulated fishing, leading to the reduction of biomass production and other important processes. Destructive fishing reduces habitat and reproductive potential, and impairs reef recovery.



POLLUTION
Increasing imports of nutrients, pesticides, plastics, and sediments from unsustainable land use, untreated sewage, and poor waste management increase growth of algae and other nuisance organisms, anoxia, smothering, coral disease, and mechanical damage.

INVASIVE SPECIES
Non-native pathogens and species such as lionfish in the Caribbean, introduced through releases, escapes, and ballast water of ships, disrupt food webs and cause disease or mortality of corals and other important reef species.

Figure 2. Coral Reef Threats. The diverse threats to reefs often act synergistically. Corals weakened by pollution, mechanical damage, or heat stress are more susceptible to disease. Unhealthy corals are more prone to bleaching from heat-stress. Overfished reefs are usually less resistant to overgrowth by algae or other nuisance organisms.

36 McCauley et al. 2015
37 IPCC 2019
38 Ateweberhan et al. 2013

Local stressors, such as habitat destruction (including from harmful fishing practices such as dynamite use), harmful land-use practices (including coastal development, agricultural and land-based pollution, increased sedimentation and run-off due to monocropping and clearcutting of riparian vegetation, and the destruction of coastal vegetation for poorly-planned aquaculture development), overfishing, and invasive species are major problems for coral reefs [39,40,41] that further exacerbate coral loss from heat-wave induced bleaching events [42].

However, at the global scale, the chief concern now is the unprecedented threat to coral reefs posed by growing concentrations of greenhouse gases, particularly CO_2, in the atmosphere. The resulting warmer temperatures have led to mass coral bleaching, more disease, and catastrophic coral mortality globally [43,44]. Without significant efforts to curb greenhouse gas emissions, all tropical coral reefs will experience annual severe bleaching. The average projected year for annual severe bleaching under the representative concentration pathway (RCP) 8.5 scenario is 2034. However, there is considerable variation among and within countries, and many locations will experience regular severe bleaching much sooner [45]. In addition, hypoxia can result from warming temperatures, resulting in increased coral mortality and sublethal stress [46]. Rising CO_2 concentrations also cause ocean acidification, which while not immediately lethal to coral reef organisms at current or projected end-century levels, compromise reefs by reducing rates of calcification, increasing rates of dissolution, and impairing coral reproduction and stress tolerance [47,48], all of which have implications for the growth of the reef foundation.

Hence, which carbon emissions pathway we choose to follow will profoundly impact live coral cover and reef calcification and dissolution rates [49], and thus the ability of coral reefs to maintain the reef structures which protect shorelines and support high biodiversity. Under the RCP 2.6 scenario, almost two-thirds of coral reefs will remain net accretionary through the end of this century, while under the RCP 8.5 scenario, 94% will be eroding by 2050 [50].

NOTE: Representative Concentration Pathways (RCPs) are greenhouse gas concentration trajectories adopted by the IPCC, describing different potential climate futures based on particular concentrations of greenhouse gases and other radiative forcing. RCP 2.6 represents a very stringent pathway, while RCP 8.5 represents a worst-case scenario of continuously rising emissions.

39 Richmond et al. 2007
40 Jackson et al. 2014
41 Morrison et al. 2019
42 Donovan et al. 2021
43 Hughes et al. 2018
44 ISRS 2018
45 van Hooidonk et al. 2020
46 Hughes et al. 2020
47 Albright et al. 2010
48 Albright et al. 2018
49 Eyre et al. 2018
50 Cornwall et al. 2021

1.3 Current and Future State of Coral Reefs

The cumulative result of past damages is the loss of at least half of the living coral cover on reefs since the 1870s with losses accelerating in recent decades [51]. In addition, even reefs that have retained similar levels of live coral cover have already undergone dramatic shifts in their species composition [52]. While coral cover is often seen as the principal benchmark of healthy reefs, this is but one component of a healthy reef community, and appropriate indicators and benchmarks will depend on the local context (e.g., [53]). Coral reef ecosystems are of high integrity—i.e., are highly intact—when their dominant ecological characteristics (e.g., composition, structure, function, and ecological processes) occur within their natural ranges of variation, and can withstand and recover from most perturbations imposed by natural environmental dynamics or human disruptions [54]. Coral reef scientists and managers already assess coral reef integrity through a variety of measurements, including common metrics like hard coral cover and composition, cover of key benthic

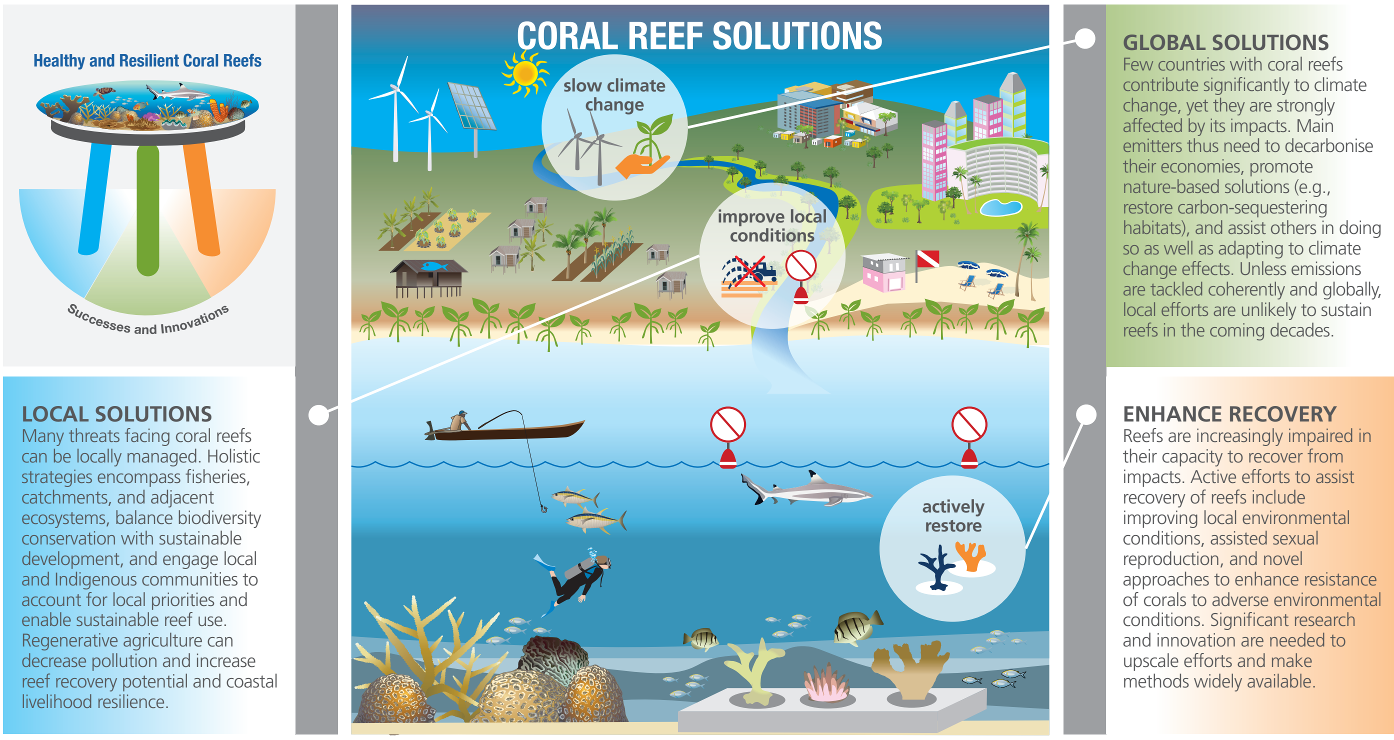


Figure 3. Coral Reef Solutions. Three interdependent strategies form the pillars to sustain healthy and resilient coral reefs into the future: addressing global and local threats and enhancing recovery potential. Well-managed, diverse reefs cope better with climate change. Improved local conditions enhance the recovery potential of reefs, and reef restoration cannot succeed if conditions are unsuitable for corals. Intact coastal habitats are nature-based solutions that protect coasts and sequester carbon.

51 IPBES 2019
52 McWilliam et al. 2020
53 McField and Richards Kramer 2007
54 Hansen et al. 2021

groups, and reef fish abundance and biomass (e.g., [55]). Many reefs are effectively gone (i.e., they have lost their integrity and capacity to provide key ecosystem services), and the future for thriving reefs is highly uncertain. Yet, some reefs have improved in health, and retained an ability to recover, thanks to steps taken to manage, protect, and restore them. Studies of these "bright spots" [56,57,58,59,60] provide important lessons to guide future actions, such as how local community participation can improve management outcomes.

It is not too late to ensure a future for coral reefs, but we are clearly running out of time for taking meaningful action [61,62]. Reef decline becomes ecologically and economically catastrophic long before individual species are at risk of extinction. Stresses on coral reefs are reaching levels beyond which the ecosystem services provided by reefs that humans depend on will rapidly deteriorate globally and be extremely difficult to restore. Reefs are increasingly shifting into novel ecological configurations which function in ways that are difficult to predict, but will need to be managed appropriately to maximise the services these reefs can provide [63,64]. While novel coral reef configurations may continue to maintain a few ecosystem services, such as fish biomass production, other vital ones, such as coastal protection and reef accretion, will be severely diminished in degraded reefs with low coral cover and complexity [65,66]. Reef accretion will not be able to match projected rates of sea level rise by the end of the century under RCPs 4.5 and 8.5 [67]. Without the prioritisation of coherent, synergistic, decisive, and rapid actions to address threats, coral reefs will vanish from the globe as functioning ecosystems, taking with them most of the invaluable services they provide to the ocean and to humanity.

Today's decision makers are thus faced with a stark reality: for the first time, an entire globally dispersed ecosystem that supports millions of species and people may be lost at the hands of humans. Moreover, the time window to prevent the crossing of critical tipping points is rapidly closing [68], with 10-30% of reefs remaining if temperature rise is limited to 1.5°C but only 1% remaining if the increase reaches 2°C [69] by the end of this century. Furthermore, a shift from RCP 8.5 to RCP 2.6 is estimated to prevent economic damage of approximately AUD$28 billion in Australia alone [70]. The recently conducted *Concept Feasibility Study* for the *Australian Reef Restoration and Adaptation Program* highlights that "time is of the essence: the longer we [wait], the more expensive and difficult it [will] be to successfully intervene at any scale and the greater the risk [that] the window of opportunity [will] close" (*www.gbrrestoration.org/the-program/*). The present decade therefore offers a critical, and likely the last, opportunity to prevent irreversible damage.

55 Cinner et al. 2020
56 Jackson et al. 2014
57 Cinner et al. 2016
58 Beyer et al. 2018
59 Richmond et al. 2019
60 Knowlton 2021
61 Hoegh-Guldberg et al. 2018
62 Kleypas et al. 2021
63 Williams and Graham 2019
64 Lester et al. 2020
65 Lester et al. 2020
66 Cornwall et al. 2021
67 Cornwall et al. 2021
68 IPCC 2019
69 Frieler et al. 2013
70 Anthony et al. 2019

Gregory Piper / *The Ocean Agency*

2 Strategies for Success

BENEFITS FROM PREVENTING THE COLLAPSE OF CORAL REEF ECOSYSTEMS far outweighs the costs, whether on socio-economic, cultural, or moral grounds. Investments in measures to protect and otherwise conserve coral reefs pay off several times over, with potential return on investment of more than 40:1 in some cases [71]. We have seen the minimisation of the worst possible outcomes to the COVID-19 pandemic in countries that acted collaboratively, decisively, and quickly. The same principle applies to coral reefs: decisive, coherent, and immediate action is urgently needed to minimize costly consequences later.

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71 UN Environment Programme et al. 2018

2.1 The Three Pillars

The challenge is clear—both global and local impacts are interacting to drive reefs into decline, and current practices and commitments are insufficient to counteract them. A healthy reef, or one that is highly intact or of high ecological integrity, is resilient to disturbances and can recover after suffering occasional setbacks from events such as a cyclone or a marine heat wave (bleaching). In other words, it is capable of staying within its natural range of variation. However, most reefs today are not healthy and are either unable to recover at all or cannot fully recover before the next wave of mortality occurs [72,73,74]. This leads to a continuous loss of live coral cover and an accelerated disintegration of the reef framework through negative feedback loops. In order to restore the health and resilience of coral reefs, the sources of coral mortality and reef framework erosion must be slowed, and coral reef recovery enhanced. This can be accomplished with the following three necessary and interdependent strategies (Figure 4):

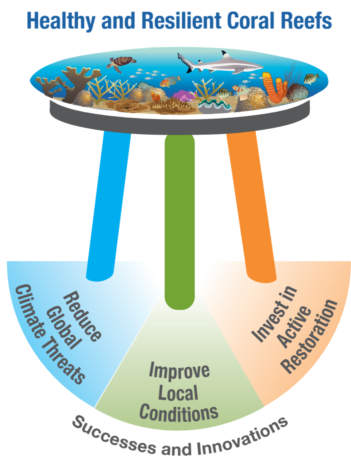


Figure 4. Three Pillars. Restoring the health and resilience of coral reefs requires three necessary and interdependent strategies to be addressed, underpinned by innovation and building on successes.

PILLAR 1. Reduce global climate threats by lowering greenhouse gas emissions and increasing carbon sequestration.

This is the foremost action needed to ensure long-term coral reef survival, and critically, it must limit warming to 1.5°C. More severe heat waves are now the greatest source of mortality for corals, and their increasing frequency is making it impossible for reefs to recover [75,76].

PILLAR 2. Improve local conditions by increasing protection and improving management for coral reef resilience.

This may entail more extensive regulations, but also the participatory, active, and effective enforcement of existing rules. Local stressors such as overfishing and pollution are still large factors in coral reef degradation. Reducing local stressors increases the ability of reefs to recover from losses [77] and may even reduce short-term mortality rates associated with bleaching [78].

PILLAR 3. Invest in restoration science and active coral reef restoration to enhance recovery and adaptation rates, maintain or restore biodiversity, and explore new restoration technologies.

When degradation is severe, recovery may fail or be extremely slow without jump-starting the recovery process. New restoration methods are showing increasing promise as tools for enhancing coral reef recovery to 'buy reefs time' [79]. However, coral reef restoration cannot work if global climate and local conditions remain unsuitable for corals.

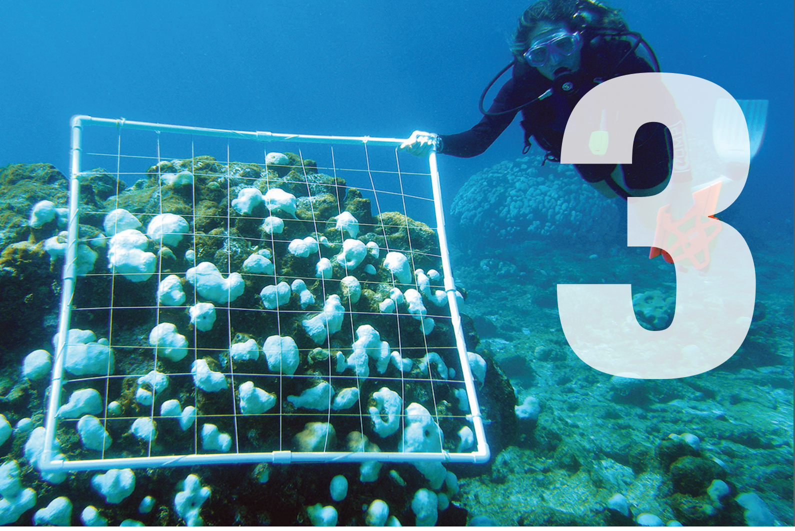
72 Grottoli et al. 2014
73 Hughes et al. 2018
74 Ortiz et al. 2018
75 Hughes et al. 2018
76 Ortiz et al. 2018
77 Mellin et al. 2016
78 Donovan et al. 2021
79 NASEM 2019

2.2 The Importance of Adaptive Innovation

All of the efforts described previously will require deploying the best available natural and social science. There is a growing consensus that the current approaches to conservation research and practice are no longer sufficient, and coral reef scientists are increasingly looking for innovations to improve prospects for coral reefs [80,81,82]. Thus, it remains important to invest in and test science-based innovations during the coming decade. Considering a 10-year timeframe to achieve effective change, nascent innovations need to be assessed against the criteria of (1) near-term availability, (2) ecological/economic (cost) effectiveness, (3) adverse/unintended side effects (risk), (4) acceptability, and (5) scale [83].

The application of innovative technical and socio-economic solutions to protect coral reefs could make the difference between retaining some functional coral reef ecosystems and having no functional reefs left at the end of this century. These new approaches include improvements in data acquisition and processing, better understanding of key aspects of coral biology related to stress resistance, innovations to assist reef resilience and conservation, and more effective integration of the social sciences, ranging from finance innovations to Indigenous and traditional knowledge (e.g., [84]). Societal innovations, such as a transition to green energy, sustainable transport, and sustainable tourism, currently being spurred on by recovery packages and other structural changes in response to the COVID-19 global pandemic, can also contribute to and support forward-thinking, coral conservation practices.

80 NASEM 2019
81 Anthony et al. 2019
82 Anthony et al. 2020
83 Kleypas et al. 2021
84 Mead et al. 2019



NOAA

PILLAR I: Reduce Global Climate Change Threats

REDUCE GLOBAL CLIMATE CHANGE THREATS: lower greenhouse gas emissions and increase carbon sequestration.

3.1 Rationale

Reducing greenhouse gas emissions, particularly CO_2, is essential to reduce ocean warming and acidification as both of these are obstacles to securing a future with healthy coral reefs [85,86]. Reducing CO_2 emissions to levels that limit warming to 1.5°C as required in the *Paris Agreement* would slow the rate of ocean warming and acidification sufficiently to mitigate the worst-case scenarios for coral reefs and set the stage for increasing the probability of success in protecting still healthy reefs and restoring degraded ones, important for climate adaptation and resilience of both nature and society. Specifically, 70-90% of reef corals will be lost if global warming exceeds 1.5°C, and 99% will be lost if it exceeds 2.0°C above pre-industrial temperatures [87]. Although the benefits to coral reefs may not be seen for years, due to inertia in both the physical earth system and human social systems, slowing and ultimately stopping climate change would hasten the recovery of the environment before ongoing impacts overwhelm the capacity of reefs to recover. Neglecting to address climate change would undermine, and ultimately make useless, most attempts to mitigate or otherwise address local threats.

85 Hoegh-Guldberg et al. 2018
86 Heron et al. 2018
87 Hoegh-Guldberg et al. 2018

3 PILLAR I: Reduce Global Climate Change Threats

Reducing global greenhouse gas emissions is logically and morally the responsibility of the largest emitters—with the top ten emitting countries or country groupings producing two thirds of the world's emissions[88]. However, the benefits of transitioning to green energy accrue broadly, because renewable energy is now typically less expensive, even without subsidies, than fossil fuel-based energy (e.g., [89]). It is also cleaner (resulting in less air pollution and promoting human health) than fossil fuel-based energy (e.g., [90]). Green energy also reduces dependence on imported fossil fuels (benefiting the economy) and lowers the risk of polluting spills (which can have serious and long-lasting impacts on reefs, e.g., [91]).

Sequestering carbon, so that it cannot enter the atmosphere or the ocean, complements efforts to reduce atmospheric emissions[92]. While coral reefs are not carbon sinks[93], they are ecologically interdependent with tropical wetland ecosystems, such as mangrove forests and seagrass beds[94], that have enormous potential in this regard[95]. The carbon captured by these marine ecosystems is often referred to as blue carbon[96]. Thus, while many countries that have coral reefs are not major greenhouse gas emitters, they have major opportunities for carbon sequestration associated with adjacent mangrove and seagrass ecosystems, including access to international financing for these efforts. Moreover, mangrove and seagrass conservation also provide ancillary (win-win) benefits for reefs and human communities living nearby. For example, mangrove forests retain sediments, enhance fish biomass of adjacent reefs[97,98], and provide considerable flood protection[99]. The coastal protection benefits of coral reefs noted above are increased by the presence of healthy adjacent mangrove and seagrass ecosystems, as together they provide stronger coastal protection than they do individually[100] and offer nature-based solutions for climate adaptation and resilience[101].

88 WRI 2020
89 Laslett 2020
90 Koengkan et al. 2021
91 Guzman et al. 2020
92 Lal 2008
93 Gattuso et al. 1998
94 Nagelkerken 2009
95 Macreadie et al. 2019
96 Nellemann et al. 2009
97 Harborne et al. 2006
98 Mumby et al. 2004
99 Menéndez et al. 2020
100 Guannel et al. 2016
101 Martin and Watson 2016

3.2 Examples of Success

RENEWABLE ENERGY RESOURCES

Many countries have abundant wind and/or sun and are thus prime candidates for transitioning to renewable energy resources. A recent report documents a growing uptake of non-fossil fuel energy, with solar and wind increasing strongly as a percentage of renewable energy in recent years [102].

ENERGY EFFICIENCY AND ELECTRIFICATION

There are initiatives to promote improved energy efficiency and electrification (e.g., in transport) in a variety of countries throughout the world. Enormous and as yet largely untapped potential exists in this area.

CARBON SEQUESTRATION

With respect to carbon sequestration, slowing of mangrove deforestation and degradation and investing in mangrove restoration are perhaps one of the best reef-related, nature-based solutions to mitigating the impacts of climate change that capitalise on blue carbon. The rate of mangrove loss a few years ago was so extreme that some scientists predicted mangroves would vanish entirely by 2100, but rates have slowed considerably in recent years [103]. While mangroves form only a narrow band along coastlines, they store carbon at considerably higher rates than do inland forests. This makes them particularly relevant, in the context of meeting commitments for the *Paris Agreement*, to countries with large tropical coastlines and moderate greenhouse gas emissions (e.g., Indonesia—the country with the greatest surface area of mangroves and the greatest mangrove loss in 2014) [104]. Blue carbon habitats are recognised within the text of the UNFCCC and the *Paris Agreement* as sinks and reservoirs of greenhouse gases. This provides the opportunity for countries to include mangroves and other relevant coastal habitats within their *Nationally Determined Contributions* (NDCs) [105]. In the first round of NDCs, 28 out of 118 countries with mangrove forests had included blue carbon habitats as a mitigation component [106], thus presenting an opportunity to increase ambition in the forthcoming round to refresh NDCs.

Examples of successful mangrove blue carbon projects in Kenya, India, Vietnam, and Madagascar point to the need for engaging local communities and incorporating livelihood components from the beginning of a project [107]. The narrow habitat of mangroves along the coastlines makes them particularly vulnerable to sea level rise and likely necessitates active management and restoration in order to maintain carbon sequestration and coastal protection benefits. While national level approaches are highly efficient [108], it is also critical that a desire to meet national commitments does not lead to inappropriate and counterproductive efforts (e.g., through poor choice of species and/or locations, as many species have very specific environmental requirements) [109,110].

102 IRENA 2021
103 Duarte et al. 2020
104 Taillardat et al. 2018
105 TNC et al. 2018
106 TNC et al. 2018
107 Wylie et al. 2016
108 Taillardat et al. 2018
109 Lee et al. 2019
110 Lovelock and Brown 2019

3.3 Near-term Innovations

On the energy front, the expectations for solar and wind are largely in the realm of continuing decreases in price, including for energy storage. However, technological innovations are vital, including in wave and tidal energy, which are more difficult to predict but potentially important. Widespread adoption of renewable energy has clear benefits for coral reefs and societies. Technological innovations in renewable energy are of value everywhere but can be of particular value for Small Island Developing States, where they can contribute to self-sufficiency [111].

With respect to carbon sequestration, there is considerable fluidity in carbon markets, with the potential for new financing and quality control mechanisms being developed over the next decade, including for blue carbon. These new mechanisms have the potential to increase the viability of these approaches for individual projects, which can currently be challenging administratively [112]. There are, however, a growing number of projects exploring these nascent voluntary markets for the trading of blue carbon credits to help fund the conservation of carbon sequestering ecosystems, such as mangroves and seagrasses. One example is the *Mikoko Pamoja* project (meaning “mangroves together”) in Southern Kenya. This is a community-led development project self-funded by the sale of carbon credits on the voluntary carbon market through a Payment for Ecosystem Services Agreement with the UK-based organisation *Plan Vivo* [113].

Importantly, additional activities in the marine environment such as offshore wind parks and carbon capture and storage, while potentially contributing to tackling greenhouse gas emissions, also have the potential to undermine ocean health. Thus, these activities need to be planned carefully and accompanied by thorough environmental impact assessments and marine spatial planning.

111 IRENA 2021
112 Wylie et a. 2016
113 Wylie et a. 2016

Frank Kovalchek / *Flickr Commons*

4 PILLAR II: Improve Local Conditions to Build Resilience

IMPROVE LOCAL CONDITIONS TO BUILD RESILIENCE: increase and improve management of land and ocean areas.

4.1 Rationale

Effective conservation and management of coral reefs requires a variety of interventions to reduce the negative impacts of over-exploitation, pollution, and habitat damage which result from human activities taking place at national to local levels. The goal of these actions is to promote overall reef health and resilience (i.e., coral reef integrity) to damaging events that cannot be prevented. While the execution of specific plans can be challenging, the strategies for success are broadly understood and include: 1) committing to coherent action at national, regional, and local levels, 2) taking action to remove barriers to cross-sector and cross-jurisdiction cooperation, and 3) implementing and enforcing the action.

The protection—or partial protection if sustainable fishing is permitted—of a reef typically requires the implementation of a Marine Protected Area (MPA) or other area-based conservation measures or management tools—some of which would qualify as Other Effective Area-Based Conservation Measures (OECMs) in accordance with Convention on Biological Diversity (CBD) Decision 14/8. Best international practice is that these should be designated in accordance with International Union for the Conservation of Nature (IUCN) guidance [114]. Such area-based tools for protecting the marine environment have a long history and essentially originated with traditional approaches for managing reefs in the Pacific, developed over centuries (e.g., [115,116]). Many coral reefs are protected within MPAs that are managed by governments, at state or national level, but increasingly it is recognised that co-management with environmental or community groups is a better approach to MPA governance [117]. In many cases local communities are proving successful with locally-managed marine areas (e.g., [118,119]).

114 Day et al. 2019
115 Johannes 1982
116 Johannes 1992
117 Cinner et al. 2012
118 Govan et al. 2009
119 Rocliffe et al. 2014

PILLAR II: Improve Local Conditions to Build Resilience

Unsustainable fishing is a primary cause of reef decline, with over-exploited fish populations correlating strongly with reefs that are in poor condition [120]. Where seaweed-eating reef fish (herbivores) have been fished out, the community structure of a reef may rapidly shift to one in which algae dominate, and corals are outcompeted [121]. No-take MPAs play an important role in building up fish populations [122], but there is also a need for introduction of, and compliance with, wider fisheries management interventions [123]. This might include aiming for particular levels of fish biomass that prevent the loss of key ecological processes [124,125], regulations to protect important herbivores [126], ensuring that the focus is on managing reef fisheries for local consumption rather than export as much as possible [127], and eliminating the many destructive fishing methods that are used worldwide and lead to loss and damage to corals and the benthic communities on which reef fish depend [128]. Allowing for some level of fishing often is less detrimental to local livelihoods and may thus result in higher compliance. Which strategy is most effective and appropriate thus depends on the local context and specific management goals [129].

Effective management of reefs also depends on policies and legislation governing activities on land (coastal zone and watershed management) to prevent pollution from deforestation, agriculture, industry, and coastal development through release of sediments, toxic materials, plastics, pharmaceuticals, and nutrients [130,131]. These can negatively affect corals directly or via their interactions with seaweeds, bioeroding invertebrates, and pathogens. Reducing these impacts is particularly important in situations where runoff and erosion are exacerbated by steep gradients and large amounts of rainfall. The nature-based solutions approach to water quality improvement is again preferable, such as providing opportunities for filtration of run-off by protecting coastal wetlands and riparian mangroves or creating wetlands. These measures have a variety of additional benefits, such as carbon sequestration.

International actions need to empower local communities without whose support conservation typically fails [132]. The benefits of healthy reefs must be returned to the people whose lives depend on them, and who play an essential role in their management. The rights and stewardship role of local and Indigenous communities must be respected (e.g., [133,134]).

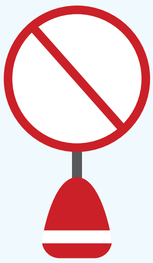
Understanding reef condition and health trends is essential for determining the actions needed. Long-term monitoring is essential for understanding the impact of interventions undertaken and identifying whether a change in course is needed [135]. For this reason, there are globally and regionally coordinated efforts for coral reef monitoring and reporting, such as the *International Coral Reef Initiative* (ICRI), *Global Coral Reef Monitoring Network* (GCRMN) and its *Status of Coral Reefs of the World* reports (in preparation), and Australia's Long-Term Monitoring Program. The metrics used must be evidence-based and informed by an understanding of coral reef functions and processes [136,137]. Besides cover by live coral and other key benthic groups, monitoring should include measures of structural complexity, and fish abundance and biomass [138]. National monitoring programmes allow countries to determine their progress towards meeting targets,

120 Jackson et al. 2014
121 Done 1992
122 Cinner et al. 2020
123 Steneck et al. 2019
124 McClanahan et al. 2011
125 McClanahan et al. 2015
126 Steneck et al. 2019
127 Birkeland 2017
128 Burke et al. 2011
129 Cinner et al. 2020
130 Carlson et al. 2019
131 Richmond et al. 2019
132 Ferse et al. 2010
133 Cetas and Yasué 2017
134 Richmond et al. 2019
135 ICRI 2020
136 Flower et al. 2017
137 Ford et al. 2018
138 ICRI 2020

learn which interventions are working or not working, and adapt their conservation and management efforts accordingly. There is considerable guidance on monitoring from broader science networks that coral reef managers and policy makers can build on, such as the *Global Ocean Observing System* (GOOS) and the *Group on Earth Observations' Biodiversity Observation Network* (GEOBON) [139].

4.2 Examples of Success

MARINE PROTECTED AREAS (MPAS) AND WATERSHED MANAGEMENT



MPAs can effectively protect reef fish populations if there is good compliance with regulations, which may lead to improvements in coral health. For instance, an increase in herbivorous fish abundance can lead to reduced algal cover and greater coral cover [140]. As one example, Bonaire's reefs are all protected inside the Bonaire National Marine Park and recovered from hurricane and bleaching mortality within ten years, as evidenced by a decline in macroalgae and a recovery of juvenile and adult corals to pre-disturbance levels [141,142]. This recovery points to the effective management of the MPA which included the banning of parrotfish fishing and spearfishing, the phasing out of fish traps, regular ecological monitoring, and the support of the island-wide national park by user fees managed by a non-governmental agency. As a result, the reefs of Bonaire are far superior to most Caribbean reefs today and resemble those that prevailed in the Caribbean before 1975 [143]. A similar trajectory of parrotfish recovery, a decline in macroalgae, and coral resilience to disturbance has been documented in Belize following the banning of parrotfish harvesting [144].

However, MPAs also need broad scale measures of protection and management at the watershed scale. Watershed management has led to improved coral reef health in Hawaii, Guam, Palau, and Pohnpei [145,146,147]. The methods employed are varied and include control of sewage to reduce nutrient inputs, the use of "sediment socks", tree and crop planting, and the reduction of mangrove and upland deforestation to reduce erosion and trap sediments. The case of Ngerikiil Bay in Palau offers several lessons. Local fishers quickly noticed that the cutting of mangroves to create additional housing to support tourism caused damage to coral reefs (mangroves trap about 30% of sediments from the land) and reduced success in fishing. This led to a moratorium on clearing of mangroves in the area, and eventually national legislation protecting mangroves. This was followed by further community-based efforts and the establishment of taro fields in more upland locations (taro fields trap 60-90% of the sediment, two to three times the level of sediments trapped by mangroves). This solution also eliminated damage to crops from seawater flooding in the original lower-elevation fields, improved food security, and supported cultural traditions. Of particular note in this example are the synergies between local and national efforts, and the importance of local ecological knowledge and community-led management initiatives [148].

139 Obura et al. 2019
140 Steneck et al. 2018
141 Steneck et al. 2019
142 Steneck et al. 2020
143 Steneck et al. 2019
144 Mumby et al. 2021
145 Maragos et al. 1985
146 Richmond et al. 2007
147 Richmond et al. 2019
148 Richmond et al. 2019

4.3 Near-term Innovations

Advances in the natural sciences related to local protection and management of reefs are occuring on many fronts, ranging from basic ecological knowledge of how reefs in the Anthropocene function [149] to tracking of coral reef fish and coral predator populations using environmental DNA (eDNA) [150,151]. Marine spatial planning can now incorporate local projections of coral bleaching conditions and the level of bleaching risk, which are important when developing climate policy and management responses [152,153,154,155]. There are rapid improvements in remote sensing of the health of coral, mangrove, and seagrass habitats (e.g., [156]), and fishing effort [157]. New technology for monitoring, essential to increase the amount and type of data collected at lower financial and human resource needs, include increasingly effective remote sensing (use of robotics and drones, increasing number of satellites, and improved resolution) and greater computing power (including artificial intelligence and the ability to handle the increasing amounts and complexity of the data). These improvements help alleviate spatial and temporal gaps in monitoring and increase the potential for data sharing, management, and archiving under application of FAIR principles (findability, accessibility, interoperability, and reusability), thereby creating the opportunity to revolutionise the pathway of data collection to decision-making.

In the social sciences there are also enormous changes underway to assist in the conservation and sustainable use of coral reefs. Increasingly, adaptive governance structures that better integrate principles of equity (including participatory processes such as community monitoring and research, Indigenous Partnership Plans, and Indigenous Ranger Programs), agency, resilience, co-production, and decolonisation are changing the face of coral reef conservation [158,159].

New financial models include debt conversion [160], fish banks [161], and a variety of training tools [162]. The newly established *Global Fund for Coral Reefs* could offer opportunities to accelerate these developments.

149 Williams et al. 2019
150 Uthicke et al. 2018
151 West et al. 2020
152 Obura et al. 2019
153 Voolstra et al. 2020
154 UN Environment Programme 2017
155 van Hooidonk et al. 2020
156 Asner et al. 2020
157 Fujita et al. 2018
158 McLeod et al. 2019
159 De Vos 2020
160 McGowan et al. 2020
161 Sala et al. 2016
162 Venkat et al. 2018

Martin Colognoli / *The Ocean Agency*

5 PILLAR III: Invest in Active Restoration to Enhance Recovery

INVEST IN ACTIVE RESTORATION: enhance recovery rates and explore new technologies.

5.1 Rationale

Because of the scale of destruction of nature to date, and the acknowledgement of some already-committed warming, there is increasing interest in active restoration to sustain some coral reefs and to jump-start recovery on others [163,164]. Active restoration is also needed as a ‘bridge’ to sustain corals through a (potentially extended) period of increasingly unsuitable climatic conditions [165]. Some coral species, particularly branching forms, grow quickly and are adapted to rapidly recover from physical disruptions from regular occurrences of major storms in many coral reef regions. Other species grow more slowly, but can be more resilient in the face of coral bleaching caused by high temperature [166]. However, these patterns may change under more frequent (i.e., annual) bleaching intervals [167]. Examples of unassisted reef recovery are well documented (e.g., most dramatically after nuclear test bombing in the Marshall Islands; [168]), but some situations require a more interventionist approach. These include cases where the reef framework has been severely damaged or lost (e.g., by dynamite fishing [169] or ship groundings), where coral recruitment and connectivity are poor, or where the establishment of alternate stable states inhibits return to coral dominance without intervention [170]. Coral reef restoration efforts may also build local social capital and enhance engagement in coral reef conservation [171], although this aspect is poorly studied.

As noted above, reef restoration cannot succeed in the short term without adequate local conditions for newly established corals to thrive (e.g., healthy

163 Boström-Einarsson et al. 2020
164 Hein et al. 2021
165 Kleypas et al. 2021
166 Loya et al. 2001
167 Grottoli et al. 2014
168 Duarte et al. 2020
169 Fox et al. 2019
170 Edwards 2010
171 Hein et al. 2019

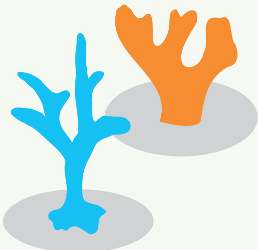
fish communities and good water quality), and is futile in the longer term without addressing climate change. In addition, active restoration is both time and labour intensive, and financially costly, which means that the spatio-temporal scales for implementation and subsequent monitoring have often been limited [172]. Thus in the near term, the best approach is to jump-start the restoration process at strategic locations to boost local resilience and recovery potential [173], while more scalable and cost-effective technologies are developed.

The potential benefits of restoration are not restricted to the immediate outcomes of individual projects. Although historically, restoration consisted of opportunistic 'gardening' efforts, by their nature, restoration projects offer the potential to explore new approaches and incorporate rigorous scientific investigation that can inform future conservation and restoration efforts [174]. Indeed, a recent study investigating the feasibility of applying reef restoration techniques in Australia found that "the positive response of coral cover to multiple interventions operating in combination was greater than the sum of responses from interventions operating individually" [175], highlighting the potential synergies in applying a suite of restoration techniques. There has been a particular interest in finding and targeting genetic and phenotypic variability within existing populations of corals and reef organisms to improve the likelihood of restoration success [176,177,178,179]. Coral nurseries can serve as platforms for adaptation-based reef restoration in which the pheno- and genotypes most suited to particular environmental conditions are selected [180]. Beyond nurseries, a number of new aquaculture and field-based methodologies (i.e., larval seeding) using sexually produced corals [181] are under development to expand the diversity and abundance of corals produced for restoration [182].

NOTE: "Restoration" and "rehabilitation" are used by some authors interchangeably. *The Society for Ecological Restoration* definition of "restoration" ("the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed") [183] is currently the most widely accepted. While the goals of "restoration" include the re-establishment of the pre-existing species composition and community structure, "rehabilitation" is focused on restoring ecosystem processes, functions, and services [184]. The shifting conditions faced by coral reefs will result in future (i.e., adapted) reefs with different compositions from the original reefs [185]. This is recognised in UNEP's guide to coral reef restoration [186], where "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". The use of the term "rehabilitation" avoids often unrealistic assumptions regarding the return to an original state, but instead embraces the changing nature of reefs, and reflects the focus on promoting the protection and adaptation of future reefs. Thus, while the term restoration is used throughout this document for consistency, current efforts on reefs should more accurately be understood to constitute rehabilitation.

172 Bayraktarov et al. 2019
173 Hein et al. 2020
174 NASEM 2019
175 Anthony et al. 2019
176 van Oppen et al. 2015
177 van Oppen et al. 2017
178 Baums et al. 2019
179 Parkinson et al. 2020
180 Rinkevich 2021
181 Randall et al. 2020
182 dela Cruz and Harrison 2020
183 SER 2004
184 SER 2004
185 Graham et al. 2014
186 Hein et al. 2020

5.2 Examples of Success



CORAL REEF RESTORATION

Some of the best examples of coral reef restoration have been carried out following acute events, such as blast fishing, storms, and ship groundings, where previously healthy reefs have suffered major sudden damage. For example, at sites with good water quality, Fox et al. [187] used active restoration to improve the stability of the reef framework damaged by blast fishing, and relied on natural recruitment processes to allow further recovery. In Indonesia, fishers formerly engaged in destructive fishing practices have turned to sustainable forms of catching marine ornamental fish and reef restoration in a form of conservation-development [188]. Other successful projects are targeting coral colonies with particular resistance to thermal bleaching for restoration, or have established partnerships with local communities and the tourism industry to implement restoration activities [189].

5.3 Near-term Innovations

The importance of innovation is particularly notable in the case of coral reef restoration, as scientists are explicitly tackling the challenges of improving scale and efficacy [190] as well as managing genetic enhancement [191] and variation [192] to optimise restoration success in a changing world. A shift from coral propagation by means of fragmentation to sexual propagation is being actively investigated (e.g., [193,194,195]) to tackle issues of genetic diversity and scalability. In addition, there are efforts to conserve the standing genetic diversity through means of cryopreservation or with the help of public aquaria to house corals [196,197]. Novel methods aim to improve the selection of source coral material (e.g., through standardised stress-testing [198]), maintaining genetic diversity through sexual propagation [199,200], or increasing thermal resilience of outplanted corals and recruits by means of environmental hardening (e.g., [201]), or microbial association (e.g., [202,203,204]). Both the integration of superior stress-tolerant local corals and coral probiotics can aid restoration approaches, leading to improved resilience and survival of outplanted coral recruits [205,206]. In the Caribbean and Australia, new research is already guiding restoration efforts to consider coral resilience, genetic diversity, and adaptability in coral propagation strategies [207,208].

187 Fox et al. 2019
188 Frey and Berkes 2014
189 Hein et al. 2020
190 NASEM 2019
191 van Oppen et al. 2015
192 Baums et al. 2019
193 Craggs et al. 2017
194 Randall et al. 2020
195 Schmidt-Roach et al. 2020
196 Hagedorn et al. 2012
197 Zoccola et al. 2020
198 Voolstra et al. 2020
199 Randall et al. 2020
200 Schmidt-Roach et al. 2020
201 Putnam et al. 2020
202 Rosado et al. 2019
203 Doering et al. 2021
204 Peixoto et al. 2021
205 Rinkevich 2019
206 Boström-Einarsson et al. 2020
207 Baums et al. 2019
208 Bay et al. 2019

PILLAR III: Invest in Active Restoration to Enhance Recovery

Once considered extreme and unrealistic, approaches like reseeding large areas of reef with corals selected or engineered to be resilient to climate change (e.g., [209]) or installing underwater flow generators to enhance mixing and reduce local seawater temperatures [210] are now being considered as part of a large tapestry of strategies for protecting and restoring coral reefs. In the laboratory, CRISPR DNA modification technologies are being explored as a mechanism to understand coral resilience (e.g., [211]), although there is current reluctance to create genetically modified corals for transplantation in the field [212]. A suite of novel and ambitious intervention strategies, from cloud brightening to assisted gene flow, are being developed and tested by a large research and development consortium under the *Reef Restoration and Adaptation Program*, funded with AUD$100M as part of the partnership between the Australian Government's *Reef Trust* and the *Great Barrier Reef Foundation* [213,214].

In some cases, novel economic instruments, such as reef insurance, or the involvement of the 'environmentally aware' tourist sector are providing financial incentives for restoration [215,216]. Support for the development and testing of more technological interventions and creative solutions for upscaling restoration efforts on local and regional scales are still needed [217], and require effort and funding on par with other grand challenges, such as the NASA's *Apollo* or *Mars Exploration Programs* [218]. The Australian *Reef Restoration and Adaptation Program* is a notable example in this direction.

Increasingly, the human dimensions of reef restoration are considered [219]. Examples include the development of social-ecological indicators to define goals and evaluate success [220], or the accounting for socio-cultural benefits of restoration and integration with sustainability science [221]. An area in need of particular attention is the co-design and co-implementation of restoration efforts and leadership by local and Indigenous communities [222].

209 Suggett et al. 2020
210 Sawall et al. 2020
211 Cleves et al. 2018
212 van Oppen and Oakeshott 2020
213 Bay et al. 2019
214 Anthony et al. 2019
215 Reguero et al. 2020
216 Schmidt-Roach et al. 2020
217 NASEM 2019
218 Kleypas et al. 2021
219 Westoby et al. 2020
220 Hein et al. 2017
221 Hein et al. 2019
222 Gibbs et al. 2021


Erik Lukas / *The Ocean Agency*

6 Moving Forward

6.1 The Fierce Urgency of Now

By 2050, the window for opportunities to act on both on coral reef adaptation and on climate change mitigation will have closed for good.[223] The ongoing and projected catastrophic collapse of coral reefs around the world and the escalating calamities caused by climate change on their own would argue for strong and immediate action to ensure the future of coral reefs. But these disasters are not 'on their own'. The COVID-19 pandemic with its enormous economic losses, and the growing appreciation of the connection between social injustice and environmental injustice, have created a turbulent moment in history where social dynamics, economic organisation, and legal infrastructure are rapidly changing. On the one hand, we have learned that even a dramatic reduction in human activity has not reduced greenhouse gases to the level required by the *Paris Agreement* [224], which is itself not adequate to protect coral reefs over the long term[225]. Greenhouse gas emissions have continued to increase even amid the global pandemic[226]. Meanwhile economic losses from the pandemic have reduced funds available for conservation actions[227,228,229].

On the other hand, we have seen an extraordinary change in human behaviour occurring extremely rapidly, and many countries have embraced the concept of using the disruptions caused by the pandemic to substantially increase their environmental ambitions, including stimulus packages aimed at speeding up energy and mobility transitions. For the *EU Green Deal*, 25% of the EU COVID recovery package is earmarked for energy-efficient and clean technology[230], although these ambitions need to be translated into actions. There is thus a real possibility that the pandemic 'pause' could enhance commitments to protect

By 2050, the window for opportunities to act both on coral reef adaptation and on climate change mitigation will have closed for good.

223 Kleypas et al. 2021
224 UN Environment Programme 2020
225 Frieler et al. 2013
226 WMO 2021
227 IMF 2020
228 IMF 2021
229 WEF 2020
230 Sinha 2020

and restore nature and seed societal transformations (e.g., in terms of green energy, sustainable tourism, and localised production). Investment in nature conservation and restoration is recognised both for its potential to generate sizable economic returns and to reduce risks of future pandemics [231,232,233].

We need to recognise this moment as an opportunity to act for coral reefs because there is no time to spare [234]. There are key decision points in the coming months that will shape the action agenda over the next decade relating to climate, biodiversity, and sustainable development. These will be critical for ensuring a positive pathway for the future of coral reefs. While a “moonshot” approach is appropriate for certain technological aspects of the solutions needed to conserve, manage, and restore coral reefs, much of what needs to be done is more akin to the challenge of controlling a global disease, which depends on actions taken at thousands of locations around the world in a coordinated effort [235].

231 UN Environment Programme et al. 2018
232 Waldron et al. 2020
233 Dasgupta 2021
234 Anthony et al. 2020
235 Kleypas et al. 2021

6.2 The Coral Reef Policy Landscape

There are over 230 international policy instruments that directly or indirectly support conservation and sustainable use of coral reefs, 73 binding instruments at the global and regional scale, and almost 600 commitments [236]. These include the *United Nations Framework Convention on Climate Change* (UNFCCC), the *United Nations Agenda 2030* and the *Sustainable Development Goals*, the *Sendai Framework for Disaster Risk Reduction*, and the *Convention on Biological Diversity* (CBD) and the upcoming *Post-2020 Global Biodiversity Framework* currently being considered by most of the world's governments.

However, the actions commensurate with these policies have not yet started or are poorly implemented. Thus, the status and function of coral reefs continues to decline. Most international policy instruments address the major stressors impacting reefs and focus on actions by Countries, which have the primary responsibility for at least 75% of obligations at the national scale and are largely voluntary in nature. Many key threats and drivers of coral reef decline, such as climate change, cannot be addressed by single states in isolation, and international policy action and collaboration are needed at the regional and national scales to enhance national delivery. 88% of the world's warm water coral reefs are under the jurisdiction of 25 States. Regional entities such as the *Regional Seas Conventions*, economic blocs, sectoral agencies (such as *Regional Fisheries Management Organizations*), and other partnerships such as the *International Coral Reef Initiative*, are well-placed to support countries in developing regionally-tailored and coordinated policies and actions for the management and sustainable use of coral reef ecosystems.

As the COVID-19 pandemic has shown, decisive and coordinated action is pivotal. Scientific results need to be taken up rapidly, while acknowledging that best practice must evolve as does our understanding. Scientific disagreements should not be taken as a signal to hold off decisions. Management needs to be nimble and adaptive as newer information becomes available (i.e., taking a precautionary approach as articulated under *Principle 15* of the *Rio Declaration* [237]). The price of inaction and procrastination outweighs the costs of early, robust measures. Science and policy need to establish an adaptive framework for policy to be able to accommodate scientific uncertainty with mechanisms to react quickly to the inevitable evolution in scientific understanding [238,239].

236 UN Environment Programme 2019
237 UNCED 1992
238 Anthony et al. 2015
239 Anthony et al. 2020

6.3 What is Needed

Three key pillars of action are necessary for coral reefs to persist into the future—reducing/halting greenhouse gas emissions, building resilience of coral reefs and coastal communities locally, and developing and implementing effective restoration tools to fast-track recovery. This decade provides an unprecedented opportunity to coordinate policy commitments and actions at local to global scales, and to seed the innovation that is necessary to maintain healthy coral reef ecosystems on the planet.

We call on policy makers and other actors in all countries to heed the collective voice of the coral reef science community. We have identified three big “Asks”, the responses to which are needed to build the political will for integrating actions ‘on the ground’, and promoting innovation that will help protect and restore coral reefs over the coming decades. Success will result in a future with functional coral reefs and the huge benefits that we derive from them. Failure will have wide reaching and dire consequences for both biodiversity and people.

ASK 1: Establish Commitment—Ensure ambitions are enough to halt dangerous climate change and coral reef biodiversity loss, and that they are implemented.

To ensure a future for reefs, we must forge political commitment from local to global levels. Both climate change and biodiversity loss are at an inflection point where they will either proceed to a ‘new normal’ that is harsh for people and unsuitable for coral reefs, or be turned towards a more habitable state for both.

There are key decision points at the respective *Conference of Parties* to the *UN Framework Convention on Climate Change* (UNFCCC) (i.e., COP26) and the *Convention on Biological Diversity* (i.e., COP15), that provide vital opportunities for making commitments and developing mechanisms for their implementation. It is critical to ensure that decisions at these COPs are ambitious enough to halt dangerous climate change and biodiversity loss, and that they are implemented, to secure a positive outcome for coral reefs, as for almost all other ecosystems on the planet. The time for action is now.

IN THE IMMEDIATE FUTURE (2021/2022)

- UNFCCC COP26: Lobby all delegates to ensure that parties commit to significant increases in ambition with regard to *Nationally Determined Contributions*, in order to limit warming to 1.5°C and to ensure that *National Adaptation Plans* (NAPs) better account for climate—ocean interlinkages, and highlighting the role of coral reefs as nature-based solutions for climate adaptation and resilience.
- CBD COP15: Ensure that the CBD Post-2020 *Global Biodiversity Framework* prioritises positive outcomes for nature and people by adopting robust science-based goals and targets with consistent, accessible, meaningful, and ecosystem-specific indicators, relevant to coral reef ecosystems, that allow governments and other stakeholders to measure progress towards these goals and targets in a standardised way.

- Establish and implement global enabling mechanisms (e.g., the *Global Fund for Coral Reefs*) to ensure implementation of the commitments made at COP26 and COP15.
- *5th United Nations Environment Assembly* (UNEA 5): Urge Member States to agree on and enable a suitable framework for policy implementation to protect and restore coral reefs.
- Build on previous efforts of informal governance structures to emphasise coral reefs in the context of the climate-biodiversity-development nexus, such as the efforts under the 2019 French Presidency of the G7 and the 2020 Saudi Presidency of the G20.

Stakeholders that are not parties to the international conventions mentioned above also have a key part to play in achieving this Ask: there is a window of opportunity from now until the COPs of the CBD and UNFCCC later this year to lobby and inform national delegations of the plight facing coral reefs, and to take up the recommendations outlined in this document as a contribution to the CBD and UNFCCC negotiations.

OVER THE COMING DECADE

The 2020-2030 decade is critical for multiple processes addressing global policy and action, including:

- Ensuring prioritisation of coral reef actions is coherent across policy frameworks. For example, ensure that ambitions expressed within *National Adaptation Plans* or *Nationally Determined Contributions* are coherent with obligations under the CBD and supported by initiatives undertaken in the context of the *UN Decades of Ocean Science for Sustainable Development* and on *Ecosystem Restoration*.
- The CBD *Global Biodiversity Framework* (GBF) will contain milestones for 2030 (leading to the 2050 goals) relating to biodiversity protection and the sustainability and equity of its use by people. Ensuring effective implementation of the Post-2020 *Global Biodiversity Framework*, along with the necessary capacity development and resource mobilisation, will be critical.
- The *United Nations Agenda 2030* and the *Sustainable Development Goals* (SDGs) will be due in 2030, seeking a balance between economic development, the state of nature, and social wellbeing for all. It is noted that the targets and indicators may be updated in line with the CBD GBF, presenting an opportunity to further standardise coral reef monitoring efforts.
- Two UN decades provide key opportunities for raising coral reef commitment and actions—the *UN Decade of Ocean Science for Sustainable Development* (UNESCO) and the *UN Decade on Ecosystem Restoration* (UNEP).
- Under the UNFCCC, two five-year assessment periods will fall within this next decade, providing opportunities to calibrate and implement political commitments to stated agreements.

These global processes and concomitant funding support for poorer countries will be essential for implementing the Three Pillars of action, and to enable Asks 2 and 3. Effective policy development and implementation has the potential to generate the unprecedented political commitment needed between now and 2030 to ‘flatten the curve’ of coral reef loss.

6 Moving Forward

ASK 2: Promote Coherence—Build strong coordinated and synergistic actions across related policy fields at all levels of governance.

Effective action at local and national levels is hindered by persistent geographic, sectoral, policy and disciplinary fragmentation. Efforts across the Three Pillars of action—on climate, coral resilience, and coral restoration—must be appropriately resourced and brought into coherence across sectors and at all scales.

IN THE IMMEDIATE FUTURE (2021/2022)

- ICRI plays a key role as the global partnership for coral reef conservation and if used to its maximum effect stands to be an important mechanism for addressing the coral reef emergency. Those governments not yet engaged should consider membership in ICRI, and ICRI members and partners should work towards strengthening its platform to ensure that its strategy continues to provide leadership to save coral reefs.
- Donors, governments, and conservation organisations should renew efforts to build capacity, ensure sustainable finance, and seek evidence-based solutions (both traditional and innovative), at national and local levels, for actions that lead to healthy, resilient coral reefs.
- Use the 14th and 15th International Coral Reef Symposia in 2021 and 2022 as an opportunity to strengthen:
    - the policy-science dialogue to ensure the production and dissemination of timely scientific evidence for reef conservation and management.
    - the development of resilience-based management and nature-based solutions as the underpinning approaches for integration of the Three Pillars.

OVER THE COMING DECADE

- Establish and/or strengthen local and national mechanisms (such as national coral reef task forces) to ensure policy coherence is achieved and that multiple targets are implemented synergistically, across multiple sectors (e.g., climate, biodiversity, maritime sectors, blue economy).
- Recognise explicitly the role of ecosystem-based and resilience-based management, and nature-based solutions in supporting local and national economies and societal benefits by promoting actions on the ground and by developing relevant national strategies and action plans.
- Ensure that the interests and rights of local and Indigenous communities are at the forefront of coral reef conservation and sustainability.

ASK 3: Drive Innovation—Develop new approaches where current solutions are insufficient to tackle the emergency facing coral reefs.

Although many tools in the current tool box for reef conservation will remain essential (capacity building, long-term monitoring, assessment of management effectiveness, etc.), a future with coral reefs will require innovation to address the extreme rapidity of change not only on the reefs themselves, but also in the economies and societies that depend on them. New technologies and solutions are needed to ensure that evolving future reef ecosystems will continue to support human health, nutrition, wellbeing, and employment.

IN THE IMMEDIATE FUTURE (2021/2022)

- Ensure, in operationalising the *Global Fund for Coral Reefs*, the *G20 Global Coral Reef R&D Accelerator Platform*, and other such mechanisms, that they prioritise support for research and testing of new solutions and technology to protect coral reefs.
- Encourage ICRI, or other suitable bodies, to develop a think tank for researchers and practitioners to develop solutions to key reef conservation problems and challenges (e.g., set up innovation/idea generation hubs, etc.).
- Promote the engagement of governments, scientists, and NGOs with the *UN Decade on Ecosystem Restoration* in order to accelerate understanding of the efficacy and limitations of coral reef restoration, and to implement best practices.
- Promote the engagement of governments, scientists, and NGOs with the *UN Decade of Ocean Science for Sustainable Development* to strengthen the dialogue between coral reef science and policy makers, and to develop a more equitable approach to science and management that is fully inclusive of the Global South.

OVER THE COMING DECADE

- Create opportunities for social and technical innovation that can support progress towards building resilience in reefs and those people that depend on them, learning from initiatives such as the *Coral Reef Rescue Initiative*, *Vibrant Oceans Initiative*, and the *Resilient Reefs Initiative*.
- Work to enable data transparency and knowledge exchange (including traditional knowledge and community science) to ensure accessible and valuable evidence availability for decision-making.
- Build a circular economy via innovation in economy, technology, governance (e.g., through innovation legislation), and establishment of national planning commissions to ensure sustainable modes of production.
- Ensure that national planning processes take into account the needs of sustaining coral reefs and linkage to SDGs (e.g., commitment to SDGs can spur a new batch of national development planning).

Joe Sylvester / WorldFish / Flickr Commons

Conclusions

CORAL REEFS ARE ESSENTIAL FLAGSHIP ECOSYSTEMS that support extraordinary diversity and hundreds of millions of people around the world. However, these ecologically and socio-economically valuable ecosystems are threatened by the continued escalation of local and global threats. Yet examples of healthy, well-managed, and recovering coral reefs exist, upon which additional successes can be built. New technologies are also being developed at a rapid pace that have the potential to increase the rate of progress. Hence the upcoming global biodiversity and climate discussions and negotiations represent an irreplaceable opportunity to change the trajectory of coral reef health for the benefit of coral reefs and associated ecosystems, and the people that depend on them. We cannot repair all past damage in the next ten years. However, by preventing irreversible damage we can lay the groundwork for future progress and begin to repair the degradation of these extremely valuable ecosystems.

Steps must be taken now to slow and reverse climate change, improve local reef conditions, jump-start recovery through restoration, and accelerate innovation towards adaptation. These urgently needed actions must be designed so that they can respond to both changing conditions and changing scientific understanding and capabilities. They must also take advantage of, and increase the synergies between, steps taken at the international, national, and regional scales and implementation at the local level. Approaches that rely on co-management and local and Indigenous knowledge stand to be the most successful. There is no time to spare.

> By preventing irreversible damage we can lay the groundwork for future progress. There is no time to spare.

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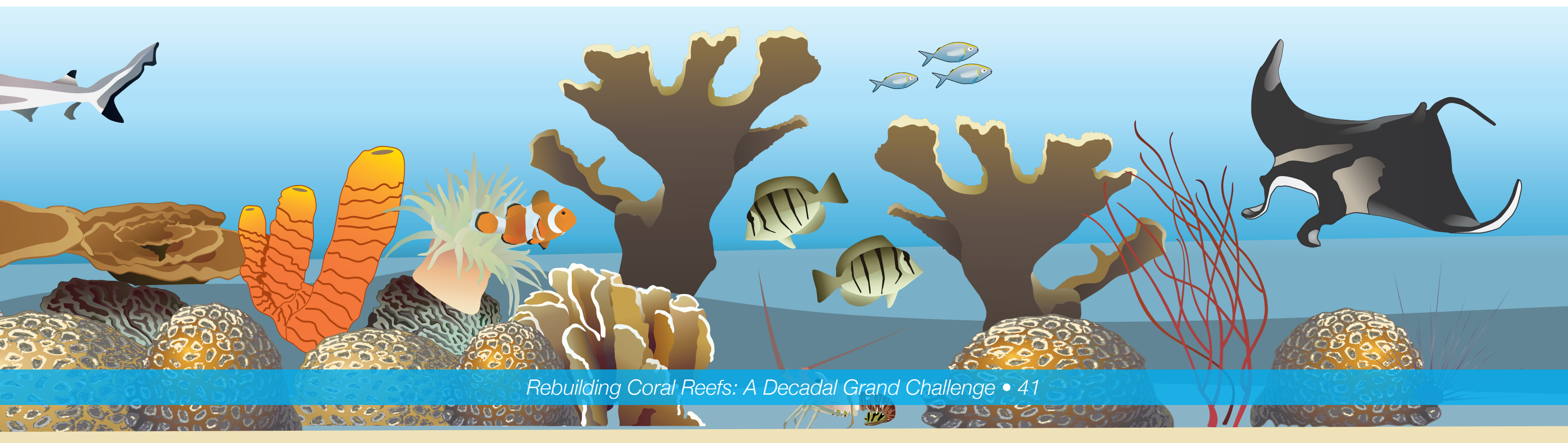

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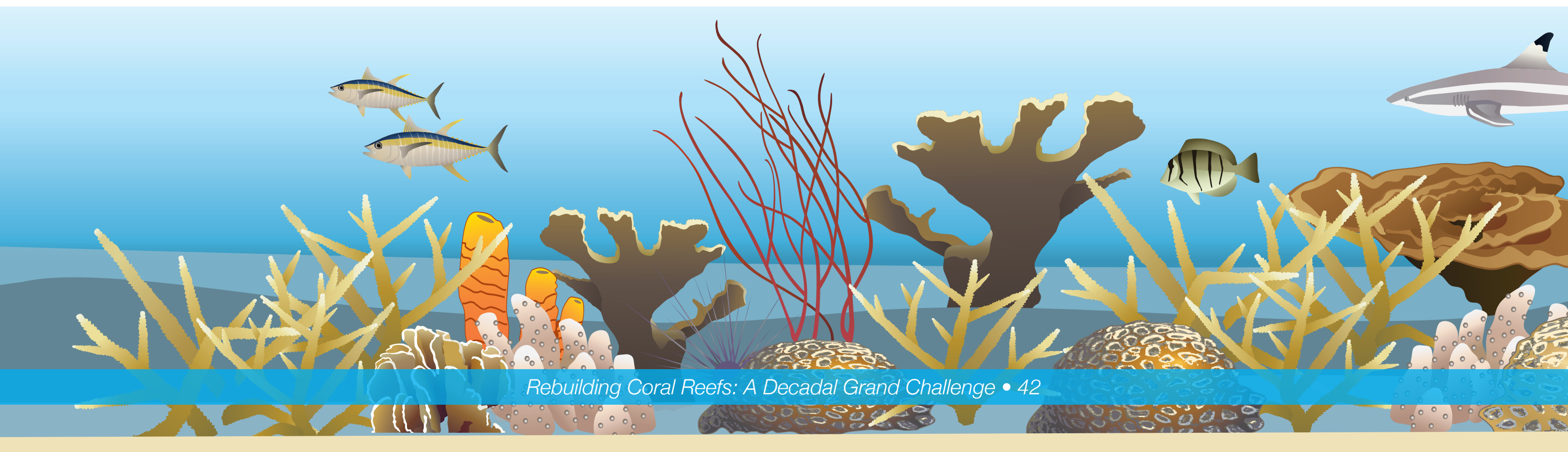

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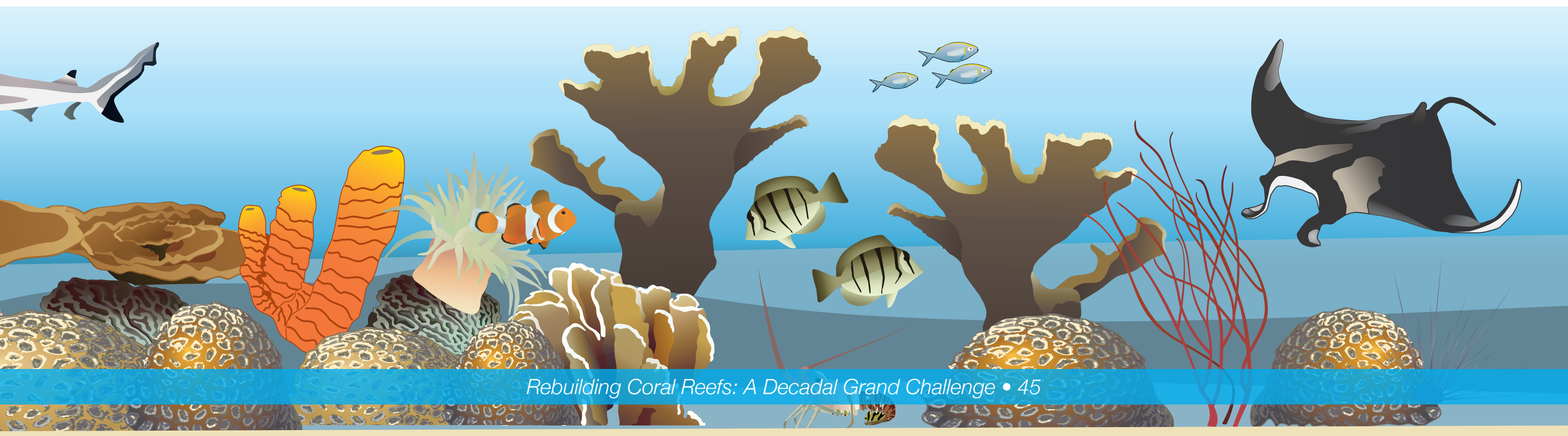

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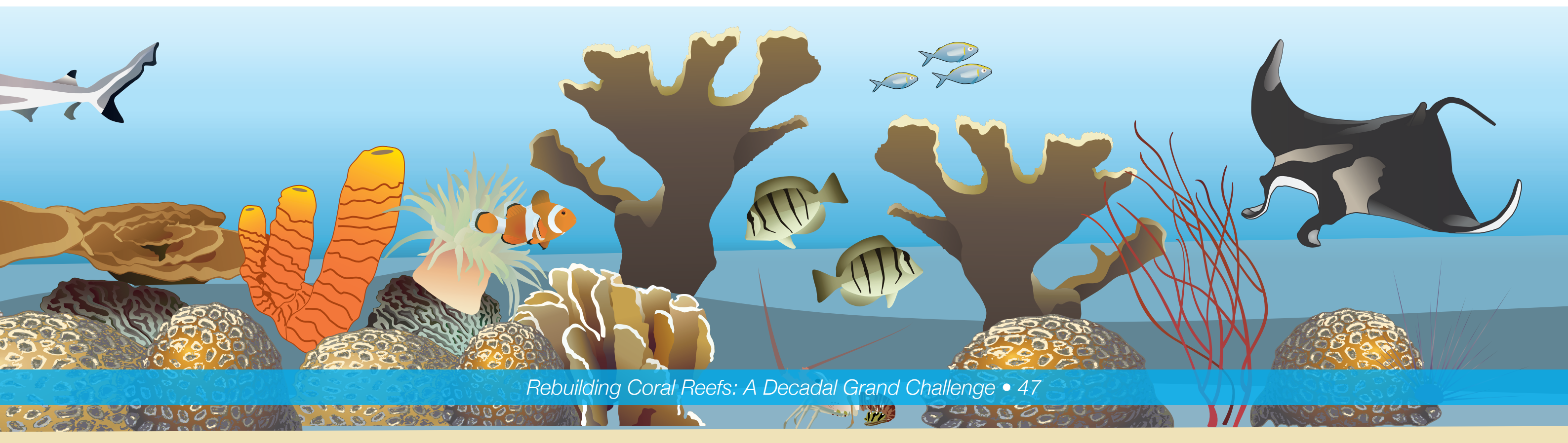

Appendix: Reference list of Organisations, Meetings, Programmes, and Agreements Noted in this Document

MEETING / CONFERENCE	ACRONYM
5th United Nations Environment Assembly	UNEA 5
15th Conference of the Parties to the CBD	COP15
26th Conference of the Parties to the UNFCCC / UN Climate Change Conference	COP26
UN Food Systems Summit	
World Economic Forum	WEF

INTERNATIONAL TREATY / AGREEMENT / RESPONSE	
2015 Paris Agreement	
Convention on Biological Diversity	CBD
Nationally Determined Contributions	NDC
Post-2020 Global Biodiversity Framework	GBF
Rio Declaration on Environment and Development	
Sendai Framework for Disaster Risk Reduction	
United Nations Agenda 2030	
UN Framework Convention on Climate Change	UNFCCC
UN Sustainable Development Goals	SDGs

AGENCY / ORGANISATION	
Global Coral Reef Monitoring Network	GCRMN
Great Barrier Reef Foundation	
Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services	IPBES
International Coral Reef Initiative	ICRI
International Coral Reef Society	ICRS
International Panel on Climate Change	IPCC
International Renewable Energy Agency	IRENA
International Union for Conservation of Nature	IUCN
National Academies of Sciences, Engineering, and Medicine	NASEM
Plan Vivo	
Society for Ecological Restoration	SER
The Nature Conservancy	TNC
United Nations Educational, Scientific and Cultural Organization	UNESCO
United Nations Environment Programme	UNEP

PROGRAMME / INITIATIVE / STRATEGY	ACRONYM
Australia's Long-Term Monitoring Program	LTMP
Australian Reef Restoration and Adaptation Program	RRAP
Coral Reef Rescue Initiative	CCRI
EU Green Deal	
G20 Global Coral Reef R&D Accelerator Platform	
Global Coral Reef Fund	GCRF
Global Fund for Coral Reefs	GFCR
Global Ocean Observing System	GOOS
Group on Earth Observations' Biodiversity Observation Network	GEOBON
Mikoko Pamoja Project	
Resilient Reefs Initiative	RRI
The Reef Trust (Australia)	
UN Decade of Ecosystem Restoration (UNEP)	
UN Decade of Ocean Science for Sustainable Development (UNESCO)	
Vibrant Oceans Initiative	VOI


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