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Perspective

Designing a blueprint for coral reef survival

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A B S T R A C T

Maintaining coral reef ecosystems is a social imperative, because so many people depend on coral reefs for food production, shoreline protection, and livelihoods. The survival of reefs this century, however, is threatened by the mounting effects of climate change. Climate mitigation is the foremost and essential action to prevent coral reef ecosystem collapse. Without it, reefs will become extremely diminished within the next 20–30 years. Even with strong climate mitigation, however, existing conservation measures such as marine protected areas and fisheries management are no longer sufficient to sustain the ecosystem and many additional and innovative actions to increase reef resilience must also be taken. In this paper we assess the suite of protections and actions in terms of their potential to be effective according to a set of criteria that include effectiveness, readiness, co-benefits and disbenefits. Even with the best scientific innovation, saving coral reefs will require a well-funded, well-designed, and rapidly executed strategy with political and social commitments at the level of other grand challenges.

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1. Introduction

Over two recent meetings, the authors of this Perspective assessed (a) the need for an ambitious but realistic plan to sustain coral reefs through the 21st century; and (b) the need to objectively evaluate interventions that should be included in the plan. The urgency of taking action is clear based on many previous projections of coral decline. Here we present additional projections to illustrate that a strategy to save coral reefs requires both a reduction in ocean warming and an increase coral resiliency. For the latter we provide a summary of an assessment of various interventions through expert opinion. We then outline the principles of a coordinated strategy to sustain reefs, with the goal of stimulating the design of a blueprint with input from many more stakeholders.

2. Background

Coral reefs are succumbing rapidly to rising ocean temperatures, and the recent and rapid degradation of reefs worldwide is well documented (Bindoff et al., 2019). Passive recovery (i.e., natural recovery without human intervention) is proving increasingly inadequate (Ortiz et al., 2018) as coral bleaching and mortality events become more frequent and severe, adding to the impacts of local anthropogenic stressors such as overfishing and pollution (Hughes et al., 2018). As stressors increase and coral cover declines, so do reproductive and recruitment success, preventing many reefs from recovering (Richmond et al., 2018). Major losses of reef corals and reef structure are expected if global warming exceeds 1.5 °C above the pre-industrial average temperature (Hoegh-Guldberg et al., 2018), and the most effective action to reduce the decline of coral reefs remains rapid and effective mitigation of greenhouse gas emissions (Hoegh-Guldberg et al., 2019). Even if the Paris Agreement is fully implemented, however, warming over the coming two-three decades will increasingly threaten the ability of reefs to recover.

To illustrate this trajectory, a new modeling analysis was performed by combining a coral bleaching model (van Hooidonk et al., 2013) with sea surface temperature projections for two emission scenarios from the NCAR Community Earth System Model Version 1.2 (Fig. 1A; see Supplementary 1 for details): high (RCP 8.5; RCP = Representative Carbon Pathway) and low emissions (RCP 2.6). We also allowed corals and coral communities to adapt, both naturally and through human actions, at a rate consistent with the change in the average annual maximum temperature of the previous 50 years (see Logan et al., 2014), which for this analysis infers a variable rate of adaptation with a maximum of 0.2 °C per decade (Fig. 1B). While some species may adapt more quickly, and others more slowly, we assume this rate includes the overall ability of reef communities to persist due to community shifts, natural adaptation, and resilience gained from human interventions (discussed below).

Regardless of the shape of the trajectory, reefs will experience a rapid increase in exposure to temperature anomalies predictive of severe bleaching (more than two severe bleaching events per decade), which will be unsustainable for most coral species (Fig. 1B). The main advantage of the low-emissions trajectory is that it buys time for corals to adapt to rising temperature through both natural processes and human interventions (Bindoff et al., 2019). Relative to the high-emissions trajectory, adaptation could greatly reduce the percentage of reefs experiencing high-frequency bleaching, despite exposure to increasingly elevated temperature, through 2040–2050 (Fig. 1B, see also Logan et al., 2014). However, the difference between the high and low emissions trajectories becomes more apparent after 2050. Under the high-emissions trajectory, temperature continues to increase, and adaptation and interventions can delay but not prevent the eventual high-frequency bleaching of all reefs. Under the low-emissions trajectory, the temperature increase slows, allowing some corals to adapt (Fig. 1B). These results are similar to adaptation models that incorporate phenotype shifts (Logan et al., 2014; Walsworth et al., 2019) or genomic-based adaptation to warming temperatures (Bay et al., 2017); i.e., adaptation delays the loss of coral populations but even these fail under all but the low emission climate scenarios (Fig. 1B, C).

The window for opportunity to act on both mitigation and adaptation is thus between now and 2050 (Anthony et al., 2017; Hardisty et al., 2020). How fast we act within this window will determine what reefs, species, and ecosystem functions and services can be sustained. Without action, coral reefs as we know them today – and their associated services to humankind (food production, shoreline protection, tourism, economic resources, cultural values) – could therefore be one of the first major ecosystems in this century to collapse under the weight of climate change.

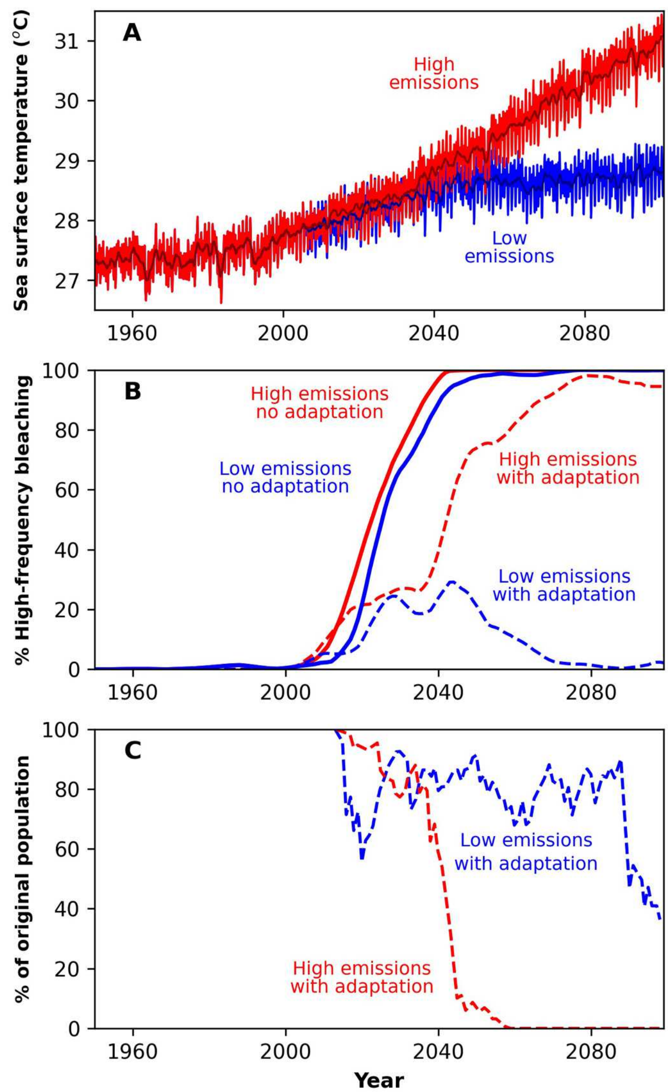

Fig. 1. Modeled projections of average sea surface temperature and bleaching: (A) temperatures for high (RCP8.5) and low (RCP2.6) emissions scenarios, and (B) the percentage of 1 × 1 degree reef cells experiencing high-frequency bleaching (≥2 severe events per decade) for four combinations of mitigation and adaptation; lines are smoothed with 10-year moving averages. For comparison, (C) is the change in modeled coral population size under a multi-locus genetic adaptation model at different future emission levels (Bay et al., 2017), beginning in year 2010. The dashed lines in (B) showing bleaching frequency with adaptation are mirrored by the lines in (C) showing percentage of original coral population size.

3. Evaluating existing and new interventions to improve the outlook for reefs

3.1. Actions to sustain coral reefs

In addition to mitigation of greenhouse gas emissions, we consider a suite of actions (Fig. 2) that fall within two categories: (1) solar radiation modification (SRM), and (2) enhancing biological, ecological, and socio-economic adaptation. SRM consists of untested strategies to reflect sunlight back to space, such as stratospheric aerosol injection that acts at the global scale, marine cloud brightening at the regional scale, surface albedo enhancement, and shading of the ocean surface that work at the local scale. We do not condone SRM because it does not reduce ocean acidification, and presents significant uncertainties and risks (Gattuso et al., 2018). SRM and other physical interventions to cool reef waters, such as pumping deep seawater into reef areas, were not included in the modeling predictions in Fig. 1B, but we list them here because they are considered by some proponents as local, high-cost actions to reduce heat stress in tourist zones or other high value areas.

Biological, ecological, and socio-economic actions are necessary partners to mitigation of emissions. These aim to enhance the natural resilience and stabilization of corals, reefs and societies (Gattuso et al., 2018). Many of the interventions are existing, proven practices that reduce reef stressors, such as management of watersheds, coastal zones, and fisheries, often as part of the establishment of marine protected areas, and often reinforced with socio-economic incentives and regulatory measures to protect coastal ecosystems, and maintain ecosystem services (Hilmi et al., 2019). An additional suite of interventions is being developed to support biological and ecological adaptation of reef organisms, including ecological engineering, assisted adaptation, and managed relocation (Rinkevich, 2020). While most of the existing practices aim to indirectly increase coral reef resilience by improving environmental conditions, most of the newer interventions aim to directly increase resilience of corals and other reef building organisms to environmental change.

The US National Academy of Sciences reviewed the science and risks/benefits of interventions to enhance the persistence and resilience of coral reefs (National Academies of Sciences and Engineering, 2019; National Academies of Sciences, Engineering and Medicine, 2018). Many of these interventions build on the practice of active reef restoration (Rinkevich, 2014; Hein et al., 2020), which entails sexual and asexual propagation of corals for outplanting into the natural environment. Active reef restoration will most likely succeed in the long term if it also incorporates (a) innovations such as assisted fertilization and recruitment (dela Cruz et al., 2015; Nakamura et al., 2011); (b) actions to speed natural selection and adaptation through assisted gene flow and managed relocation (Aitken and Whitlock, 2013; Van Oppen et al., 2017) with possible incorporation of assisted adaptation and evolution (Van Oppen et al., 2017); and (c) a focus on preserving and enhancing species diversity and genetic variation within populations, and managed species assembly to maximize the best adapted species consortia (National Academies of Sciences and Engineering, 2019). A plan for a World Coral Conservatory, i.e., ex situ coral conservation in aquaria, has also been proposed (Zoccola et al., 2020).

Deployment of most of these interventions will rely on active restoration in regions where pollution, overfishing, and other human-driven reef stressors are well managed. Active restoration still focuses on too few species and is limited to small spatial scales: even large efforts struggle to restore a hectare per year. The effectiveness of active restoration thus depends on strategies that harness coral population connectivity to accelerate the spread of heat-tolerant corals, i.e., focusing restoration on reefs where larval dispersal and recruitment can spark

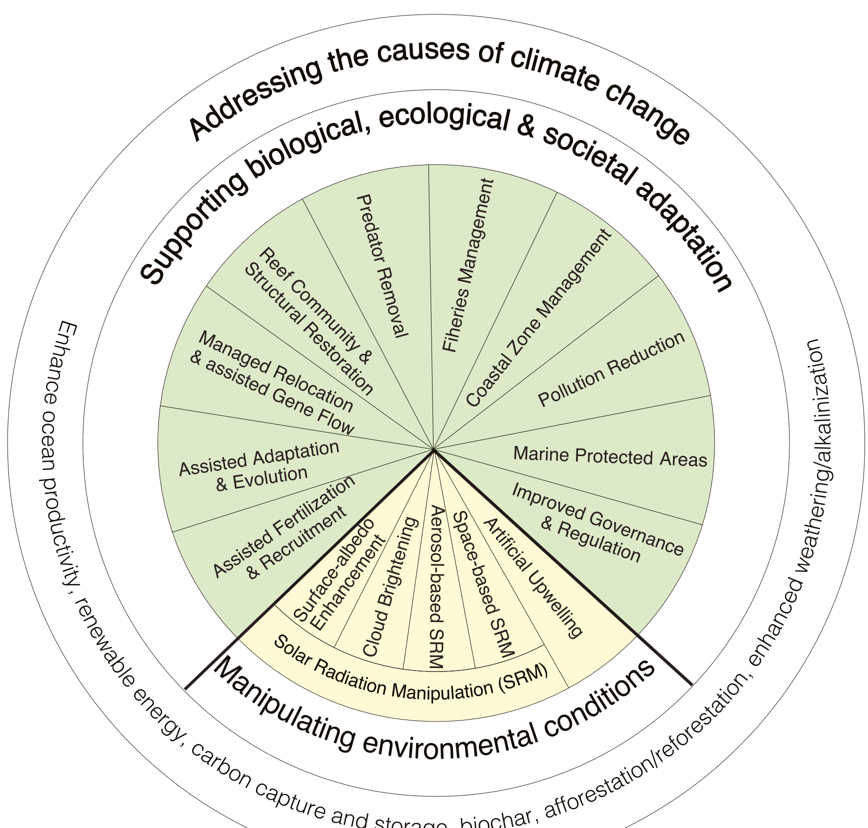

Fig. 2. Potential actions to sustain coral reefs and the benefits they provide, ranging from mitigation (addressing the cause of climate change), to a variety of biological, ecological, and social interventions and adaptations, and to solar radiation manipulation. An evaluation of these measures is illustrated in Fig. 3.

year-to-year spread over larger areas (Hock et al., 2017; Walsworth et al., 2019). In some regions, structural restoration will be needed to enhance ecological recovery of shorelines (Beck et al., 2018) and fish production (Rogers et al., 2018). All of these innovations, which are broadly reviewed in the context of management, policymaking, and fund-raising (Hein et al., 2020), will require rigorous field testing prior to large-scale deployment.

3.2. Assessment of actions

Although coral reef scientists and managers agree that an ambitious plan is needed to fortify coral reefs against climate change and other stressors, there is considerable debate on the elements that should be included in such a plan. The participants of both teams of this paper ($n = 21$) were asked to provide their expert opinion for each of the actions in Fig. 2 based on six criteria and with the next 20–30 years as a timeframe: (1) *Effectiveness* in moderating drivers of ocean changes and/or impacts on coral reefs; (2) *Readiness*: the current state of technological development; (3) *Co-benefits*, or additional benefits to other ecosystems; (4) *Disbenefits*, or adverse consequences; (5) *Acceptability* of the action culturally, societally, politically; and (6) *Scale* (see Supplementary 2). A 0–5 scoring system (unknown, very low to very high) was used except for Scale, which was scored from 1 to 3 (local, regional, global) (Fig. 3A, B). An overall score was determined as the sum of the first five criteria, while scale was addressed separately (Fig. 3C).

Addressing the causes of climate change ranked the highest overall. Among the suite of local to regional actions to support biological, ecological, and societal adaptation, those that have been in place for longest (e.g., improved governance, coastal zone management, fisheries management) were scored as effective, ready, with mostly high co-benefits and few disbenefits, but had mixed scores in terms of acceptability, which reflect conflicts associated with increased regulations. Removal of predators and invasive species was broadly considered to be less effective as a stand-alone action, but perhaps necessary to guarantee success of other actions (e.g., reef restoration; assisted fertilization and recruitment). The four remaining biological and ecological interventions (restoration, managed relocation, assisted adaptation, and assisted fertilization) are untested, or still confined to local deployment. There was relatively low agreement among the responders on their effectiveness, readiness and co-benefits, although most actions scored highly in terms of lacking disbenefits. Among these, assisted adaptation and evolution received the lowest overall scores, and reef restoration the highest. The issue of scalability (across both space and across a range of species) was cited as a major reason for the low effectiveness scores, except for assisted fertilization and recruitment, which has the potential to operate over larger scales.

The geoengineering approaches received the lowest overall scores, reflecting a high degree of uncertainty and difficulty with evaluating them. Notably, co-benefits were considered to be low but disbenefits high, particularly with the regional to global scale actions of cloud brightening, aerosol-based SRM and space-based SRM.

The overall score (Fig. 3C) is an insufficient assessment of each action because one cannot assume that the criteria of evaluation are equally important. However, it does provide a coarse insight into expert opinions. Among the two global-scale actions, only reducing carbon emissions scored highly (aggregated score of 24.5 out of a maximum score of 25) while the other (aerosol-based SRM) scored very low (<7 out of 25). Most of the regional scale actions are already well-established within "coastal zone management." Among the local actions, a few would rank more highly if scalability could be increased, such as through networks of local actions (restoration, assisted reproduction, assisted gene flow) to increase resilience within a reproductively connected population or metapopulation.

This expert assessment can serve as an example framework for constructing a blueprint for sustaining coral reefs. The evaluation highlighted the consensus that mitigation of greenhouse gas emissions is not only essential to reef survival, but is also the most wide-reaching, effective, achievable, beneficial, and acceptable action. It also highlighted that reduced emissions must be paired with continued local to regional actions to protect the coral reef environment and to increase coral reef resilience. Many of these actions need improvement, and some need further development and testing with the acknowledgment that some may never be implemented if risks are deemed to be too high.

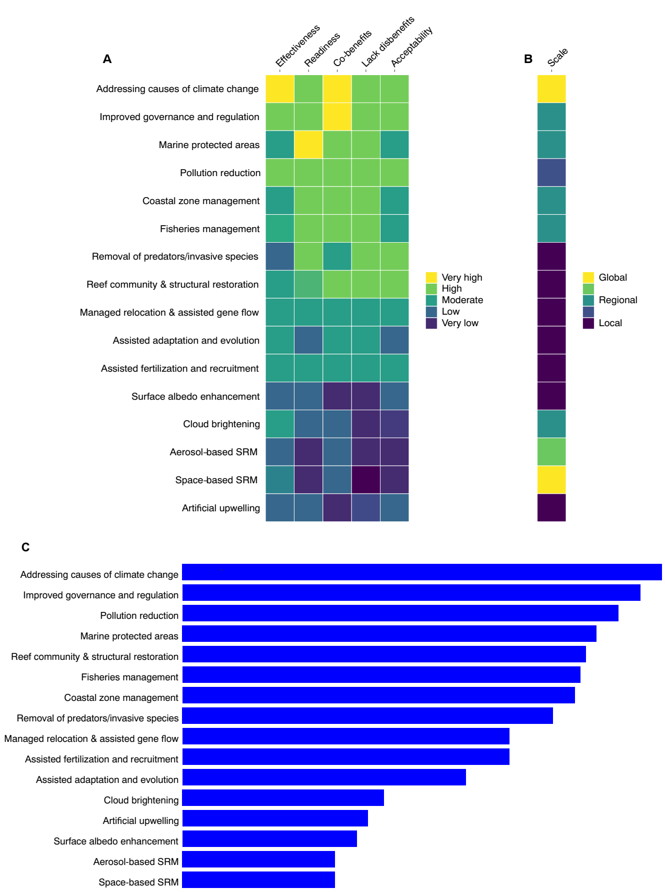

Fig. 3. Results of expert ranking of potential actions shown in Fig. 2 on (A) effectiveness, readiness, co-benefits, disbenefits (lack of), and acceptability, as well as on (B) scalability. Sum of scores in A are shown in (C).

4. A blueprint for reef survival

At the outset of designing a blueprint to sustain coral reefs into the future, three key constraints must be acknowledged. First, fully protecting and restoring the global coral reef estate of the 1890s or 1990s is impossible, even if global warming is kept to 1.5 °C. Areas for protection and restoration must be prioritized and one must accept that future reefs will be very different than reefs of the past. Second, the goals of reef protection and restoration are already shifting from what is desirable (e.g., species protection, maintaining species diversity, and returning the ecosystem to its former state) to what is possible (e.g., maintaining sustainable reef function, supporting fisheries, culture and tourism, and enhancing reef-building to protect shorelines). Third, current approaches to reef conservation must be rapidly converted to an organized strategy, underwritten by strong governance and investment, to sustain coral reefs and the services they render to humankind.

4.1. An organized strategy

We stress the need for an organized strategy that coordinates the science, policy, governance, and investment to achieve the common goal to sustain coral reefs as viable socio-ecological systems into the future. Overall, the *scientific commitment* to the blueprint should build on and improve previous actions to reduce local to regional stresses on coral reefs but will also need to encourage and test new innovations, as has been required for all previous world challenges. Even the best scientific innovation, however, requires a level of political, social, and economic commitment similar to when society came together to confront other huge challenges. A few prominent examples include the US Apollo program, efforts to cure cancer and AIDS, and eliminating famine, each of which have achieved different levels of success. The two necessary actions to save coral reefs, mitigating climate change and increasing coral resilience, require different models.

The challenge of mitigating climate change is often compared to the challenge of the Apollo program to put a human on the moon (King et al., 2015). The Apollo program was largely an engineering challenge, received tremendous financial backing (about 4% of the US federal budget in each of the years 1964–1967), and employed thousands of scientists and engineers. Solving climate change through innovations in renewable energy and carbon capture is similarly considered a technological challenge, although failures in the political and economic systems have greatly impeded progress (van Renssen, 2018).

The challenge of saving an ecosystem, however, requires more than technology and must be deployable at hundreds to thousands of locations in developed and developing countries. An effort to save the reef ecosystem is actually more akin to global efforts to cure disease. Using cancer as an example, research led by the U.S. National Cancer Institute has led to a substantial decline in mortality due to progress not only in treatment, but also in social programs that promote positive human behaviors such as healthy eating and reduced smoking (Kort et al., 2009). Some of the biggest hurdles to finding cures for cancer include the disease's inherent biological complexity, the need for translational research (applying biological findings and clinical trials to improve health outcomes), and the drug approval process. Other hurdles include delivering these benefits to communities throughout the world, often at medical technology centers. A strategy to save coral reefs should build on these lessons, for example: new technologies that can scale up reef restoration and adaptation, policies and strategies to accelerate widespread deployment while minimizing risks; and incentivizing local communities and global society to adopt behaviors that improve the environmental conditions on reefs. The latter requires efforts to vastly improve public literacy on ocean issues (Steel et al., 2005) with an approach tailored to different nationalities, cultures and demographic groups (Buckley et al., 2017).

The urgency of the coral reef crisis also calls for much stronger coordination across disciplines. Traditional coral reef science is mostly carried out by biological researchers who are rarely organized within a larger plan to help sustain reefs. The basis for this coordination would ideally take advantage of multiple existing organizations and networks (e.g., International Coral Reef Society, Reef Resilience Network, International Coral Reef Initiative, the Coral Restoration Consortium), and numerous government organizations, NGOs, and private institutions that are already partnering to achieve common objectives. Such partnerships must be strengthened with a clearly defined mission of top priorities over the next 20–30 years, and a flexible plan for coordinating the multiple measures of adaptation (Fig. 2).

4.2. Strong backing by governments and investment

Large-scale missions are more likely to succeed when they have well-defined goals and outcomes, and "when government plays a deliberate role in directing innovation and growth to achieve a desired objective" (Mazzucato, 2016). Policies to sustain coral reefs should be based on achieving a series of prioritized objectives rather than a set of poorly defined goals (e.g., "save coral reefs"). This may be the most difficult challenge, because priorities (ecosystem function, biodiversity, fisheries support, tourism, reduction in shoreline flooding and erosion) will vary from region to region and across coral population boundaries, which are inherently transnational, or even trans-governance within national jurisdictions (e.g., Great Barrier Reef; village or atoll-level governance across wide stretches of the Indo-Pacific).

Previous multi-national agreements to protect marine resources provide examples and lessons in how this challenge can be achieved (e.g., the Micronesia Challenge, Coral Triangle Initiative, Western Indian Ocean Challenge, Caribbean Challenge). One can also build on several regional plans under development, such as Australia's Reef Restoration and Adaptation Plan (RRAP) for the Great Barrier Reef (Hardisty et al., 2020). The Australian government has begun to identify potentially scalable actions and develop an economic case for further research, followed by an AU$100 m investment to build a decision-support system that allows potential restoration options to be integrated with other management actions. In the U.S.A., Congress is considering modest funding (US$36 m) to strengthen coral reef conservation and restoration, and increase collaboration among stakeholders (S2429, Restoring Resilient Reefs Act). The newly developed Global Fund for Coral Reefs, a partnership of private philanthropy, finance institutions, and UN agencies, seeks to invest US$500 m through blended finance in coral reef conservation over the next decade. These efforts are a good start, but the cost of sustaining enough of the coral reef ecosystem to prevent collapse will require billions in US dollars. While this value seems high, by comparison hundreds of billions of US dollars will be required to protect U.S. coastal infrastructure from rising sea level alone over the next 20 years (LeRoy et al., 2019).

5. Conclusions

The scientific vision for a 20 to 30-year blueprint should prioritize reducing greenhouse gas emissions and enhancing the capacity of reefs to recover from climate impacts, adapt to stress, and respond rapidly to their changing environment. Some strategies, such as supported breeding and assisted gene flow, can be deployed now. As demonstrated for biomedical research (Chalmers et al., 2014), new technologies will require translational research to speed up their testing, risk assessment, approvals, and deployment in the field. One must hasten natural selection of a wide array of species that are better adapted to the new biophysical regime, and then find ways to sustain those adaptations throughout entire populations, which can range over hundreds, even thousands of kilometers. Dissemination of adapted corals and other innovations could be modeled after agricultural and forest extension services, which provide guidance to cultivators toward improving their productivity, including in the context of climate change, and in the value of species and genetic diversity in the face of an uncertain future. Finally, strong governance that includes a supportive regulatory framework for implementing and enforcing policies must be addressed concurrently with the scientific approaches and public communication and engagement; otherwise, critical time will be lost along with the potential for success.

We present this Perspective as a broad view of the global challenge to save coral reefs, and to help define the elements needed to design a comprehensive plan. What we propose is possible with a clear 20 to 30-year plan that attracts the necessary public interest, investment, and policies on par with major efforts in space research and human health. It requires a 'Grand Bargain' with world leaders: if they reduce global emissions to keep warming below 1.5 °C, reef scientists will work in partnership with management agencies, conservation NGOs, and communities to save a sufficient number of reefs to sustain key services to coastal communities and allow their global recovery once emissions are effectively mitigated. The economic value of coral reefs in US waters alone is estimated at US$3.6 billion annually (Brander and Van Beukering, 2013), and globally the value is at least an order of magnitude higher. With support equal to the scale of this problem, coral reefs can be protected for future generations. Developing a blueprint to save coral reefs may be the first major attempt to save an ecosystem, but it will also provide a roadmap of action for other ecosystems at risk (Duarte et al., 2020).

Declaration of competing interest

All authors of this paper attest that:

The work is all original research carried out by the authors.

No part of the research has been published in any form elsewhere.

The manuscript is not being considered for publication elsewhere while it is being considered for publication in this journal.

Any research in the paper not carried out by the authors is fully acknowledged in the manuscript.

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Appendix A. Supplementary data

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