NOAA Action Plan on Coral Interventions

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U.S. Department of Commerce
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Cover photo: Hanna Koch / Mote Marine Laboratory. *Orbicella faveolata* grown in a lab, spawning on the reef.

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EXECUTIVE SUMMARY

NOAA recognizes the deterioration of global coral reef ecosystems and is committed to intervening in US reefs where it has the authority to act and support, and to promote the restoration and intervention of reefs worldwide. The recently completed National Academies of Sciences, Engineering, and Medicine (NASEM) reports on coral interventions have helped NOAA to develop this high-level plan of action that will guide how the agency approaches coral interventions in the next one to three years. The plan encompasses four actions for the agency: (1) research and test priority interventions, (2) develop local or regional structured decision support, (3) review policy implications of coral interventions, and (4) invest in infrastructure, research, and coordination. This action plan in no way encompasses all of what is needed to ensure the persistence of reefs; it merely delineates the steps NOAA aspires to undertake in the near term. While NOAA is currently conducting some research and implementation, referenced below, implementing sufficient and lasting interventions will require significant additional investment.

INTRODUCTION

Scleractinian corals are responsible for building reefs that harbor an estimated one-third of oceanic biological diversity and provide human society with critical ecosystem services, such as coastal flood risk reduction and fishing, valued at almost $10 trillion/year (Costanza 2014). Overfishing, poor water quality, ocean warming, and rampant coastal development have caused 60% of the world's reefs to be considered degraded or destroyed, and reefs are predicted to be functionally extinct by 2050 under current environmental trajectories (Bindoff et al. 2019). Substantial investment has been made in conventional management strategies (e.g. reducing local stressors such as overfishing, restoration via 'coral gardening'). These efforts, along with actions to limit CO_2 emissions, are necessary to maintain an environment that is hospitable to corals in the long-term.

However, conventional management is proving insufficient to foster coral recovery in the short- to medium-term, because the magnitude of environmental change is outpacing corals' natural ability to adapt. In 2018 NOAA commissioned the National Academies of Sciences, Engineering, and Medicine (NASEM) to review and evaluate the quickly evolving science of novel ecological and genetic coral intervention strategies. These interventions have the potential to enhance recovery and sustainability of corals under near-future environmental scenarios, and include stress-hardening, translocation of non-native stocks, manipulation of symbiotic partnerships, selective breeding, and genetic modification (for a full list see Appendix A). The NASEM review was completed in September 2019 and comprises two reports:

1. A Research Review of Interventions to Increase the Persistence and Resilience of Coral Reefs, and
2. A Decision Framework for Interventions to Increase the Persistence and Resilience of Coral Reefs

The NASEM reports are a relevant and timely toolbox to help NOAA and others respond to reefs in crisis. They include detailed descriptions of interventions including their benefits and tradeoffs, as well as a framework that can help groups reach scientifically sound decisions on this complex topic. Given the accelerating pace of threats to reef ecosystems, it is clear that effective, timely interventions, will need to be judiciously applied. Furthermore, coordinated bodies of scientists, governmental officials, and other stakeholders will have to decide which blend of conventional management and interventions will maximize their local reefs' ability to persist considering budget, local buy-in, and policy.

This high-level action plan describes NOAA's intended path forward regarding coral intervention research, application, and decision-making. This document is a near-term action plan, informed by the NASEM reports, and to be accompanied by more detailed plans in the coming years. This plan does not take the place of the recently completed Coral Reef Conservation Program's Strategic Plan, a broader plan of action for much of NOAA's investment in coral reef conservation.

ACTION I. RESEARCH AND TEST PRIORITY INTERVENTIONS

The first NASEM Report described 23 types of interventions to increase the persistence and resilience of coral reefs. These interventions were categorized into four groups that address issues at various scales (Figure 1). “Genetic & Reproductive” interventions focus on factors that may increase corals resilience and may be heritable. “Population & Community” interventions focus on optimizing coral resilience across a sub-population, regional population, or the entire species range. “Physiological” interventions focus on manipulating internal mechanisms of the coral, symbiotic algae, or other portion of the holobiont to proffer resilience. Lastly, “Environmental” interventions manipulate the external environment to be more hospitable to corals. In the second report, the 23 interventions were characterized by availability (immediate, short-term (~5-year time frame), or long-term (~20-year time frame)). While all the described interventions require more research and testing, those available immediately and in the short-term have had at least limited lab or field tests.

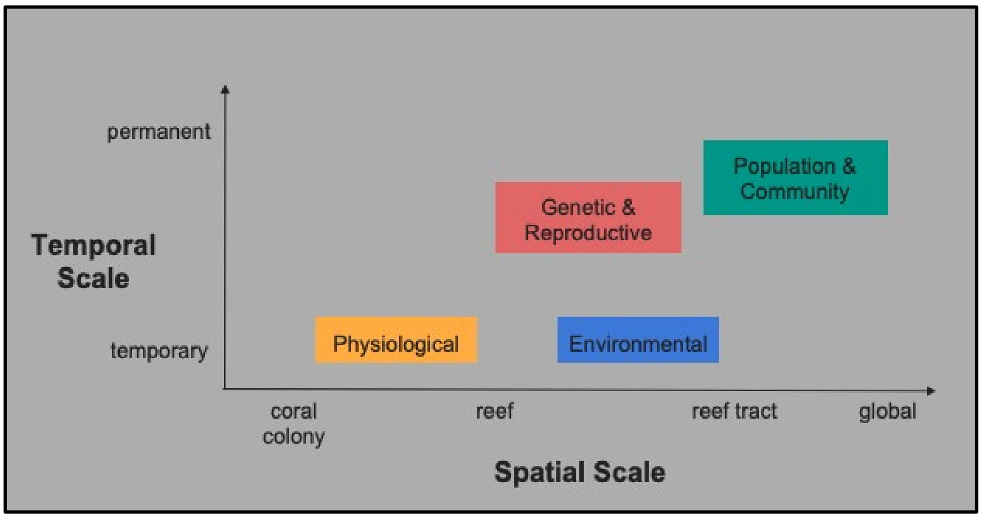

Figure 1. The four categories that the NASEM ascribed to interventions are in the colored boxes. Categories vary in the scales they address - from individual coral colonies to the world’s reefs, and from repeated applications to trans-generational, potentially permanent fixes. This graph is an approximation, individual interventions within a category may fall outside of the colored box. See Appendix A for more details.

In commissioning the NASEM reports and in preparing this report, NOAA faced two issues. First, the pressing need for research to guide active interventions where the science is incomplete. Second, the need to organize and prioritize recommendations that are coming from a field of study that is growing extremely quickly. The NASEM reports helped organize the research on interventions so that NOAA and others could move forward in a coordinated and deliberate approach. Since many of the interventions assessed by the NASEM are not yet ready for implementation, considerably more research and testing is needed, hence the focus of this report on Action 1: *Research and Test Priority Interventions.*

Under the first action we identify NOAA’s objectives for intervention research and testing based on the information presented in the NASEM review. How did NOAA choose which interventions to prioritize? Because no single intervention is likely to “save the reefs”, we included interventions from each of the NASEM’s four categories - Genetic & Reproductive, Population & Community, Physiological, and Environmental. Considering limited resources, we then prioritized these interventions based on their availability, feasibility, relevance to specific environmental emergencies (e.g., disease in the Caribbean), and applicability to current management objectives.

Below we combine the prioritized interventions into six concrete objectives. The objectives include interventions for further research and development, field testing, or operationalizing. Any terminology used by the NASEM appears in quotes to facilitate cross-referencing. NOAA is currently providing or planning to provide research, technical assistance, and/or financial assistance to advance these objectives; however, existing resources are insufficient to make them fully operational in the near-term. NOAA's ongoing or planned activities that relate to the below objectives are referenced. NOAA is not committing to addressing all of the research gaps in this Action Plan, but rather will explore opportunities through a variety of mechanisms and partners.

1. **Increase Diversity of Coral Populations.** Coral populations are becoming increasingly small and fragmented, leading to depensatory effects that further limit spawning and recruitment. Increasing the stress tolerance or simply the genetic diversity of small, fragmented populations by importing corals from populations in different parts of the species' range (e.g. "Assisted Gene Flow", "Outcrossing Between Populations") or even from within a population ("Supportive Breeding"), may be some of the least risky and most effective intervention strategies. NOAA was involved in one of the first demonstrations of "Assisted Gene Flow" using "Outcrossing Between Populations" and "Coral Cryopreservation" in the endangered Caribbean elkhorn coral (Hagedorn et al. 2018). The next steps are stress testing the corals for heat tolerance. NOAA plans to continue investing in and promoting this type of research.

2. **Improve techniques to support interventions.** The three interventions listed below have benefit as interventions in their own right; however, they are primarily techniques that enable other interventions. These techniques will promote the most immediately available and some of the least risky interventions. They also capitalize on existing restoration infrastructure. Thus, NOAA is committed to improving their availability.

    a. **Identify stress tolerant coral colonies or genes ("Managed Selection").** NOAA is developing scalable protocols and methodologies to provide data products on genotype performance and resilience to disease, ocean acidification, and warming. When available, this information will be given to restoration practitioners with nursery facilities to inform and improve restoration success. This includes identifying resistant phenotypes in precisely known locations across broad gradients of stress exposure, studying corals in extreme and marginal environments, and combining genomic, transcriptomic, and proteomics approaches to understand the molecular mechanisms of resilience. NOAA, along with many other research institutions, is actively investing and engaged in this research. Once reliable techniques are established, we recommend that coral restoration practitioners identify stress tolerant corals if they are capable and have the funding to do so.
    b. **Expand cryopreservation capabilities to capture current genetic variation for future research and restoration ("Coral Cryopreservation").** This is a foundational technique that is increasingly necessary for the long-term persistence of corals in the Caribbean and may soon be necessary elsewhere. Research and development in coral cryopreservation is needed as species vary in reproductive modes. Further, species' gametes, larvae, and tissue behave differently under the cryopreservation process (i.e., collection, freezing, and thawing). Due to infrastructure and expertise needed, coral cryopreservation requires stable, consistent support such as that provided by federal governments. NOAA will seek to play a more active coordination role in this endeavor.
    c. **Harness the diversity and abundance of coral spawning.** Millions of genetic recombinations are potentially available during each coral spawning event. "Gamete and Larval Capture and Seeding" allows users to capture spawn and re-seed reefs, or create new brood stock for asexual propagation, either with lab-based fertilization and settlement, or using mobile pools. It is an efficient and non-risky technique that facilitates "Outcrossing Between Populations." This technique has shown great promise

in the Philippines and in the Southern Caribbean, but needs significant investment to demonstrate reef or regional scale restoration success beyond the post-settlement bottleneck. This research is currently led by other institutions and researchers, such as the Coral Restoration Consortium's Larval Propagation Working Group, SECORE International, Southern Cross University, Akajima Marine Science Laboratory, and Seikai National Fisheries Research Institute.

3. **Develop a framework for coral epidemiology.** A disease is currently ravaging Caribbean corals, and worsening climate conditions are likely to increase the frequency and severity of coral disease outbreaks worldwide. The research, veterinarian, management, and restoration communities need an epidemiological framework for coral-disease intervention, as well as research and development of therapies and delivery mechanisms. NOAA is researching coral disease mechanisms, potential treatments, and applications of proteomics and transcriptomics, developing models of infection and transmission, and quarantining susceptible individuals. Although disease-halting interventions such as "Antibiotics" and "Microbiome Manipulation" are not quite as easily or widely applicable as some of the other interventions, coral epidemiology is a critical and under-funded area of research for long-term reef persistence. Further investment in early detection and treatment is needed to avoid reacting late and spending funds on containment and treatment. NOAA coordinates the Coral Disease and Health Consortium and is actively engaged in this field of research.

4. **Stress-harden corals ("Pre-exposure").** Multiple lab experiments and field observations have demonstrated that corals can increase their resilience to temperature and ocean acidification stress under certain conditions. Harnessing this capability holds potential for restoring resilient reefs. Promisingly, in NOAA's automated wet lab, growing corals under elevated temperature stress has resulted in increased *disease* resistance. In order for this technique to be operationalized at an appropriate scale, stress-hardening interventions need significant investment, something akin to Australia's $35M National Sea Simulator. NOAA will capitalize on early results, and work with partners to continue funding and actively engaging in this field of research.

5. **Manipulate algal symbionts to improve thermal tolerance ("Algal Symbiont Manipulations").** Coral bleaching is expected to increase in frequency over the next decades. Algal symbionts vary in their thermotolerance. Interventions that take advantage of this variability have experimentally increased the thermotolerance of the coral holobiont. The logical next step to bring this intervention closer to field-testing is to experiment with specific algal symbiont introduction in a coral larval rearing facility. This is a relatively low-risk intervention that has great potential; however, if successful, like stress-hardening, it would require significant infrastructure to operate at scale. Currently, this research is being spearheaded primarily in academic institutions.

6. **Assess feasibility of environmental interventions.** "Environmental" interventions are manipulations to the physical or chemical environment to reduce or prevent bleaching, or reduce acidification. They can be geared to protect high-value sites, such as nurseries or frequent tourist destinations. Examples include "Shading" corals from incident light or "Mixing of Cool Water," and changing the alkalinity of reef waters by restoring nearby plant communities ("Seagrass Meadows and Macroalgal Beds"). None of the environmental interventions listed in the NASEM reports is immediately available. However, assessing their feasibility is worthwhile as "Environmental" interventions could complement longer-lasting

biological ("Genetic & Reproductive" or "Population & Community") interventions (Figure 1). Most of the research on environmental interventions is spearheaded in Australia, but NOAA is actively researching mitigation of local acidification. By restoring seagrass beds adjacent to reefs, local ocean acidification can be reduced with the bonus of capturing carbon from the atmosphere.

Table 1. NOAA objectives for researching and testing priority interventions (Action 1) and the corresponding NASEM interventions. For a full list of NASEM interventions see Appendix A. NMFS = National Marine Fisheries Service. PIFSC = Pacific Islands Fisheries Science Center. NOS = National Ocean Service. OAR AOML = Oceanic and Atmospheric Research, Atlantic Oceanic and Meteorological Lab. CRC = the Coral Restoration Consortium which NOAA co-leads. There are CRC working groups on cryopreservation and larval propagation. Indirect - indicates that NOAA might fund the work, but the work occurs at a non-NOAA institution. *Most of the funding for coral work at NOAA comes from the Coral Reef Conservation Program.

Objective	NASEM Intervention	Intervention Availability	*Current NOAA Involvement
1. Increase diversity of coral populations	Assisted Gene Flow	Immediate	NMFS, Ruth Gates Coral Innovation Grant
	Outcrossing between Populations	Short-term	
	Supportive Breeding	Immediate	
2. Techniques to support interventions	Coral Cryopreservation	Immediate, Short-term	Indirect, CRC
	Managed Selection	Immediate	NMFS PIFSC
	Gamete and Larval Capture and Seeding	Immediate	Indirect, CRC
3. Epidemiology	Antibiotics	Short-term	NOS - Coral Health and Disease Consortium
	Microbiome Manipulation	Short-term	
4. Stress-hardening	Pre-exposure	Immediate	OAR AOML
5. Increasing thermal tolerance	Algal Symbiont Manipulation	Immediate	Indirect
6. Environmental	Seagrass Meadows and Macroalgal Beds	Short-term	OAR AOML
	Marine Shading	Short-term	Indirect
	Mixing of Cool Water	Short-term	Indirect

ACTION II. DEVELOP STRUCTURED DECISION SUPPORT FOR CORAL INTERVENTIONS

The single most salient and concrete recommendation arising from the two NASEM reports was to conduct adaptive management planning based on local stakeholder input, predictive decision-making models, local quantitative ecological reef data, and biophysical models including environmental parameters (e.g., water quality, toxicants, pollutants) based on those data. While this recommendation sets an extremely high bar in terms of data needs, an intervention decision-modeling exercise would be helpful in deciding which interventions are most applicable to be tested on a particular reef or region and most palatable to stakeholders. Importantly, interventions should never be considered or implemented in a vacuum, but rather as part of an overall reef management and restoration design.

The NASEM reports' primary recommendation was to:

Create Site Specific Adaptive Management Frameworks - *A structured adaptive management framework that considers all drivers and pressures affecting coral reefs should be developed to evaluate tradeoffs across alternatives and identify when and where new coral intervention(s) will be beneficial or necessary. This framework should include:*

- *Engagement of a broad set of stakeholders to establish objectives and courses of action that reflect community values.*
- *Development of models tailored to the local environmental and ecological setting, management objectives, and preferred intervention options.*
- *Targeted monitoring of short- and long-term metrics of reef health and resilience.*
- *Iterative evaluation and adjustment of management strategies.* (NASEM 2019b)

NOAA, thanks to decades of investment, is in the rare position of having many years of biological data, internal capacity for biophysical modelling, and the ability to engage local stakeholders in determining their risk tolerance for novel interventions. NOAA currently supports jurisdictions in developing restoration plans that include stakeholder engagement, evaluation of trade-offs, and developing monitoring plans. As a result of the NASEM reports, NOAA plans to engage new or existing multi-institution groups to incorporate active intervention strategies into the broader decision-making framework of resilience-based management. Under this action, NOAA and partners will develop two decision-making pathways, one tailored to the Pacific Islands and one to the US Caribbean. The decision-making pathways will evaluate interventions against alternatives of doing nothing, using traditional conservation management, or coral gardening.

NOAA envisions a cycle of adaptive decision-support modeling and monitoring. The first step in this cycle will be to clarify goals and objectives (e.g., ecosystem service desired, geographic range of reef restored). Building on clear goals, we may be able to evaluate decisions on possible interventions using more dynamic models (e.g., Bayesian Belief Networks). This step could include more specific physiological, ecological, and evolutionary modeling. In building these models, research needs/gaps will be highlighted, and organizations in charge of monitoring (e.g. the National Coral Reef Monitoring Program) will refine monitoring targets. This cycle of adaptive modeling-monitoring and structured decision-support should provide the basic science to inform management while helping to evaluate the efficacy of any deployed interventions. The timeframe of this cycle would be designed to err on the side of a rapid but incomplete model-monitoring loop. This work would require the support of at least two post-doctoral researchers as well as several students over the next few years.

Pacific: In the short term, NOAA will coordinate with existing coral reef management bodies to incorporate interventions, identify capacity to lead decision support modeling, and tune monitoring efforts to provide relevant biological details for the first model-monitoring loop. We will also review and coordinate with existing restoration efforts in both Hawai'i and the Commonwealth of the Northern Mariana Islands. In both locations, we will clarify infrastructure needs for experimenting and eventually implementing interventions at appropriate geographic scales and identify target populations for pilot interventions. In addition, NOAA is driving a novel monitoring program allowing colony-level tracking of growth, mortality, and recruitment, is collaborating broadly to develop Artificial Intelligence tools to support scaling that effort, and developing coral demographic models from the colony-level data for use in decision support.

Western Atlantic/Caribbean: While many US Caribbean locations would benefit from regional planning for reef restoration and intervention, the one region that has all the pieces necessary to jump into the creation of a decision-support framework for intervention, management, and restoration evaluation is the Florida Keys National Marine Sanctuary (FKNMS). FKNMS has an engaged restoration community, existing restoration strategies, high quality baseline data, a straightforward management hierarchy, and an existing stakeholder advisory process. NOAA and partners are already working in FKNMS to develop a comprehensive restoration strategy with detailed plans for seven iconic reef sites.

Recommendations for the Greater Caribbean Region. The second NASEM report (NASEM 2019 b) highlighted eight interventions as being "particularly well-suited" to the Greater Caribbean Region. We have re-written the recommendation into the following nested list, with specific interventions from the list of 23 in **bold**.

Identify heat tolerant or disease resistant coral genotypes among the Caribbean standing stock to provide opportunities for AGF, managed breeding, and genetic interventions.

***Test short-distance managed relocation** (i.e. AGF) of corals across local thermal gradients, where disease incidence is not a limiting factor.*

Leverage existing coral restoration activities and infrastructure to:

- *Incentivize restoration practitioners to collect data on spawning,*
- ***Test pre-exposure methods** to increase stress tolerance of outplanted corals,*
- ***Test algal symbiont manipulations,***
- ***Expand coral cryopreservation** across the region to provide opportunities for managed breeding and assisted gene flow*
- ***Test the (3) interventions to halt the spread of disease***
- *Test the efficacy of interventions under a range of conditions (e.g. from highly degraded to less degraded)*
- *Coordinate regionally and multinationally - e.g. to assess feasibility of environmental interventions to reduce heat stress at local and sub-regional scales*

ACTION III. REVIEW POTENTIAL IMPLICATIONS OF INTERVENTIONS ON FEDERAL POLICY.

NOAA mandates related to coral reefs are derived from several laws including the National Environmental Policy Act (NEPA), the Magnuson-Stevens Fishery Conservation and Management Act (MSA), the Endangered Species Act (ESA), and the Coral Reef Conservation Act. Federally funded, executed, or authorized activities, such as federally permitted programs for coral restoration and research, undergo environmental review under NEPA, and may require additional consultation or actions to ensure compliance with the ESA and MSA. NOAA's Coral Reef Conservation Program has recently developed a Programmatic Environmental Impact Statement and is planning to conduct programmatic consultations related to ESA and Essential Fish Habitat for all activities implemented under the Program. These programmatic documents are intended to cover some of the coral intervention techniques (e.g., assisted gene flow, managed selection, and stress hardening), but NOAA recognizes that other intervention techniques (e.g., outplanting of corals with modified symbionts, movement of corals to non-native areas to enhance diversity, shading of corals/coral reefs, water cooling) will require additional environmental compliance analysis before field-testing and implementation.

In anticipation of testing and implementation, NOAA's Office of Protected Resources led a policy review of the 23 interventions identified by the National Academies Reports. The policy review assessed ESA considerations and requirements to implement these interventions. Additional policy, legal, and/or ethics studies in relation to agency mandates beyond the ESA may be contracted out (e.g. via National Sea Grant Law Center) in coordination with NOAA's Office of General Counsel. As environmental conditions change, new interventions and technology advance, and legal interpretations of laws and regulations are refined, NOAA will continue to provide guidance via its internal environmental review process, which allows for fluid evaluation and feedback. Following the ESA policy review, NOAA will revisit and broaden the Management Plan for Caribbean Acropora Population Enhancement to incorporate the findings of the ESA policy review. Currently the management plan guides acroporid propagation and population enhancement activities in the Caribbean region. NOAA will broaden the document to cover other ESA-listed coral species in the Caribbean, which include additional reef builders and species currently targeted in restoration efforts. When used in conjunction with structured decision support (Action 2), the Management Plan will serve as a guide for interventions that are consistent with current ESA policy.

ACTION IV. INVEST IN INFRASTRUCTURE, RESEARCH, AND COORDINATION

Preventing the global collapse of coral reef ecosystems is no small or straightforward undertaking, and a three-year action plan cannot accomplish it. This is an endeavor that will require significant investment, research, coordination, and management at many different levels. In the past few years, and largely as a result of the devastating global mass bleaching from 2014-2017, the coral conservation, scientific, and management communities have come together like never before. During this time frame NOAA has catalyzed coordination and collaboration. Some recent coordination efforts include: launching the Coral Restoration Consortium, commissioning the NASEM review of Coral Interventions, influencing the selection of the Saving Coral Reefs as the next X-Prize, using the US Coral Reef Task Force and the International Coral Reef Initiative to activate domestic and international partnerships, writing a new 5-year strategic plan for NOAA's Coral Reef Conservation Program, coordinating the first ever range-wide demonstration of Assisted Gene Flow in an endangered coral, leading interagency rescue efforts for endangered and diseased corals, hosting Reef Futures (the first ever global coral restoration conference), promoting and quantifying reefs' role in protecting coastlines, and collaborating closely with the Australian Reef Restoration and Adaptation Program.

NOAA will continue to build on these efforts and pursue new partnerships through socializing the results of the NASEM study and discussing opportunities with the National Science Foundation, philanthropic foundations, reinsurance companies, and other parts of the public and private sector. An issue that continues to plague progress on operationalizing coral interventions is that current investments do not match the scale of the problem. Below are the large-scale investments that require global coordination, but also long-term consistent funding.

Large-scale investments needed:

1. **Promote production efficiency to scale-up coral restoration.** Projects across the tropics prove that coral reef restoration is possible, and the spatial scale of success is increasing. However, to have an ecosystem-level effect, production efficiency needs to increase dramatically. Significant effort and enthusiasm exist, but a major funding investment in how to deploy corals is needed in the US.
2. **Implement large-scale restoration projects.** While the efficiency of reef restoration techniques is being improved incrementally, we must simultaneously plan and execute large-scale restoration projects that connect individual reefs. The first plan of its kind in the US is being developed for the Florida Keys, but funding is still required for implementation.
3. **Develop a global network of cryopreservation banks.** As a foundational technique, cryopreservation depends on long-term stable institutions and funding. Having reserves of gametes and larvae from endangered organisms is common practice in the terrestrial world and requires investment by stable governments that have coral reefs in their trust.
4. **Build a national sea simulator.** Interventions that work in the laboratory or aquaria need to be demonstrated to succeed on reefs. In order to reduce risks and increase social license, large-scale testing in something like Australia's national sea simulator would help move interventions closer to field applications. Furthermore, to scale-up some interventions (e.g., stress hardening, algal symbiont shuffling), the same type of large-scale aquarium facility will be required to repeatedly manipulate corals before they are transplanted to the reef.
5. **Build virtual reefs.** To restore the reefs, we need to know what they look like, looked like, and will look like. Photomosaics (large-scale imagery, 3-dimensional, orthographic projections) are an increasingly affordable technique to highlight where restoration and intervention are needed most, and to visualize and monitor the success or failure of restorations and interventions. Investments are needed to (a) develop a pipeline from photos to usable ecological data, (b) host and integrate photomosaics with global coral reef mapping efforts, and (c) to archive terabytes to petabytes of data. This project could be undertaken in collaboration with the private sector but may require NOAA seed-funding and data archiving.
6. **Conduct research.** The NASEM reports outlined additional research needs beyond what NOAA or any single institution can accomplish. There is much basic coral biology and ecology research to be done, and NOAA is committed to building partnerships to make progress on the 21 research topics listed by the NASEM and restated here in Appendix B.

CONCLUSION

This action plan capitalizes on momentum from the NASEM Review of Coral Interventions and lays out initial steps that may help promote the long-term persistence of coral reefs. More detailed planning on specific research activities and engagement strategies will follow. We still have the capacity to save this ecosystem from its current trajectory. We need accelerated rates of research and innovation, as well as increased and sustained investment. The coral science, restoration, and management community has enthusiasm, creativity, organization, and a collaborative spirit. NOAA is poised to be an important leader in the global effort for the persistence and resilience of coral reefs during rapidly changing environmental conditions.

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APPENDIX A: List of Interventions

This table is modified from the list of 23 interventions from [A Research Review of Interventions to Increase the Persistence and Resilience of Coral Reefs](). Interventions above the gray bar are considered priorities by NOAA (not necessarily for internal action or funding.)

NOAA Objective	NASEM Intervention	NASEM Sub-category	NASEM Intervention	What It Is	Current Feasibility	Potential Scale	Limitations	Risks	Availability
Increase diversity of coral populations	Population and Community	Managed Relocation	Assisted Gene Flow	Increasing abundance of stress-tolerant genes or colonies within population	Technically feasible with information gaps regarding successful methods	Regional reef scale; can be permanent	Uncertain maintenance of stress tolerance over time	Moving nontarget genes; ecological tradeoffs	Immediate
	Genetic and Reproductive	Managed Breeding	Outcrossing between Populations	Introducing diversity from other populations through breeding	Demonstrated in laboratory for a few species	Local reef population; potentially transgenerational	Requires transport of gametes or colonies across distances and field testing across generations	Outbreeding depression; native genotypes may be	Short-term
	Genetic and Reproductive	Managed Breeding	Supportive Breeding	Enhancing population size by captive rearing and release	Success with some species at small scales	Local reef population; potentially transgenerational	Depends on sufficient population sampling and recruitment success of released individuals	Decrease in genetic variation	Immediate
Techniques to support interventions	Genetic and Reproductive		Coral Cryopreservation	Frozen storage of gametes and other cells for later use and transport	Feasibility is high for sperm, and growing for other tissue types	Materials can be transported globally	Requires excess gametes, larvae, or tissues	Long-term survival uncertain; genetic variation reflects	Immediate, Short-term
	Genetic and Reproductive		Managed Selection	Creating increased frequency of existing tolerance genes	In laboratory and at small local scales	Local reef scale; potentially transgenerational	Needs large populations	Decrease in genetic variation	Immediate
	Genetic and Reproductive		Gamete and Larval Capture and Seeding	Collection and manipulation in the field and laboratory and release into the wild	Feasible at local scales	Laboratory to local reef scale; potentially transgenerational	Site-specific reproductive timing, recruitment success can be poor	Limited genetic diversity; selection for laboratory	Immediate
Epidemiology	Physiological	Supplements to corals	Antibiotics	Adding antibiotics to control pathogenic microbes	Used in aquaculture and demonstration in small-scale field trials	Laboratory, aquarium, and colonies on reef; requires repeated application	Lack of specificity to target pathogens limits effectiveness	Promote antibiotic resistance in deleterious	Short-term
	Physiological	Supplements to corals	Microbiome Manipulation	Maintaining/increasing abundance of the native or new beneficial microbes	Demonstrated in laboratory and nursery facilities for limited coral species	Locations on reefs to reef scale; applied at times of stress	Reef-wide delivery mechanisms are lacking; lack of known beneficial microbes; little	Potential to increase deleterious microbes, decrease	Short-term
Stress-hardening	Physiological		Pre-exposure	Using stress exposure to make colonies more tolerant	In laboratory and small-scale field trials	Local reef scale; may be temporary or transgenerational	Difficult to scale up beyond local	Could be detrimental if applied incorrectly	Immediate
Algal symbiont manipulation	Physiological		Algal Symbiont Manipulation	Changing algal symbionts to more tolerant types	Observed after bleaching events; demonstrated in laboratory	Individual coral colony or large spawning events; unknown longevity	Difficult to scale; easier for some coral species than others	Ecological tradeoffs, e.g., slower growth	Immediate
Environmental	Environmental		Seagrass Meadows and Macroalgal Beds	Reducing daytime CO2 levels biologically	Some efficacy shown in field measurements	Local reefs depending on environmental setting; long-term benefit	Limited environmental settings; need to remove macroalgae	Detritus; altered nutrient loads; competition from	Short-term
	Environmental	Shading	Marine Shading	Reducing sunlight to relieve light and heat stress	Operational at small scales	Sites within reefs; temporary	Retention and advection limit application	Altered light regimes; plastic pollution	Short-term
	Environmental		Mixing of Cool Water	Pumping cool water onto reef to reduce heat stress	Small-scale field tests with unknown efficacy	Local reef scale; temporary	Energetically costly or impossible to scale up	Altered physical and chemical (pH, nutrients) regimes	Short-term
INTERVENTIONS ABOVE ARE INCLUDED IN NOAA'S CORAL INTERVENTIONS ACTION PLAN. THOSE BELOW ARE NOT.									
	Population and Community	Managed relocation	Assisted Migration	Moving stress-tolerant or diverse genes or colonies just outside species' range	Technically feasible with information gaps regarding project design	Regional reef scale; can be permanent	Uncertain maintenance of stress tolerance and persistence over time between locations	Moving nontarget genes, species, and microbes; ecological	Long-term
	Population and Community	Managed relocation	Managed Relocation to New Areas	Moving stress-tolerant or diverse genes or colonies to new regions	Untested though technically feasible with information gaps regarding project design	Global movement impacting individual reef scale; can be permanent	Uncertain maintenance of stress tolerance and persistence over time between locations	High risk of moving nontarget genes, species, and	Long-term
	Genetic and Reproductive	Managed Breeding	Hybridization between Species	Creation of novel genotypes through breeding	Demonstrated in laboratory for a few species	Local reef population; potentially transgenerational	Limited ability to create hybrids; requires testing for fertility and fitness	Outbreeding depression; competition with	Short-term
	Genetic and Reproductive	Genetic Manipulation	Coral Genetic Manipulation	Altering coral genes for new function	Technically feasible for larvae	Would occur in laboratory; can be self-perpetuating	Gene targets and cellular raw material unidentified, long lead time to roll out to reefs	Might alter wrong genes; unknown risks	Long-term
	Genetic and Reproductive	Genetic Manipulation	Symbiont Genetic Manipulation	Altering symbiont genes for new function	Not yet feasible	Would occur in laboratory; can be self-perpetuating	Technology not established; gene targets and cellular raw material unidentified	Might alter wrong genes; kill target cells; unknown risks	Long-term
	Physiological	Supplements to corals	Antioxidants	Reducing cellular oxidative damage derived from stress using chemical treatments	Demonstrated in some laboratory experiments	Laboratory only; requires repeated application	Little understanding of direct or indirect effects	May affect other reef species	Short-term
	Physiological	Supplements to corals	Nutritional Supplementation	Using nutrients to improve fitness and increase stress tolerance	Regular use in coral research and aquaculture	Laboratory and aquarium; requires repeated application	Poor understanding of balanced coral diets; reef-wide delivery mechanisms are lacking	Shifts carbon, nitrogen, and phosphate balance	Short-term
	Physiological	Supplements to corals	Phage Therapy	Adding phage viruses to control pathogenic microbes	Demonstrated in laboratory experiments	Local reef scale; potential to self-propagate	Lack of identified target coral pathogens	Undesirable gene transfers across microbial	Short-term
	Environmental		Abiotic Ocean Acidification Interventions	Reducing CO2 levels chemically	Effective in small-scale laboratory experiments	Sites within reefs depending on environmental setting; requires consistent input	Costly to scale up chemical quantities	Impact of chemicals on environment	Short-term
	Environmental	Shading	Atmospheric Shading	Sky brightening to relieve light and heat stress	Untested	Local to regional scale; temporary	Needs appropriate atmospheric conditions and technology	Altered light regimes; aerosol (salt) deposition	Long-term

APPENDIX B: Summary of Research Needs

This summary is from Box 5.1 in A Decision Framework to Increase the Persistence and Resilience of Coral Reefs (NASEM 2019b).

Research on fundamental coral reef biology

1. Identify the cellular mechanisms of bleaching, and how these pathways are influenced by recent thermal history, host genetics, symbiont type, and microbiome.
2. Identify underlying causes of coral diseases, and develop biomarkers of coral health, heat susceptibility, and disease diagnosis as well as ecosystem health.
3. Determine functional roles of and tradeoffs among members of coral reef communities at multiple ecological scales from coral-associated symbionts and microbiomes up to the composition of coral species in reef communities.
4. Identify population structure, determine evidence for local adaptation, and define relevant management units for population recovery.
5. Develop methods to improve recruitment and survivorship for corals that are released, planted, relocated, or settled on reefs at the reef scale.
6. Develop extensive, freely available databases on coral communities, hosts, symbionts, and microbiomes to support studies on genotype-phenotype relationships, population structure, and community dynamics.
7. Identify species-specific threshold responses of corals to changes in temperature, light incidence, and ocean pH, as well as reef-scale threshold responses to disturbance and environmental change.

Site-specific research and assessment to help determine whether intervention is needed or possible

8. Identify local stressors that influence population recovery and determine whether stressors are likely to influence the success of interventions.
9. Develop appropriate metrics and recovery goals that assess the effects of the intervention on ongoing tolerance, health, fitness, and recruitment within the target management unit as well as on connected reefs.
10. Evaluate whether population recovery at a specific site can be achieved through translocation or managed breeding and if so, which intervention is most appropriate for recovery.
11. Identify host, symbiont, and microbial populations at candidate restoration sites, to ensure treatments or manipulations aimed at improving coral physiological performance can achieve recovery goals.
12. Assess in a site-specific manner the benefits, risks, and chances of success for implementing environmental interventions.
13. Identify the most appropriate site-specific, synergistic management and intervention strategies that together provide greater chance of success and reduced risks than the sum of the impacts of each intervention alone.

Research to improve assessment of the benefits, efficacy, and risks of specific interventions

14. Develop protocols for control of pathogens (biosecurity and quarantine).
15. Develop effective approaches to modify symbiotic algal and/or microbiome populations.

16. Develop effective approaches to determine whether corals that are released, planted, relocated, or settled on reefs contribute to recovery goals, while reducing risk to ongoing adaptation and ecological processes.
17. Develop and test genome-editing methods in a wide variety of ecologically important coral species.
18. Develop methods of delivery for nutrients, probiotics, antibiotics, phage therapy, and antioxidants at reef scales.
19. Assess feasibility, potential benefits, costs, limitations, and risks associated with environmental interventions.

Research to inform risk assessments and modeling

20. Targeted monitoring to evaluate performance, improve benefits, and minimize or manage risks.
21. Iterative model design to reduce uncertainties and improve model predictions to increase confidence in the decision support framework.