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A Decision Framework for Interventions to Increase the Persistence and Resilience of Coral Reefs

Second report of the

Committee on Interventions to Increase the Resilience of Coral Reefs

Report Release Event

June 12, 2019

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Study Context: Coral Reefs and Human Values

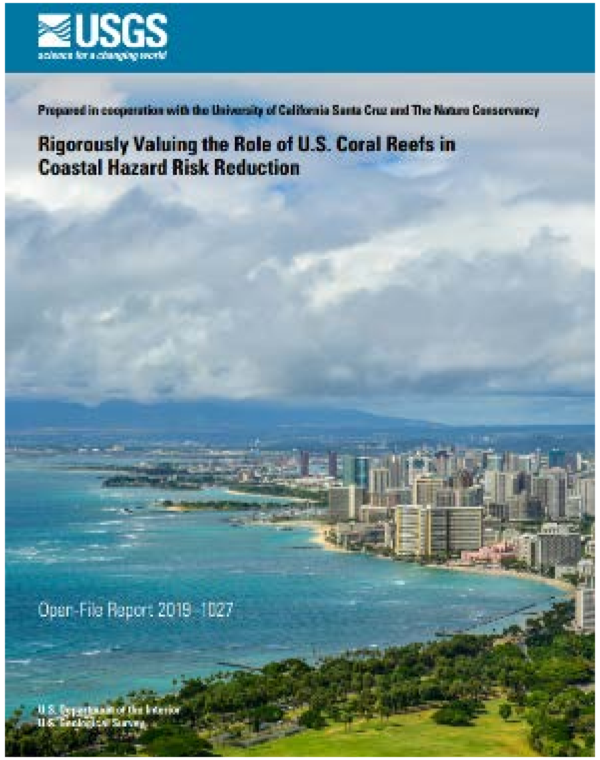
Coral reefs provide economic, ecological, and cultural value to of hundreds of millions of people worldwide, valued at billions of dollars annually.

Tourism

Fishing

Rebecca Weeks/Coral Reef Image Bank

Coastal Protection



"The annual value of flood risk reduction provided by U.S. coral reefs is more than 18,000 lives and $1.805 billion in 2010 U.S. dollars."

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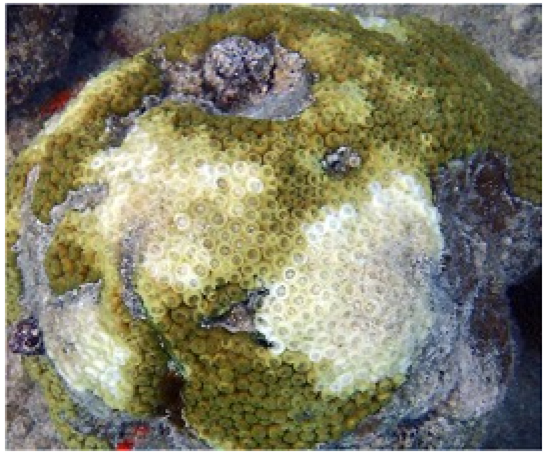
Study Context: Reefs are at Risk

Bleaching

The Ocean Agency

Disease



Andrew Bruckner, FKNMS

Ocean Acidification

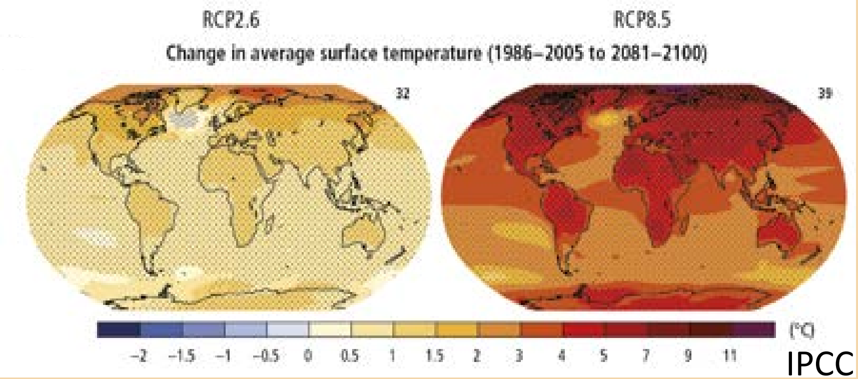
Shutterstock

Existing management tools target local stressors (e.g., fishery management, runoff control) and are not designed to address impacts from climate change.

Multi-Strategy Conservation Approach

Local stressor reduction

Global climate change mitigation



Coral Reef Persistence

THIS STUDY

Coral interventions

Manage the genetics, ecology, and local environment of coral reefs to improve persistence during environmental stress.

Study Task

1. Review state of science on interventions

First Report
Released November 2018

2. Provide a framework for evaluating risks

3. Describe a decision pathway from research to potential implementation

4. Identify priority research needs

5. Assess the potential for interventions to meet management objectives in the context of Caribbean/Atlantic coral reefs

This Report

The Committee's Approach to the Decision Framework

- The committee's approach was to
  - Outline **best practices for decision making under complex scenarios**
  - Identify tools that have or can be been applied to coral reefs.
  - Provide an **illustrative modeling exercise** using example interventions to exemplify this approach
- A fully implementable framework would require
  - Identification of management objectives and acceptable alternatives in a **stakeholder-driven process.**
  - Exploring **policy, legal, and ethical drivers.**

First Report: Reviews 23 Interventions in 4 categories

1) *Genetic and reproductive interventions* use selection and breeding of stress-tolerant traits to improve the resilience of coral populations and species. *Ex. Genetic manipulation*

2) *Physiological interventions* improve the stress responses of corals without changing their genomes. *Ex. Algal symbiont manipulation*

3) *Coral population and community interventions* alter populations or communities of coral reefs by importing stress resistant corals at varying scales—from within their range to across ocean basins. *Ex. Managed Relocation*

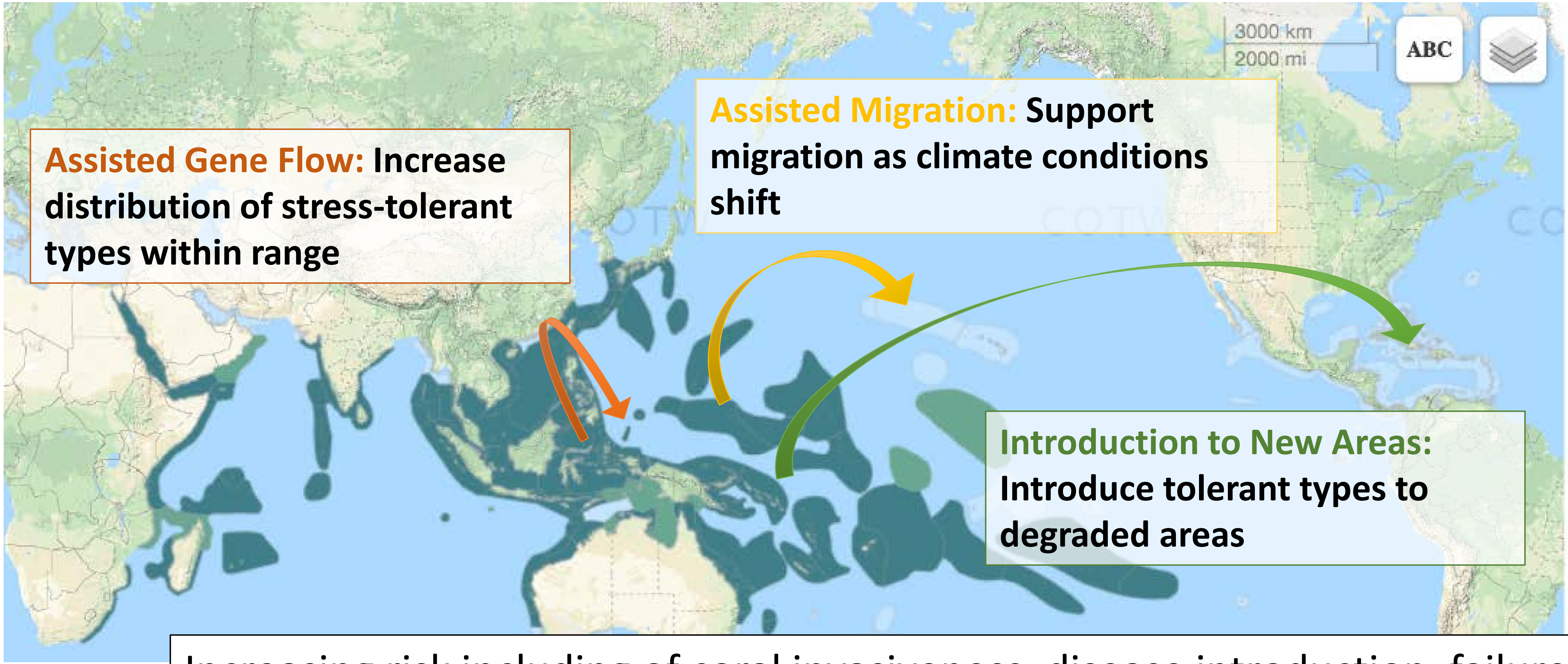
4) *Environmental interventions* reduce exposure to high temperatures or acidifying waters at a local level, as opposed to methods of global climate engineering. *Ex. Shading (atmospheric and marine)*

Immediately available interventions – all are being used in small field trials

- **Managed selection –** *identifying and using stress-tolerant corals*
- **Supportive breeding –** *increasing population sizes*
- **Assisted gene flow –** *adding heat resistant colonies to cooler reefs*
- **Gamete and larval capture –** *increasing the production and settlement of coral larvae*
- **Pre-exposure to heat –** *toughen up colonies temporarily*
- **Algal symbiont manipulation –** *toughen up the symbiosis*
- **Sperm cryopreservation –** *sperm banking and travel*

Example: Managed Relocation

Range map of the staghorn coral *Acropora hyacinthus* from **coralsoftheworld.org**



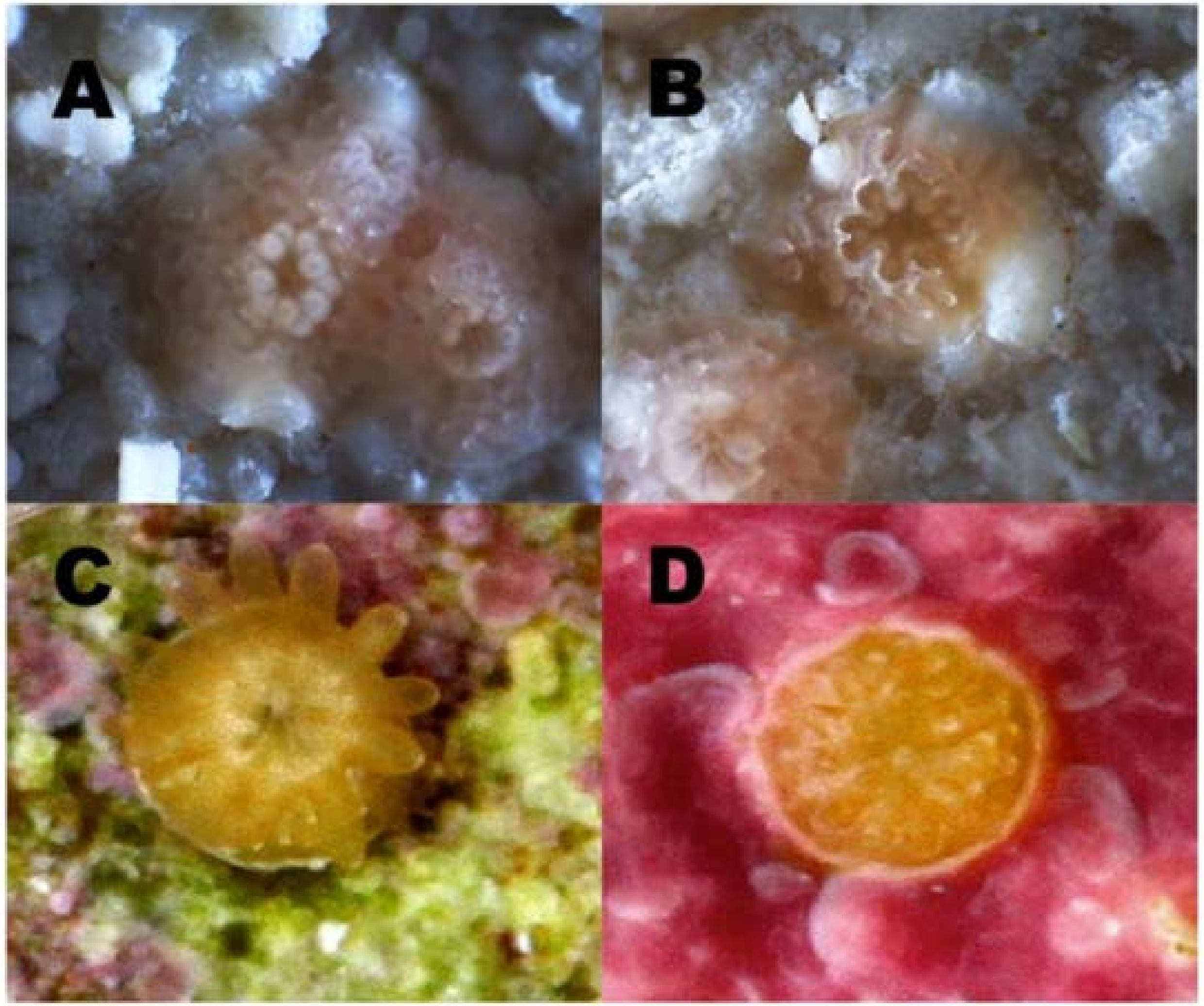
Assisted Gene Flow: Increase distribution of stress-tolerant types within range

Assisted Migration: Support migration as climate conditions shift

Introduction to New Areas: Introduce tolerant types to degraded areas

Increasing risk including of coral invasiveness, disease introduction, failure

Example: Coral sperm can be frozen and used years later to fertilize eggs



A and C are settled corals from fresh sperm. B and D are from frozen sperm (Hagedorn et al., 2017)

Interventions needing short-term development

- **Egg cryopreservation –** *needs technology development*
- **Outcrossing between populations –** *lab and field experiments ongoing, needs multi-generation study*
- **Hybridization between species –** *lab and field experiments, needs multi-generation study*
- **Supplements to corals in the field (ex. nutrients, antibiotics, microbes) –** *lab or nursery only, need to develop targeted methods*
- **Abiotic ocean acidification intervention –** *experimental only*
- **OA intervention with seagrass or macroalgal beds –** *small field measurements, highly specific environmental requirements*
- **Marine shading –** *needs low-impact, effective technology development*
- **Cool water mixing –** *energetically costly to scale up*

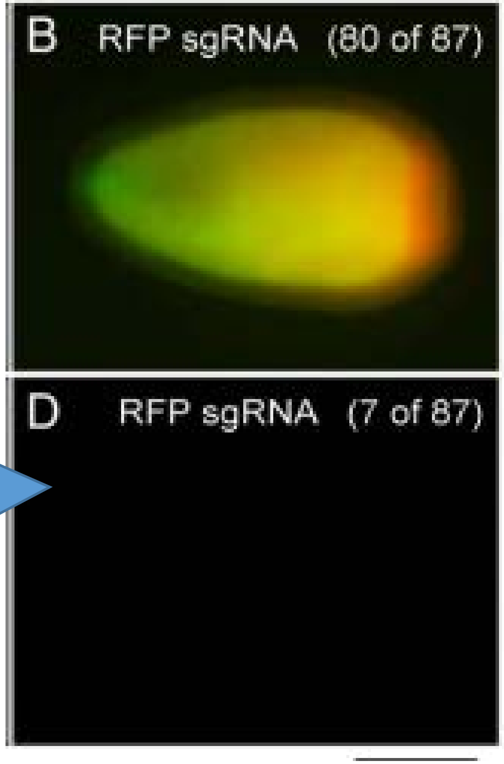
Research needed for long-term development

- **Genetic manipulation of corals and algae –** *not yet efficient (corals) or technically possible (algae) and no gene targets identified*
- **Atmospheric shading –** *theory only*
- **Migration outside normal range –** *limited knowledge of effective methods. Testing is risky*
- **Introduction to new ocean basins –** *limited knowledge of effective methods. Testing is risky*

Example: Genetic Manipulation in Coral

- Use of CRISPR/Cas9 to modify genes in coral has been demonstrated in one paper
  - Attempts to alter growth factor and fluorescence protein genes
- Currently limited in feasibility by:
  - Lack of gene targets
  - Poor success and mosaic uptake
  - Coral generation time
  - Unknown risks of gene engineering
- Important method to test gene function hypotheses

Lack of fluorescence means gene is turned off



Cleves et al., 2018, *PNAS*

Selecting Interventions by a local community will depend on:

Which ones are ready: **NONE are being deployed on large scales. The most feasible ones are being used in small local settings.**

Management setting: **Local governance and acceptance, resources available, size of jurisdiction, cooperating jurisdictions.**

Environmental setting: **Where benefits will be maximized and risks reduced.**

Interdependencies across interventions: **Some interventions are more beneficial and less costly in pairs.**

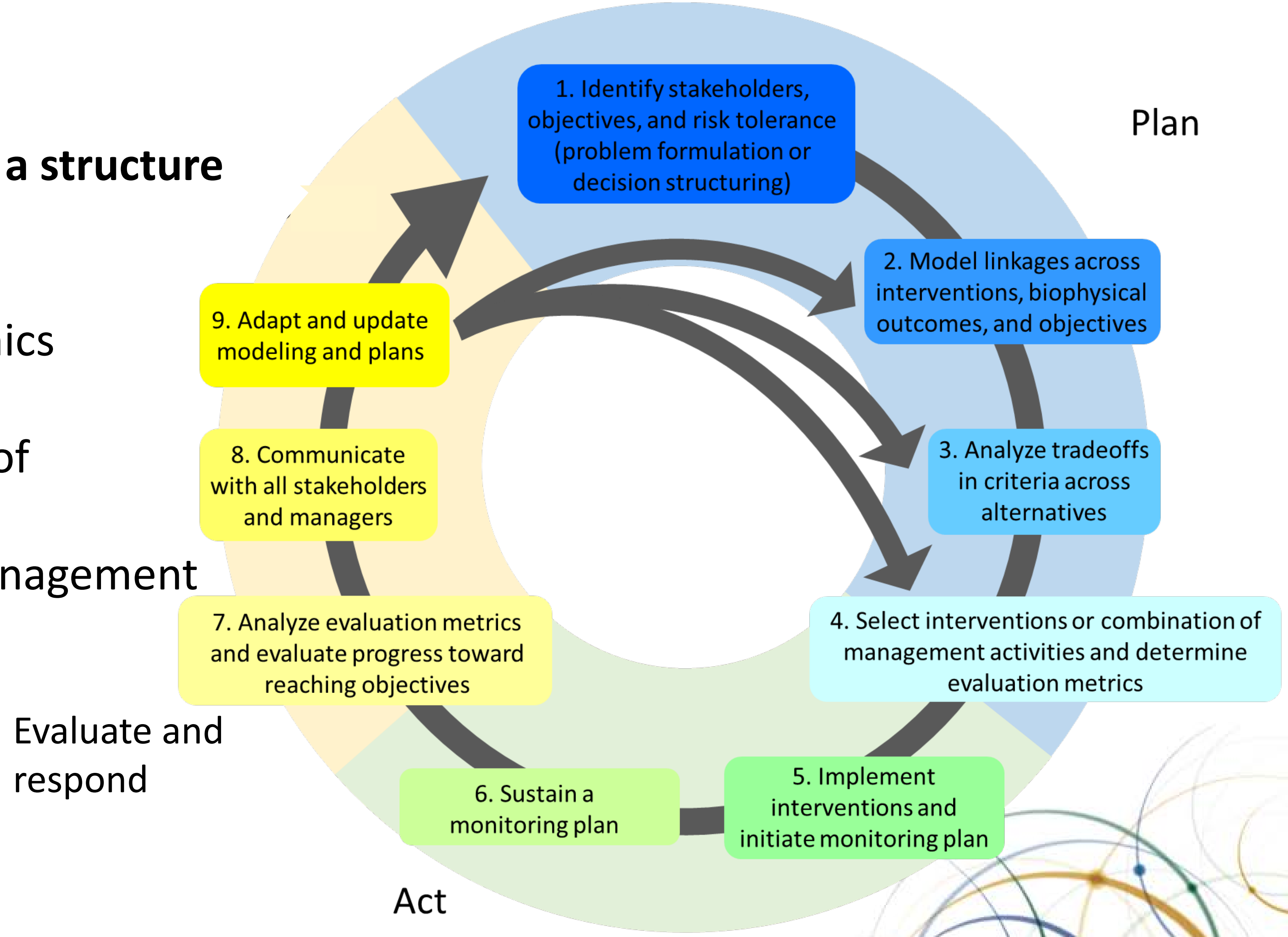
Conclusion: Multiple interventions as a **toolbox can be tested and deployed based on community goals, ecological objectives for reef management, and the benefits and risks across multijurisdictional or even multinational boundaries.**

These efforts will need to evolve over time as interventions become more feasible and as new interventions are developed.

A Structured, Adaptive Approach to Decision Making

Decision tools provide a structure to deal with:

- **Uncertainty** in
  - Coral reef dynamics
  - Climate scenario
  - Risks & benefits of interventions
- **Tradeoffs** across management objectives



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PLAN: Stakeholder-driven context setting

Step 1: Identify goals and objectives with community (stakeholder) involvement, based on community values.

<u>Possible categories:</u>

- Environmental
- Economic
- Social
- Human health
- Governance & political commitments

Can trade off

PLAN: Model Risks and Benefits of Interventions

Step 2: Tailor **model** structure, parameterization, and outputs to:

- **Objectives** that reflect community goals
- **Local** reef dynamics
- Mechanisms underlying **risks and benefits** of interventions

Analysis includes:

- **Interventions**, individually and in combination
- Baselines: **no action** and **conventional management**
- Sources of **uncertainty** e.g., multiple climate scenarios, parameter sensitivity

The committee reviewed frameworks for:

Modeling coral dynamics

&

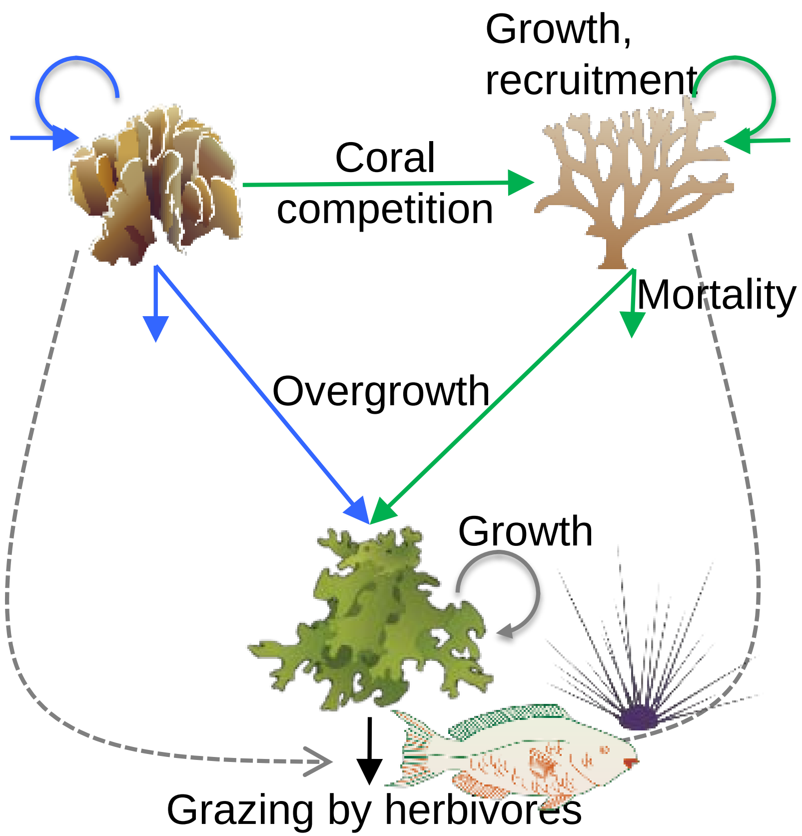
Analyzing decisions w/tradeoffs and uncertainty

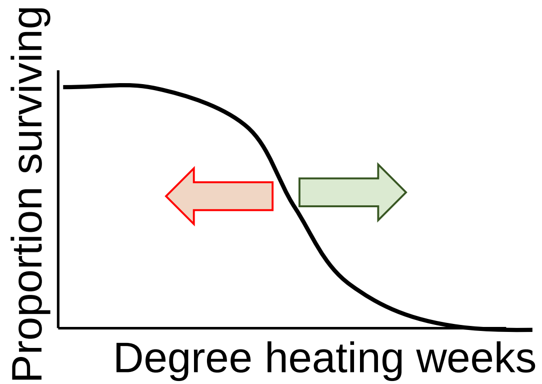
The committee provided an example model exercise to illustrate the process & potential insight

- **Objective**: coral cover > 20%
- **Interventions**:

	Assisted gene flow	Shading
Benefit:	↑ Thermal tolerance	↓ Thermal stress
Risk:	↑ Disease or other mortality	↓ Thermal tolerance

- **Conventional management**: nutrient & fisheries control
- Include **no action**





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PLAN: Comparing Management Alternatives

The model estimates the probability that coral cover is >20% by 2060 – darker green squares have higher cover

Example conclusions (based on sample model)

Scenario	Starting cover	Year intervene	No action	Conventional management (CM)	CM+ assisted gene flow (AGF)	CM+AGF+Shading	AGF+Shading
RCP 2.6	Low	2025	8	92	58	83	8
RCP 2.6	Low	2035	8	92	83	75	8
RCP 2.6	High	2025	8	92	67	75	8
RCP 2.6	High	2035	8	92	83	83	8
RCP 8.5	Low	2025	8	8	42	17	8
RCP 8.5	Low	2035	8	8	58	42	8
RCP 8.5	High	2025	8	8	50	25	8
RCP 8.5	High	2035	8	8	58	17	8

Model Outcome (Likelihood coral cover >20%)

PLAN: Comparing Management Alternatives

In this simple model, **managing local stress** increases success if climate is mitigated

Scenario	Starting cover	Year intervene	No action	Conventional management (CM)	CM+ assisted gene flow (AGF)	CM+AGF+Shading	AGF+Shading
RCP 2.6	Low	2025	8	92	58	83	8
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RCP 8.5	High	2025	8	8	50	25	8
RCP 8.5	High	2035	8	8	58	17	8

Model Outcome (Likelihood coral cover >20%)

PLAN: Comparing Management Alternatives

In this simple model, gene flow and shading increase coral cover at higher emissions

Scenario	Starting cover	Year intervene	No action	Conventional management (CM)	CM+ assisted gene flow (AGF)	CM+AGF+Shading	AGF+Shading
RCP 2.6	Low	2025	8	92	58	83	8
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RCP 8.5	High	2035	8	8	58	17	8

Model Outcome (Likelihood coral cover >20%)

PLAN: Comparing Management Alternatives

Interventions without managing local stress are not successful

Scenario	Starting cover	Year intervene	No action	Conventional management (CM)	CM+ assisted gene flow (AGF)	CM+AGF+Shading	AGF+Shading
RCP 2.6	Low	2025	8	92	58	83	8
RCP 2.6	Low	2035	8	92	83	75	8
RCP 2.6	High	2025	8	92	67	75	8
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RCP 8.5	High	2025	8	8	50	25	8
RCP 8.5	High	2035	8	8	58	17	8

Model Outcome (Likelihood coral cover >20%)

ACT: Implement and Monitor

Step 4: Select interventions and associated evaluation metrics

- Match to objectives
- Use models to predict expected outcomes and detectability over time
- Include metrics of both benefits and risks ←for “off-ramps”

Steps 5/6: Implement with a sustained monitoring plan

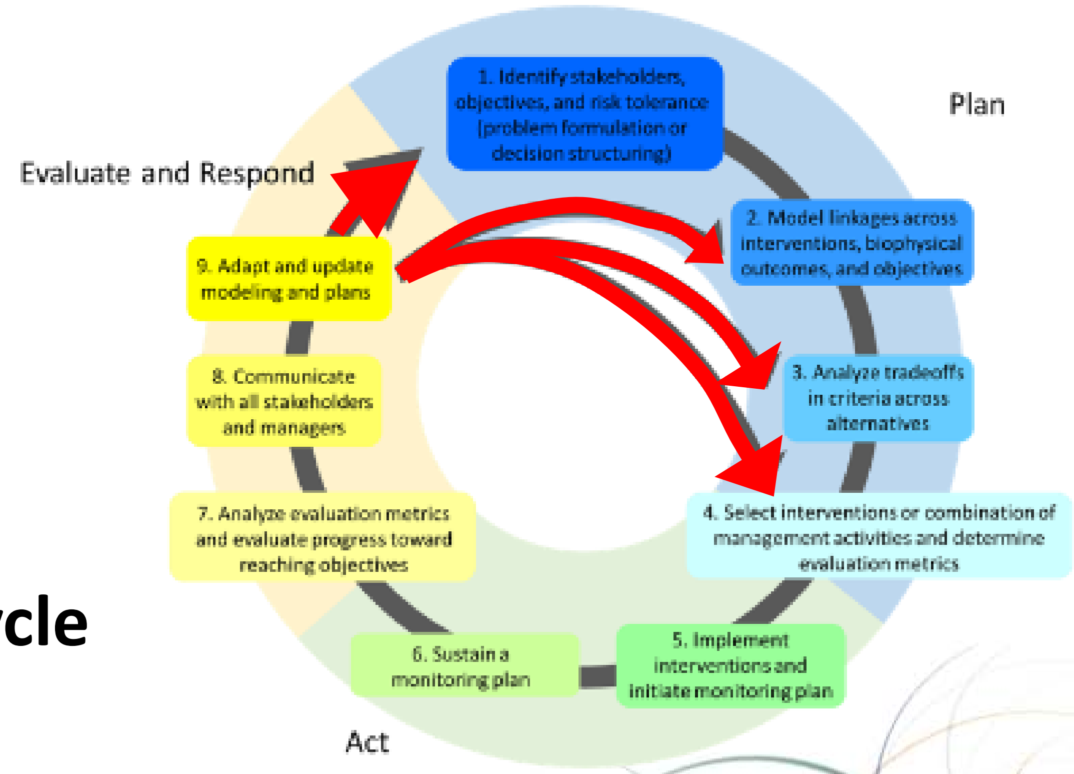
- Target monitoring plan to evaluation metrics (success and failure)

RESPOND: Evaluate, Communicate, Adapt

Step 7: Evaluate by comparing expectations to actual outcomes: where they don't match, ***Learn why***

Step 8: Communicate progress to stakeholders & decision-makers

Step 9: Based on learning, update both approach and models to continue the cycle



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Recommendation: A structured adaptive management approach should include:

- **Stakeholder engagement** to identify objectives
- **Models tailored to local considerations** to
  - Predict intervention effects → select when and where to implement
  - Select monitoring metrics & their expectations
- **Targeted monitoring** of both benefits and risks
- Iterative **evaluation and adjustment**

Conclusion: While requiring substantial effort, the payoff is a scientifically-informed process of risk mitigation and enhanced learning.

Directed Research Goals

- Create detailed, reef-specific decision support tools
- Increase understanding and the availability of more interventions

We highlight 21 Research Needs across 4 areas with the biggest chance of pivotal outcomes

- Research on fundamental coral reef biology to fuel interventions
- Site-specific research to ask whether intervention is needed or possible
- Research to improve interventions
- Research to inform risk assessments and modeling

Research on fundamental coral reef biology

Research Need Highlight: *Identify underlying mechanisms of bleaching.*

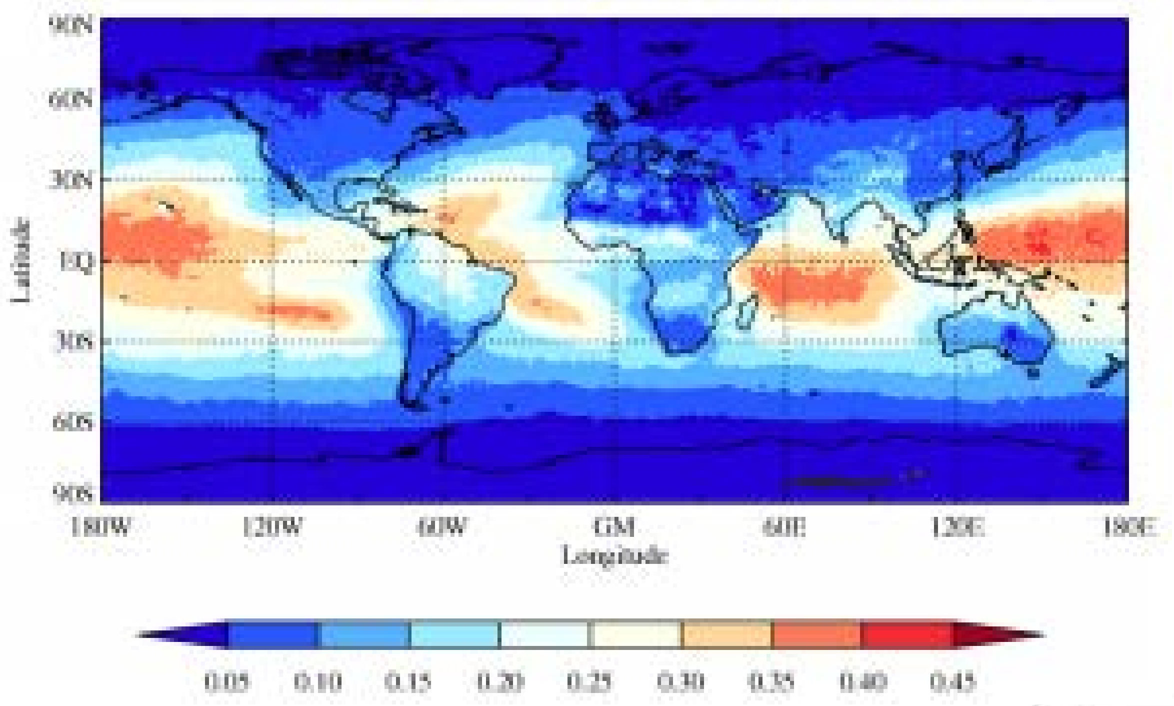
- How do some corals maintain higher bleaching thresholds?
- How can these mechanisms be harnessed to increase coral heat tolerance?

Site-specific research and assessment

Research Need Highlight: *Assess in a site-specific manner the benefits, risks, and chances of success for implementing environmental interventions.*

Environmental interventions depend on specific environmental parameters to success.

- Water residence time (Marine shading with polymers, cool water mixing, chemical OA interventions)
- Atmospheric conditions (Marine Cloud Brightening)



Cloud susceptibility
Alterskjær et al., 2012

Research to make interventions more available

Research Need Highlight: *Stage interventions from laboratory experiments to full-scale management strategies.*

- Control pathogens
- Evaluate risks of invasion
- Alter microbiome, symbiont populations

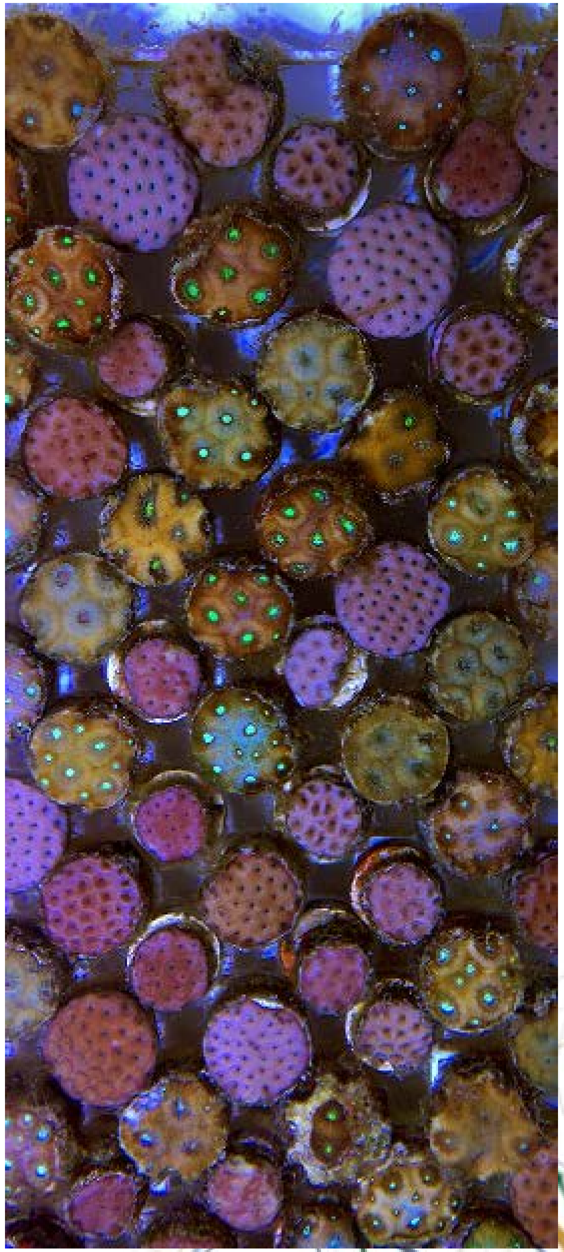
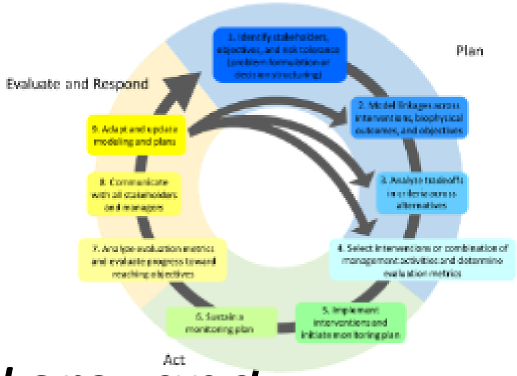


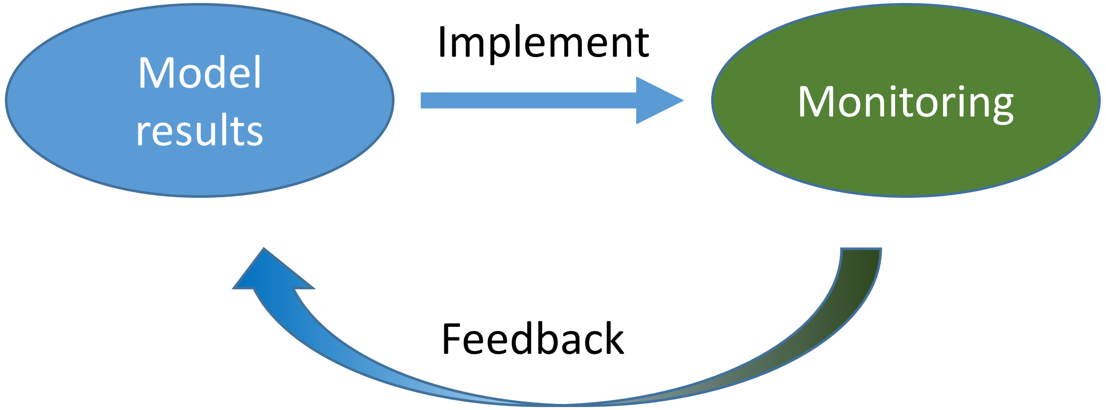
Image from Coral Reef Futures Lab, Unv. Miami

Research to inform risk assessments and modeling



Research Need Highlight: *Research on local model parameters, and iterative model design to improve model predictions and increase confidence in the decision support framework.*

- Feedback between research/ monitoring and model improvement provides improved knowledge of model structure and parameters.



A regional example: The Tropical Western Atlantic/Caribbean

Reefs in the wider Caribbean vary widely in their condition and in the intensity of local stressors.

They have recently experienced devastating coral reef losses due to bleaching, disease, hurricanes, and local stressors.

The committee uses the context of the wider Caribbean to demonstrate

- How conditions may influence selecting and modeling interventions
- Opportunities for including interventions in Caribbean management programs
- Opportunities and priorities for research in the Caribbean

Shaun Wolfe/Coral Reef Image Bank

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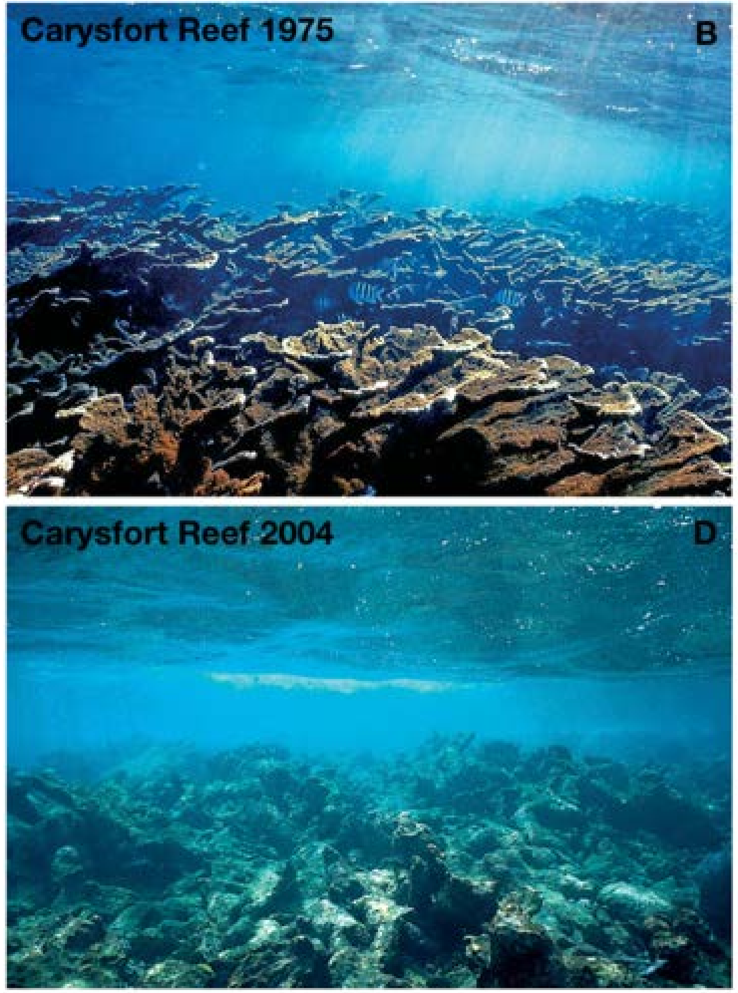
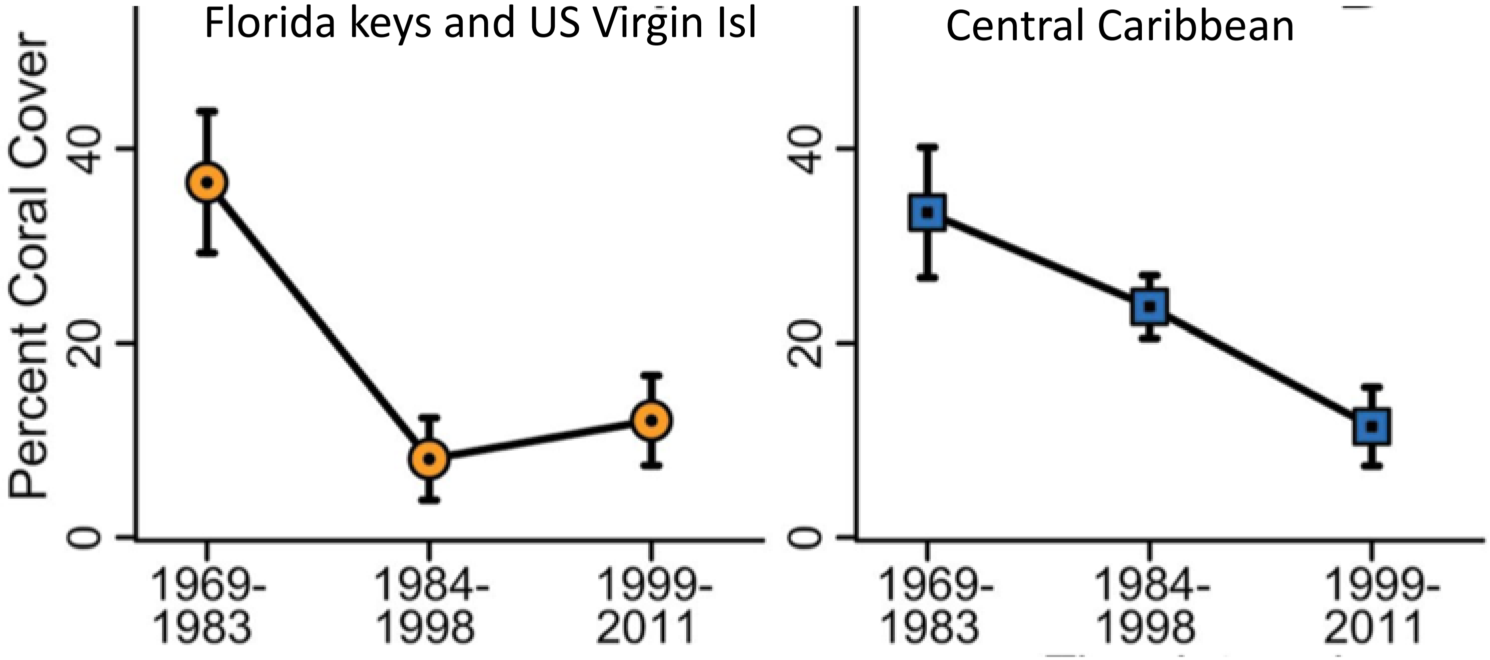
Many Caribbean coral reefs have declined





- Pollution, overfishing, bleaching, and storms have reduced corals 80%
- Collapse of larval supply in many areas
- The region has numerous marine labs, restoration projects, and marine protected areas

Data from Jackson et al. 2014

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A Caribbean scourge: coral disease

Widespread coral disease in the Caribbean, especially in Florida, will demand a specific approach to interventions.

- Need for quarantine and disinfection as part of intervention programs
- Priority to identify corals that are both heat and disease tolerant
- Increased risks of relocations of corals
- Value of research and development of interventions that target disease (antibiotics, phage therapy, microbiome manipulation)

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Conclusion: **Coral reef managers in the tropical western Atlantic/Caribbean region have a variety of interventions available to them depending on the localized management context.**

- leveraging existing restoration and infrastructure,
- increasing genetic diversity of corals (*managed breeding, gamete and larval capture and seeding, coral cryopreservation*),
- using heat tolerant species and genotypes (*managed selection, assisted gene flow, algal symbiont manipulation*),
- accelerating reef connectivity to boost thermal tolerance when disease is not a factor (*assisted gene flow*),
- reducing disease spread (*antibiotics, phage therapy, microbiome manipulation*), and/or
- reducing exposure to stress (*environmental interventions*).

Recommendation: The modeling and decision-making tools outlined in this report should be used to inform more detailed assessments to evaluate which approaches might be appropriate for specific settings, including their interactions with more traditional management approaches.

Maintaining genetic diversity in the face of multiple climate-driven stresses (e.g., bleaching and disease) is particularly important. Monitoring corals to maintain genetic diversity and identify resistant phenotypes should be simplified and standardized for research, ex situ propagation, and in situ restoration.

Research programs to model and field test the risks, benefits, and efficacy of interventions in this multinational and highly inter-connected region should be coordinated to maximize resources, co-learning opportunities, and the ability to achieve management objectives regionally.

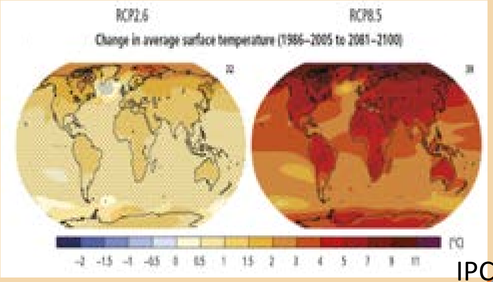
Resilience intervention as a bridge through climate change effects

Local stressor reduction

NOAA

Coral interventions

Climate mitigation



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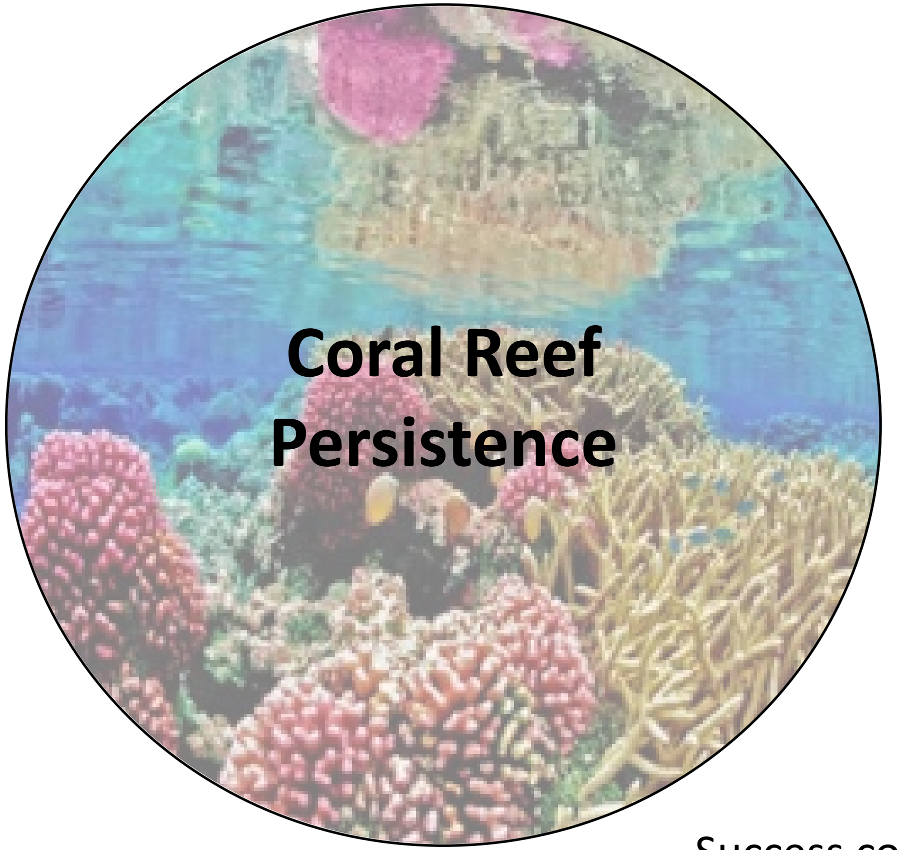


Interventions offer a toolbox to improve coral reefs in the face of rapid climate change.

Many interventions need further development and planning.

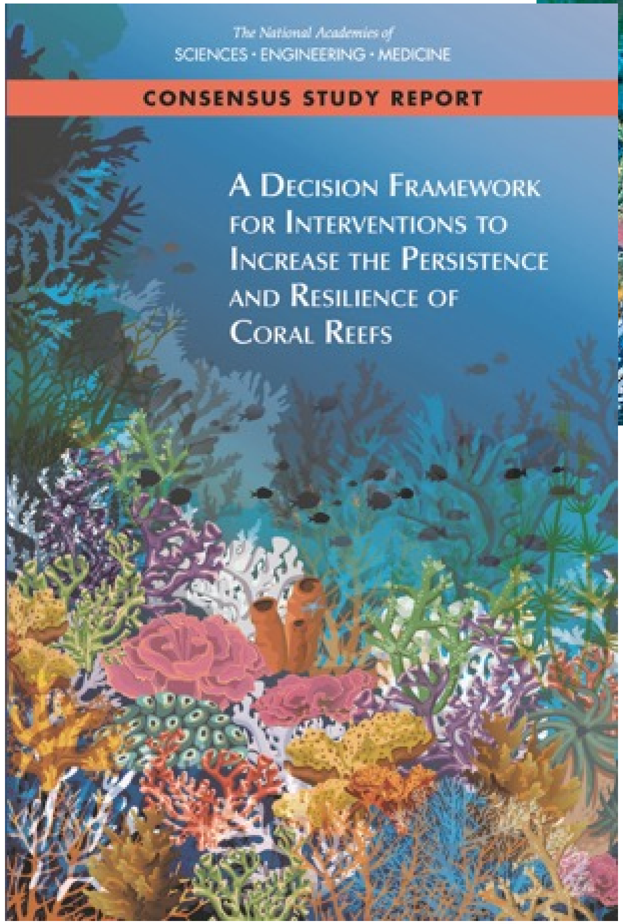
Their utility depends on local community goals, local conditions, and ability to scale up small scale field efforts.

Success comes when conservation science blends with community action and future planning.

Thank you!

Report available for free download at [nap.edu](nap.edu)

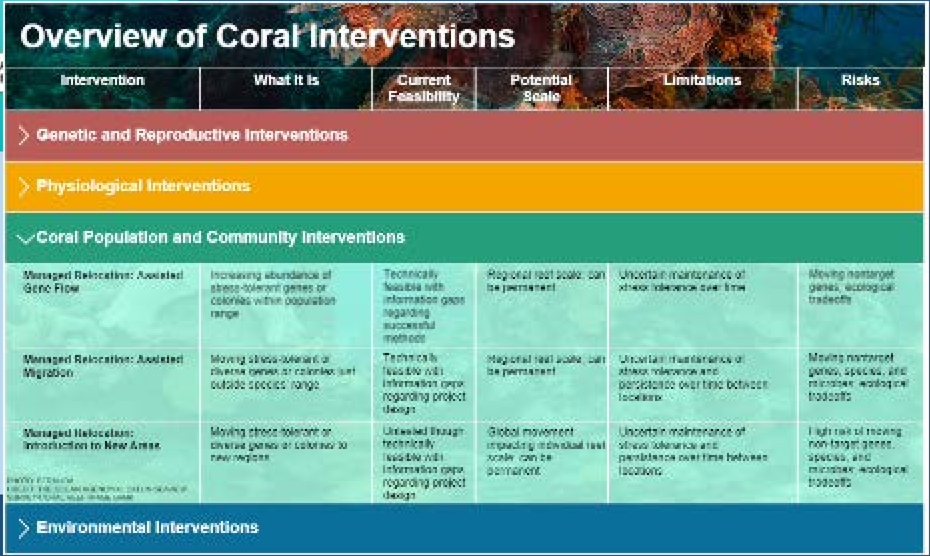
This study was requested and supported by The National Oceanic and Atmospheric Administration, with additional support from Paul G. Allen Family Foundation



Informational Materials

Learn more about the interventions with an interactive table and infographic: https://www.nap.edu/25279

Video Series (more coming soon!): https://www.youtube.com/nationalacademies



Overview of Coral Interventions

Intervention	What It Is	Current Feasibility	Potential Scale	Limitations	Risks
Genetic and Reproductive Interventions					
Physiological Interventions					
Coral Population and Community Interventions					
Managed Relocation: Assisted Gene Flow	Increasing abundance of stress-tolerant genes or colonies within population range	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
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 tradeoffs
Managed Relocation: Introduction 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 non-target genes, species, and microbes; ecological tradeoffs
Environmental Interventions					