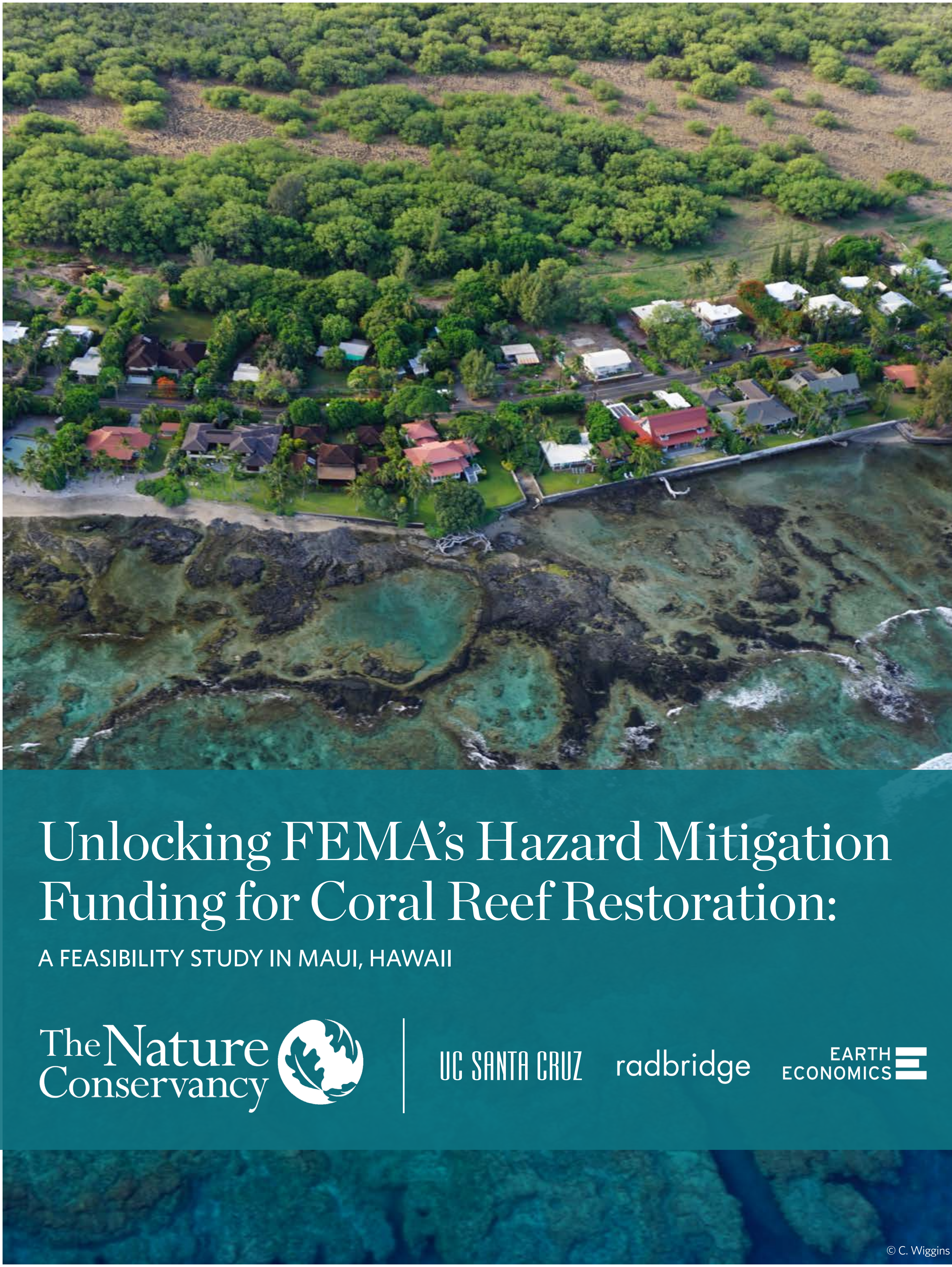

Unlocking FEMA's Hazard Mitigation Funding for Coral Reef Restoration:

A FEASIBILITY STUDY IN MAUI, HAWAII

The Nature Conservancy | UC SANTA CRUZ radbridge EARTH ECONOMICS

ABOUT THE PARTNERSHIP

The Nature Conservancy in California (TNC-CA) and the Federal Emergency Management Agency (FEMA) Region IX entered a formal partnership via FEMA's Cooperating Technical Partners program to advance the use nature-based solutions for hazard mitigation, which helped support this study. Additional research partners include the Coastal Science and Policy Program at the University of California Santa Cruz (UCSC) and Earth Economics, a science-based economics nonprofit based in Tacoma, WA, and Radbridge LLC

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Executive Summary

Climate change poses severe threats to coastal communities and the ecosystems on which they depend. Warming ocean temperatures increase the magnitude and frequency of storm and coral bleaching events, allowing less time for recovery amidst these threats. Coral reef ecosystems in the United States (U.S.) support fisheries, tourism, and coastal protection at a total economic value of $3.4 billion per year[6]. Coral reefs complex and stable structure protects against natural hazards by reducing 97% of wave energy, resulting in less coastal flooding onshore[3]. Coral reefs provide approximately $1.8 billion in flood risk reduction benefits per year in the U.S. However, as reefs degrade, they lose their effectiveness in attenuating wave energy, increasing coastal hazard risks to 18,000 people in the U.S. each year[4,5]. There is a clear need for active hazard mitigation actions to retain the critical ecosystem services of coral reefs.

Hazard mitigation is any sustainable action that reduces or eliminates long-term risk to people and property from future disasters[13]. In the U.S., the Federal Emergency Management Agency (FEMA) is responsible for responding to natural disasters and providing technical and financial hazard mitigation support. This support is primarily distributed as grant funding through FEMA's Hazard Mitigation Assistance (HMA) programs. As disasters increase in intensity and frequency, their costs also increase. FEMA seeks cost-effective solutions to mitigate disaster costs and impacts now and into the future. Nature-based solutions (NBS) utilize natural features and processes to promote resilience and adaptation[41]. NBS for hazard mitigation support coastal resilience through direct flood reduction action and indirectly through other socioecological co-benefits that, for example, impact jobs and livelihoods. FEMA has steadily shifted many of its policies to better support the implementation of NBS.

There is growing interest in the use of coral restoration for hazard mitigation action to reduce risks to people and property. Active ecological coral restoration aims to return coral reef ecosystems to a thriving state, with the goal of increased genetic diversity and a high survival rate of restored corals. The same methods used in ecological coral restoration have the potential to serve as a robust hazard mitigation strategy in the form of coral reef restoration for risk reduction (CR4). CR4 is an active restoration strategy with the aim of increasing the structural integrity and complexity of coral reef ecosystems to attenuate wave energy and reduce coastal flooding. At the completion of this report, no reef restoration project has received funding from FEMA's HMA programs, but local and federal stakeholders have expressed interest and support for exploring CR4 project eligibility for HMA.

The Nature Conservancy of California (TNC-CA) has partnered with UC Santa Cruz (UCSC) Coastal Science and Policy Program and the Coastal Resilience Lab to conduct a feasibility study to investigate whether reef restoration has the potential to be an eligible hazard mitigation project under the guidelines of FEMA's HMA grant programs. The work completed in this feasibility study aligns with the Cooperating Technical Partners (CTP) agreement between TNC-CA and FEMA Region IX to advance the use of natural infrastructure and NBS in hazard mitigation, including CR4.

We assessed the feasibility of accessing federal hazard mitigation dollars for CR4 by selecting a U.S. coral jurisdiction within FEMA Region IX based on the following criteria: availability of infrastructure data; alignment of coral management priorities; alignment of hazard mitigation priorities; political buy-in; and coral restoration capacity. The Pacific coral jurisdictions of American Samoa, Commonwealth of the Northern Mariana Islands (CNMI), Guam, and Hawai'i recognize coral reef ecosystems as cultural treasures that provide millions of dollars in annual benefits through tourism, fisheries, and coastal protection. However, when developing a FEMA HMA application, including a cost-effective benefit-cost analysis (BCA), Hawai'i is the only jurisdiction with infrastructure data that meets FEMA requirements for analysis of the site-specific flood reduction benefits provided by coral reefs. Hawai'i's reefs provide $3.4 million in flood protection value per year[4,5]. Hawai'i has plans to expand coral restoration operations throughout the islands, and the state recognizes coral reefs as critical natural infrastructure via Senate Concurrent Resolution No. 187[28].

Maui was selected as the locale to conduct site-specific preliminary case studies of the benefits and costs associated with CR4 projects and gauge stakeholders' acceptance and local knowledge of FEMA HMA programs. We evaluated the technical feasibility, community buy-in, and cost-effectiveness of CR4 projects at fifteen sites on Maui. Cost-effectiveness is a basic eligibility component for FEMA HMA and is determined by a BCA. The result of a BCA is a benefit-cost ratio (BCR) which compares the project's benefits to the costs. A project with a BCR greater than 1.0 is considered cost-effective under FEMA's HMA requirements.


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We analyzed the flood reduction benefits of coral reefs using FEMA's Flood Assessment Structure Tool (FAST) with data inputs from the National Structure Inventory (NSI 1.0) infrastructure database and Storlazzi et al. (2019)[4] spatial flood maps. The FAST analysis provides the avoided flood damages based on scenarios with current reefs and with the loss of 1 m of reef height. Thus, we estimated the avoided flood damage values attributable to the top 1 m of reefs and designed a coral restoration project to fulfill the same function and benefits. We assumed a linear reception of flood reduction benefits based on the restored corals' growth rate of 1.5 cm/year.

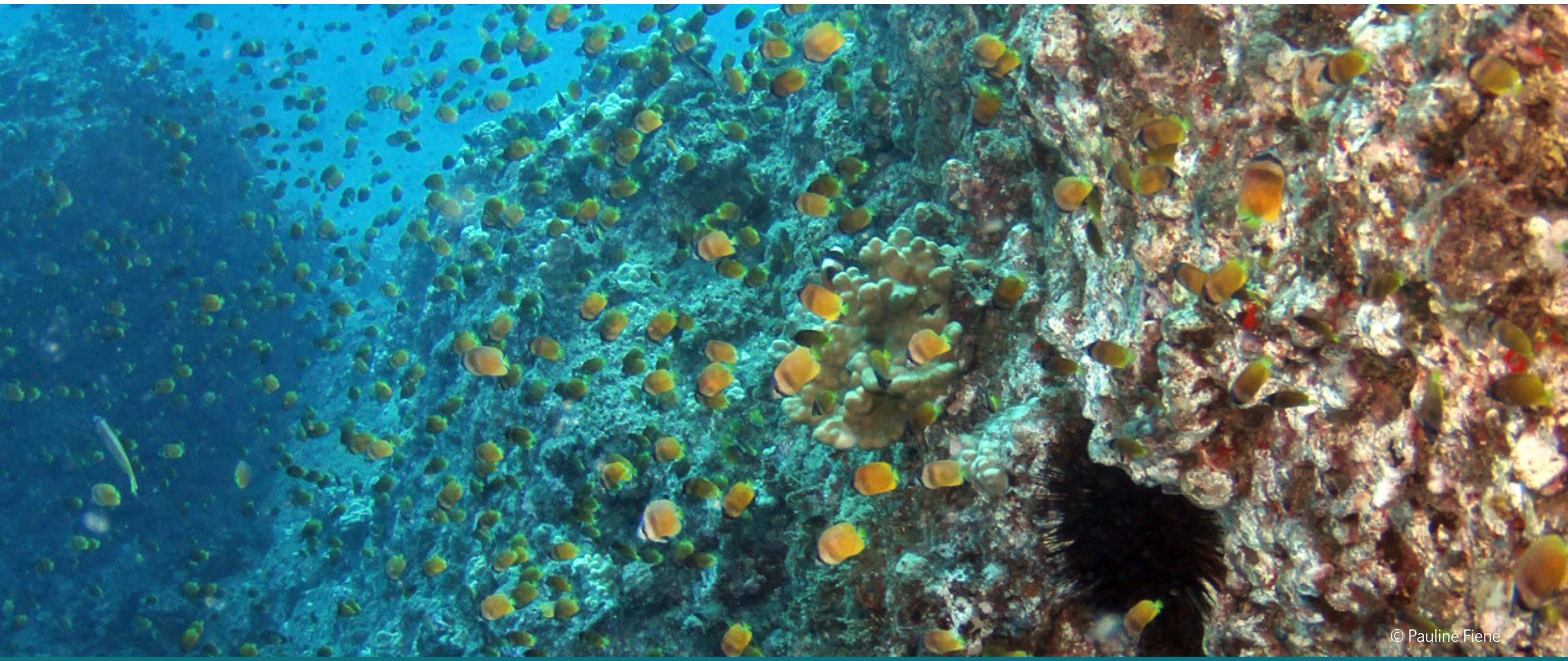
We estimated costs associated with coral gardening and hybrid reef restoration approaches. Coral gardening capital costs were estimated from global coral restoration projects and adjusted to Hawai'i-cost levels at $212,162,951/km^2. Hybrid reef capital costs included the same coral gardening costs plus submerged breakwater estimates provided by local experts at $650/m^3, resulting in a total of $410,282,655/km^2. Both approaches' ongoing project costs included monitoring and maintenance estimated from Florida Mission Iconic Reefs[38] at an average of $6,897,206/km^2/year and $17,311,215/km^2/year, respectively. The costs for a hybrid reef approach are about double the costs of the coral gardening approach because the hybrid method incorporates a submerged breakwater artificial structure with nursery-grown corals attached. We assumed the benefits of both restoration methods to be equal. Still, the time to receive full benefits is less for the hybrid method approach than for the coral gardening approach because of the upfront height addition from the structural component, which the BCRs reflect.

Overall, the results of the preliminary BCA show that **CR4 is a cost-effective hazard mitigation strategy**. Factors that influenced the BCRs included: the amount of continuous reef offshore, the size of the restoration project compared to the size (or value) of the area protected, and the recommended restoration approach. While the hybrid reef approach showed cost-effectiveness for nearly every site, there are still many remaining unknowns surrounding this methodology. As such, **coral restoration operations must establish CR4 best practices and techniques**. Coral restoration facilities should prioritize restoration techniques to maximize efficiency, utilize resilient coral genotypes for restoration projects, and scale-up outplant capacity to implement large-scale risk reduction-focused projects. Additionally, pursuing a hybrid reef restoration approach must involve substantial community involvement from planning through implementation.

Still, the **BCR is just one component of a comprehensive FEMA HMA application**. There are many other factors and benefits that FEMA might consider when deeming a project or site favorable. For example, **alignment between hazard mitigation and coral management priorities is important** to FEMA because officially established priorities show that a project has extensive buy-in and support from multiple government agencies and resource managers. Even with perfect alignment between hazard mitigation and coral management priorities, **many jurisdictions in Region IX will be limited in pursuing FEMA HMA for CR4 projects because of the lack of rigorous infrastructure data available**. Within FEMA Region IX, we could only conduct the preliminary BCA for Hawai'i because it is the only jurisdiction with NSI 1.0 data available.

Finally, **unanticipated project costs may limit the term and scale of future projects.** FEMA requires the BCA to include all costs throughout the life of a project. However, an HMA grant from FEMA will not cover all of the costs included in the BCA. FEMA grants cover a three-year project implementation phase but do not cover additional operational expenses after the project is complete. Further investigation must be made into how and if FEMA grant funding could cover additional project costs.

Coral reefs have been shaping coastlines and defending coastal communities for millennia. However, the best practices for CR4 are still under development. Demonstration projects like those now supported by Defense Advanced Research Projects Agency's (DARPA) Reefense program will help improve these practices. The work conducted through this feasibility study answered several questions surrounding CR4 such as 1) how to select sites where CR4 will be technically and financially effective 2) whether communities and agencies see CR4 as a viable hazard mitigation solution 3) whether a preliminary BCA shows that CR4 projects can meet FEMA HMA's basic eligibility criteria. Further, the methods used in this study are replicable for the development of future CR4 projects in Hawai'i and throughout the other U.S. coral jurisdictions.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Background

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The Role of Nature-based Solutions and Coral Reefs in Hazard Mitigation

As the global climate faces significant changes to temperature, rainfall patterns, and ocean chemistry, communities must prepare for the increased risk associated with these changes. Hazards due to climate change include wind and rain storm events at a higher intensity and frequency, disaster recovery costs increasing, ecosystem degradation caused by increased ocean temperatures, and food instability due to biodiversity loss. The coast is especially vulnerable to climate change impacts, including sea level rise, and those who live on the coast will experience these risks more acutely. Hazard mitigation actions are necessary to protect people and infrastructure from these increased risks, saving lives and money well into the uncertain future.

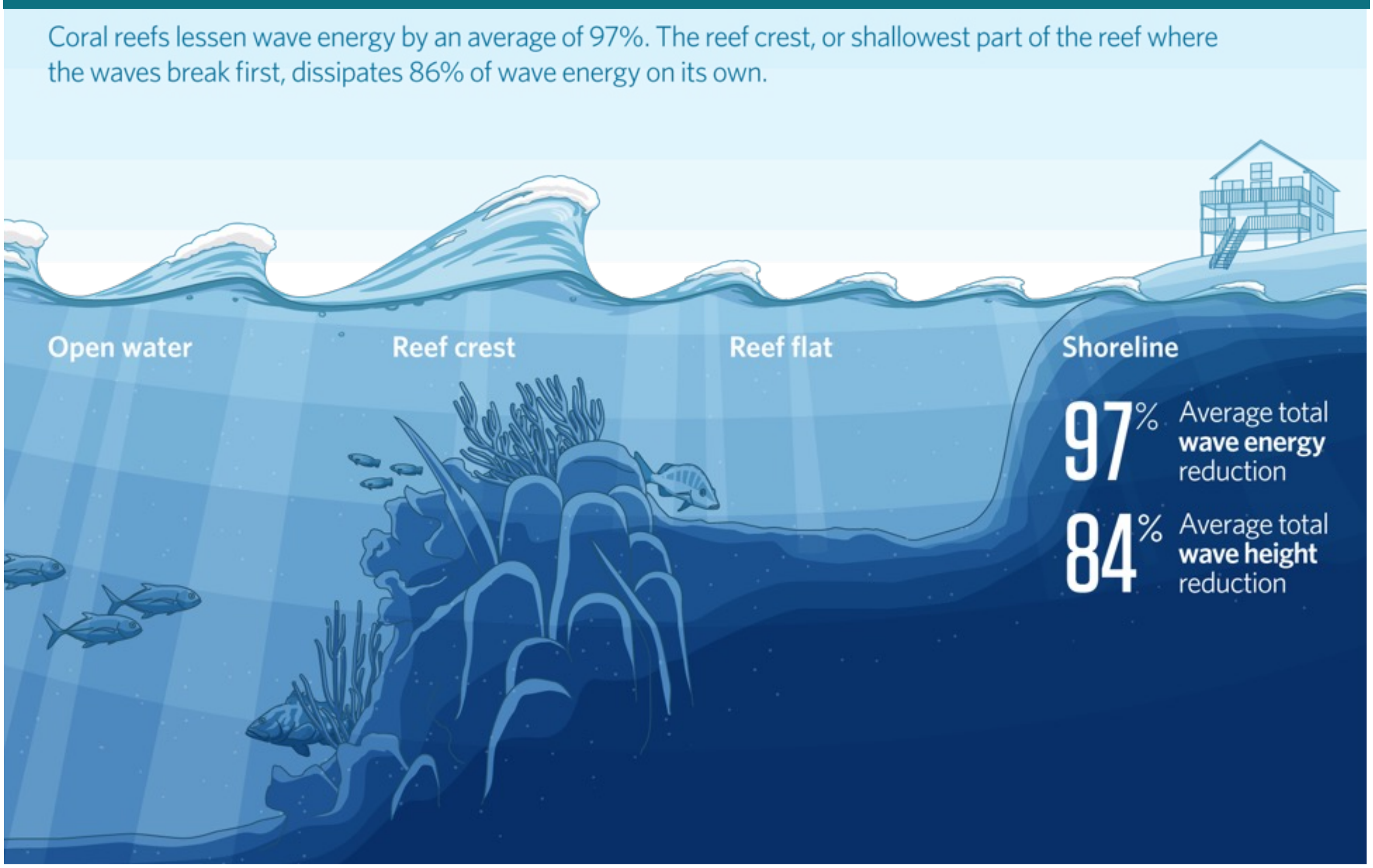
Natural ecosystems like marshes, reefs, and mangroves inherently protect coastal shorelines. A growing number of studies emphasize the importance of quantifying the protective value of natural ecosystems to make a case for investing in nature-based solutions (NBS) for their risk reduction benefits. For example, mangroves protect more than 15 million people and reduce flood damages by $65 billion globally per year[1], while coral reefs worldwide reduce flood damages by more than $4 billion annually[2].

Over 100 million people worldwide receive risk reduction benefits from coral reefs, with the U.S. among the top ten beneficiaries[3]. Healthy coral reefs promote coastal resilience in the face of climate change via their ability to attenuate wave energy, reduce flood risk, and protect coastlines from erosion. The complex and stable structure of coral reefs protect against natural hazards by reducing wave energy by 97 percent[3]. Coral reefs protect more than 18,000 people, $825 million in coastal infrastructure, and $700 million in economic activity in the U.S. from flooding annually[4,5]. Overall, coral reefs in U.S. territories and states provide $1.8 billion in flood protection annually[4,5].

As one of the most biodiverse ecosystems on earth, coral reefs support coastal communities ecologically, culturally, economically, and physically. When accounting for fisheries, tourism, and coastal protection in the U.S., the total economic value of coral reefs is $3.4 billion per year[6].

Healthy coral reefs promote recreational and commercial fisheries throughout the U.S. at an estimated value of over $200 million per year[7]. The total tourism value of coral reefs in Florida and Hawai'i alone is estimated at $2.4 billion per year[8].

CORAL REEFS REDUCE WAVE ENERGY AND HEIGHT

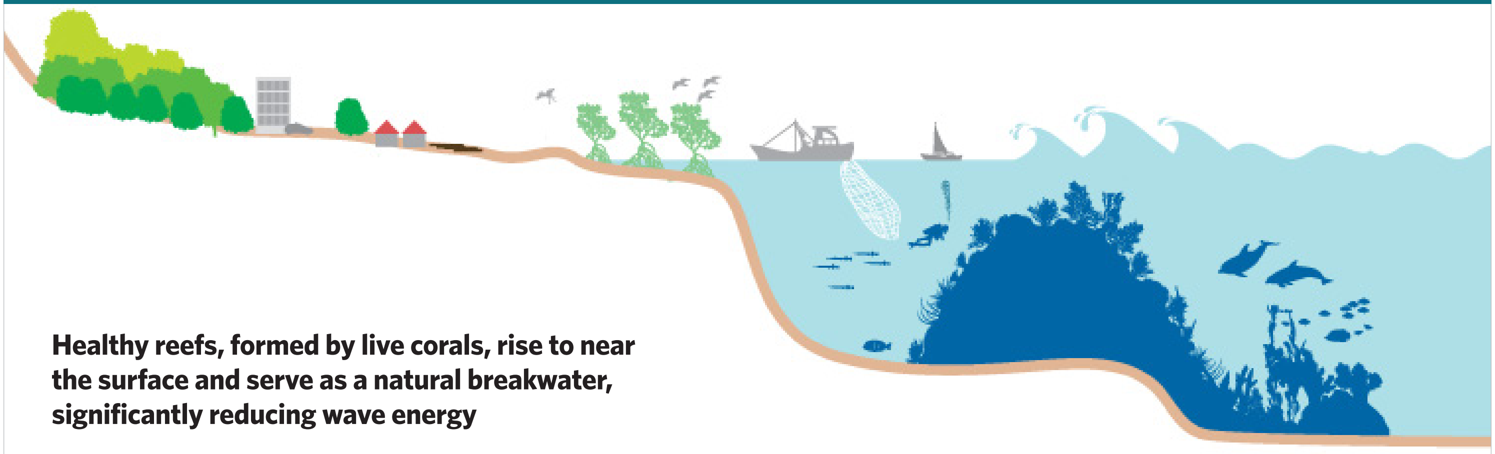


Source: F. Ferrario, M.W. Beck, C.D. Storlazzi, F. Micheli, C.C. Shepard, and L. Airoldi, "The Effectiveness of Coral Reefs for Coastal Hazard Risk Reduction and Adaptation," Nature Communications (2014), doi: 10.1038/ncomms4794 © 2014 The Pew Charitable Trusts

Reefs are inherent natural breakwaters, but their effectiveness varies with their level of coral cover[9]. As ocean waters warm, more coral reefs are dying due to bleaching and disease, and the frequency and magnitude of coastal storms and floods are increasing[10]. The accelerated loss of coral reefs increases the likelihood of coastal flooding, meaning impacts from coastal hazards will only become more costly and devastating. This threat makes it critical to invest in local and global actions to reverse reef decline and preserve ecosystem structure and function[3]. Active reef restoration could do even more to retain and enhance the myriad benefits of reef ecosystems and provide a robust hazard mitigation strategy in the form of coral reef restoration for risk reduction (CR4).

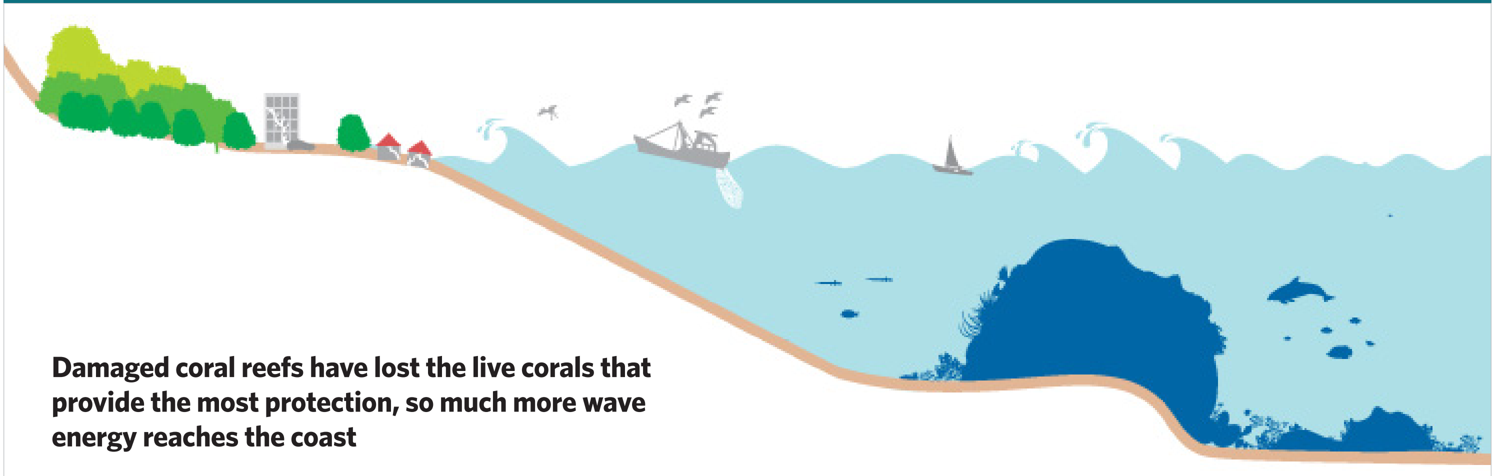
According to a recent United Nations Environment Programme (UNEP) report, most restoration project goals include the recovery or maintenance of key ecosystem processes, functions, and services[11] rather than coastal risk reduction benefits. This lack of reef restoration projects for risk reduction is most likely attributable to the size of restoration projects required to achieve meaningful risk reduction compared to ecological outcomes. The requirement for large-scale projects, combined with the high restoration costs, makes funding opportunities remarkably scant for risk reduction in coral reef restoration[12]. Given the inherent benefit of coastal flood risk reduction provided by coral restoration, there is an opportunity to fund reef restoration via existing federal hazard mitigation programs to protect people and property.

HEALTHY CORAL REEF



Healthy reefs, formed by live corals, rise to near the surface and serve as a natural breakwater, significantly reducing wave energy

DEGRADED CORAL REEF



Damaged coral reefs have lost the live corals that provide the most protection, so much more wave energy reaches the coast

Importance to The Nature Conservancy

The Nature Conservancy (TNC) seeks to partner with local reef restoration entities and emergency management agencies in U.S. coral reef jurisdictions to increase the pace and scale of coral reef restoration efforts that provide multiple benefits to people and nature, including hazard risk reduction. The Federal Emergency Management Agency's (FEMA) hazard mitigation programs, which encourage nature-based hazard mitigation projects, are a possible funding source; however, no coral reef restoration projects have been successfully funded through FEMA at the time this report was completed. Funding through these programs could be available for a coral reef restoration project in areas with built infrastructure and communities that benefit from coastal flood risk reduction provided by coral reefs. FEMA and TNC share an interest in maximizing and facilitating the use of expanded mitigation dollars for NBS. In 2019, TNC of California (TNC-CA) and the FEMA Region IX entered a formal partnership via FEMA's Cooperating Technical Partners (CTP) program to advance the use of natural infrastructure and NBS. NBS utilize nature, open space, or ecosystems that can provide multiple benefits to communities, including protection from natural hazards. FEMA's CTP program allows FEMA to build strategic and innovative partnerships with communities, regional agencies, state agencies, tribes, universities, and non-governmental organizations (NGOs). The CTP between FEMA Region IX and TNC-CA supports TNC's leadership of projects designed to expand the use of hazard mitigation funding for NBS, such as CR4, examined in this feasibility study. Further, TNC has partnered with the Coastal Science and Policy Program at the University of California Santa Cruz (UCSC) for this study as a leading research institution examining the valuation of NBS for hazard mitigation.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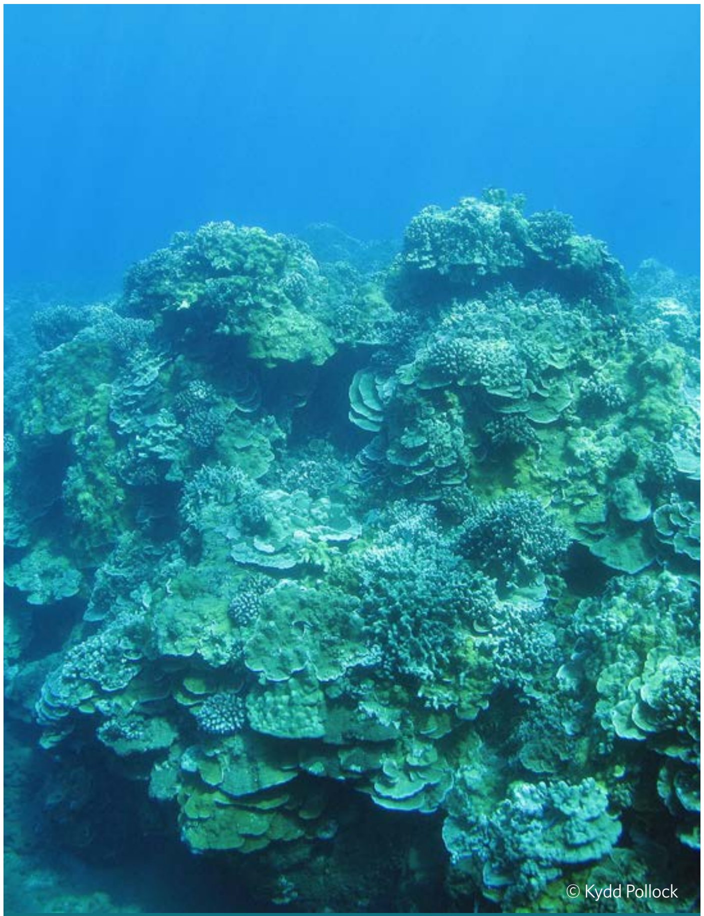
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RATIONALE FOR THE FEASIBILITY STUDY

- Hazard mitigation funds made available by FEMA have increased year-over-year.
- FEMA has an interest in funding a wide variety of NBS that reduce risks from natural hazards.
- TNC shares this interest and is actively working towards demonstrating proof of concept for FEMA funding programs across multiple NBS project types, including coral restoration.
- The importance of NBS is widely recognized, but the actual benefit-to-cost ratio of CR4 has not been evaluated.
- Determining the benefit-to-cost ratio is key to demonstrating the eligibility of NBS for federal funding. Although FEMA has expressed interest in supporting NBS, there is still unfamiliarity on both sides (funding applicant/subapplicant and reviewer) in determining the eligibility and appropriateness of NBS for hazard mitigation.

FEMA Hazard Mitigation Assistance Programs

FEMA provides billions of dollars in hazard mitigation assistance to communities to reduce or eliminate long-term disaster risks. FEMA's hazard mitigation funding programs include competitive and non-competitive grants for all U.S. states, territories, and federally recognized tribal governments. The 2018 Disaster Recovery Reform Act (DRRA) established a dedicated funding stream for pre-and post-disaster mitigation provided through FEMA's Hazard Mitigation Assistance (HMA). FEMA distributes HMA technical and financial support primarily through three programs with distinct application prerequisites and project requirements: the Hazard Mitigation Grant Program (HMGP), the Flood Mitigation Assistance (FMA) program, and the Building Resilient Infrastructure and Communities (BRIC) program. The DRRA increased funding available for pre-disaster mitigation by an average of $300-$500 million annually through a presidential set-aside of up to 6% of the federal spending on the prior year's federally declared disasters disbursed into the National Public Infrastructure Predisaster Mitigation Fund (NPIPDM)[13]. The DRRA also established FEMA's BRIC program to support proactive investment in community resilience and authorized a 75% federal cost-share for FEMA's HMGP. This most recent reform to disaster recovery assistance in the U.S. calls out resilience both in response to disasters and in mitigation projects for disaster preparation, creating a real opportunity to show how NBS inherently promotes resilience.

PRE-DISASTER	BUILDING RESILIENT INFRASTUCTURE AND COMMUNITIES	The Building Resilient Infrastructure and Communities (BRIC) program is a pre-disaster grant providing funds for hazard mitigation projects and capabilities and capacity-building activities that expand or improve the administration of mitigation assistance. Funding from this grant reduces reliance on reactive spnding and increases proactive invectments in science-based community resilience projects.
PRE-DISASTER	FLOOD MITIGATION ASSISTANCE	The Flood Mitigation Assistance (FMA) program provides pre-disaster funds for the reduction or elimination of long-term flood risk to buildings, manufactured homes, and other structures insured by the National Flood Insurance Program (NFIP).
POST-DISASTER	HAZARD MITIGATION GRANT PROGRAM	The Hazard Mitigation Grant Program (HMGP) provices post-disacter recovery funds to rebuild in a way that reduces future disacter losses in the community. HMGP is often open state-wide, and it can be used to rebuild in damaged areas and to mitigate in non-damaged areas. This grant funding is available after a presidentially declared disaster.

Source: Overview of FEMA MHA grant programs from TNC's Promoting Nature-based Hazard Mitigation Through FEMA Mitigation Grants (2021).

WHO CAN APPLY FOR FEMA HMA?

Developing and implementing a CR4 project will likely involve several organizations, including non-profits, community-based organizations, local businesses, and government agencies. The eligible lead that can apply differs for each of FEMA's HMA grant programs. For example, for the BRIC program, a state, tribal, or local government entity, known as the "subapplicant," submits a project proposal to the designated State Hazard Mitigation Office (SHMO), often a state emergency management agency, which is known as the "applicant."

ELIGIBLE SUBAPPLICANTS			
ENTITY	HMGP	PDM	FMA
STATE AGENCIES	✓	✓	✓
FEDERALLY-RECOGNIZED TRIBES	✓	✓	✓
LOCAL GOVERNMENTS/COMMUNITIES*	✓	✓	✓
PRIVATE NONPROFIT ORGANIZATIONS (PNPs)	✓	✗	✗

*Local governments/community may include non-federally recognized tribes, or consistent with definition of local government at 44 CFR 201.2, may include any Indian tribe or authorized tribal organization, or Alaska Native village or organization that is not federally recognized per 25 U.S.C. 479a et seq.

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FEMA and Nature-based Solutions

Over the past ten years, FEMA has been steadily shifting its policies to better support the application and implementation of NBS for natural hazard mitigation. These changes have included climate change and resilience language in disaster recovery policies, changes to FEMA's benefit-cost ratio (BCR) requirements to allow for easier inclusion of ecosystem services, and publishing/supporting guidance documents explicitly related to NBS. In 2021, FEMA published Building Community Resilience with Nature-based Solutions: A Guide for Local Communities. In the same year, under their FEMA CTP, TNC partnered with the infrastructure consulting firm AECOM to produce the Promoting Nature-based Hazard Mitigation Through FEMA Mitigation Grants[14], a guidebook to support practitioners interested in working with FEMA to fund nature-based hazard mitigation projects.

To date, no eligible applicant has successfully applied for a coral reef restoration project for hazard mitigation. However, FEMA partners have shown interest in supporting coral restoration and a willingness to learn about how coral restoration projects designed for coastal flood risk reduction can reduce damages to people and property in the United States. Coral restoration has been proposed as a viable strategy to provide risk reduction benefits that can be valued and recognized by FEMA. At the same time, applicants must consider several project components before developing a CR4 project that aligns with FEMA's various program application requirements. Recently, federal agencies and academic partners developed the document CR4: A Guide to Project Design and Proposal Development (in review) to outline the best practices for developing the project components of several federal hazard mitigation funding opportunities. We discuss these project components further in this feasibility study, hoping that a general outline of the project planning, design, and development phases will guide future project proposals.

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U.S. Coral Jurisdiction Review and Selection

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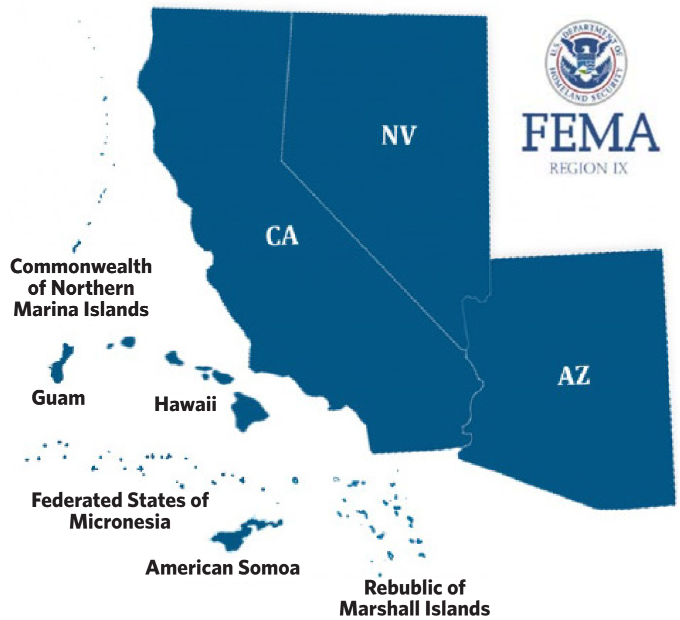
We selected a U.S. coral jurisdiction within FEMA Region IX to investigate the feasibility of funding a coral restoration project using federal hazard mitigation dollars. FEMA Region IX was chosen as the focal region because the CTP between FEMA and TNC-CA exists explicitly for FEMA Region IX, which encompasses California, Nevada, Arizona, and the Pacific Island states and territories. The U.S. coral jurisdictions within FEMA Region IX include American Samoa, the Commonwealth of the Northern Mariana Islands (CNMI), Guam, and Hawai'i. We assessed the feasibility of funding a CR4 project using hazard mitigation funding in each of these jurisdictions based on the following criteria: infrastructure valuation data availability, alignment with jurisdictional management priorities, political buy-in, and current and future coral restoration capacity.



U.S. CORAL REEF JURISDICTIONS

OVERALL CRITERIA ALIGNMENT

JURISDICTION	Infrastructure Data Availability	Coral Management Priority Alignment	Hazard Mitigation Priority Alignment	Political Buy-in	Coral Restoration Capacity
AMERICAN SAMOA	↓	↑	–	–	↓
CNMI	↓	–	–	–	↑
GUAM	↓	↑	↑	↑	–
HAWAI'I	↑	↑	↑	↑	↑

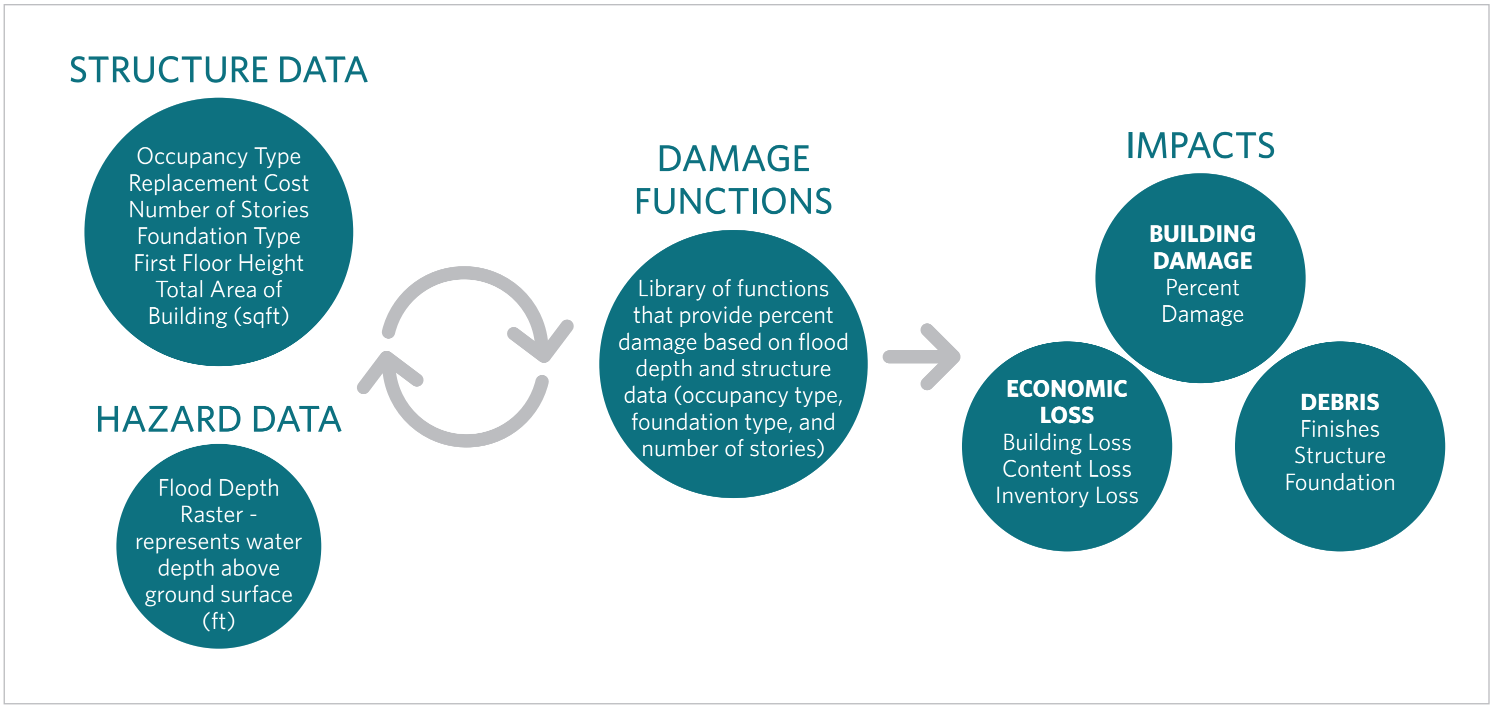
Overview of the level of alignment for the criteria assessed for each U.S. coral jurisdiction within FEMA Region IX. Each criterion is explained further in the sections below.

Infrastructure Data Availability

Several data types are required to assess the site-specific flood protection value of coral reef restoration within each U.S. coral jurisdiction in FEMA Region IX. The standard method accepted by FEMA for determining benefits from a flood hazard mitigation project is the use of FEMA's Flood Assessment and Structure Tool (FAST). FAST provides the most rapid, extensive, and building-specific damage valuation results for the flood mitigation potential of coral reef restoration projects. FAST requires two distinct inputs to rapidly analyze building-level flood risk using FEMA's Hazards United States (HAZUS) flood model methodology: (1) site-specific building data in csv form with specific attributes and (2) hazard data in the form of depth grids in tif file format with depth in feet.

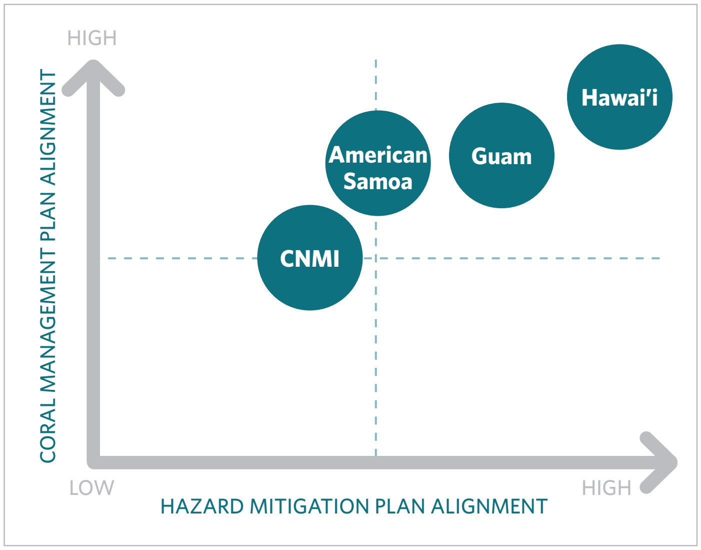
The most widely recognized building valuation data that fits the structure data requirements of FEMA FAST is the National Structure Inventory (NSI) developed by FEMA and the U.S. Army Corps of Engineers (USACE). The availability of NSI 1.0 data is crucial because it allows for the easy calculation of losses from natural hazards in a method that is rigorous enough for FEMA's benefit-cost analysis (BCA) standards. Hawai'i is the only coral jurisdiction within FEMA Region IX with high-resolution structure data available through the NSI. NSI 1.0 data is not readily available for American Samoa, CNMI, or Guam due to a lack of detailed U.S. census block-level demographic data, which informs NSI 1.0 data. This data gap will likely be a critical limiting factor for developing any future HMA applications involving coral restoration projects designed for flood risk reduction within U.S. small island territories and commonwealths.

Professionally modeled flood hazard data is widely available for U.S. coral jurisdictions. Hazard data provides a spatial map showing coastal flood depths based on modeled storm return periods and ecosystem scenarios. The study "Rigorously Valuing the Role of U.S. Coral Reefs in Coastal Hazard Risk Reduction"[4] provides modeled coastal flood depth grid data for all U.S. coral jurisdictions, representing flood depths for two reef scenarios (with and without reef) across four different storm return periods (10-, 50-, 100-, and 500- year). The "with reef" scenario represents coastal flood depths associated with the current coral reef height throughout the jurisdictions for multiple storm return periods. The "without reef" scenario represents coastal flood depths associated with losing the top 1 meter of reef for those same storm return periods. Storm return periods represent the probability of an event occurring in any given year and can also be represented as a percentage. For example, for a 100-year storm return period, there is a 1/100 or 1% chance for that event to occur in any given year. The annual expected benefit (AEB) provided by coral reefs is calculated by using FEMA FAST to calculate return-period weighted annual losses and then subtracting the expected annual losses with reefs from the expected annual losses without reefs.



Jurisdiction Priority Alignment

Alignment between coral restoration and hazard mitigation priorities maximizes the likelihood of success of project design, application development, and ultimate submission for any FEMA HMA NBS project. The most up-to-date coral reef management plans and emergency management hazard mitigation plans for each U.S. coral jurisdiction in FEMA Region IX are summarized below. Here we highlight jurisdictional management projects or programs where coral restoration and hazard mitigation priorities align with the development of a CR4 project.



CORAL MANAGEMENT PRIORITY ALIGNMENT

Each state or territory sets coral management priorities to align territorial, state, and federal coral management decisions, including funding. It is essential to consider whether coral management plans align with a potential CR4 project because jurisdictions with coral management goals and objectives that support CR4 are already on the path toward implementing strategies that would buoy CR4 success. It is important to note that each jurisdiction has included interventions for land-based sources of pollution and sustainable fisheries as management priorities. Combining these management interventions with goals for coral restoration is essential for eliminating stressors at potential restoration sites and increasing the likelihood of restoration success. The coral management plans for each jurisdiction are living documents, and there is potential to better include CR4 as a management strategy in future updates.

Overall, American Samoa, Guam, and Hawai'i have coral management priorities with high alignment for a potential CR4 project. For example, American Samoa's Local Action Strategy aims to protect and enhance the territory's shorelines and the ecological services they provide by developing and piloting natural infrastructure alternatives to hardened shorelines[15]. A CR4 project has the potential to align with this goal and fulfill this objective. American Samoa's coral management priorities also include NBS as management's best practice for conserving and restoring the territory's natural resources, with plans to incorporate green/hybrid infrastructure and coral restoration in village-level management strategies[15]. Guam's management priorities include the overall goals of reframing management efforts and priorities in the context of resilience, increasing local and federal agency cooperation, prioritizing management interventions, and shifting from reactive to proactive management efforts[16]. Hawai'i's coral management strategies include reef restoration to increase coral reef ecological function and integrity[17]. Both Guam and Hawai'i have immediate plans to increase coral restoration capacity and activities while threading resiliency throughout the priorities' goals and objectives.

CNMI is the territory with the least alignment of NBS within its coral restoration and management priorities. CNMI has plans to hire local coral restoration capacity and expand nursery operations; however, the management actions established for the other priorities such as land-based sources of pollution (LBSP) and fisheries management are much more expansive[18]. Since coral restoration is a relatively new priority in CNMI's management goals, more front-end work is likely necessary to align coral restoration strategies with hazard mitigation strategies to support a CR4 project. Overall, alignment between CNMI's coral management priorities and a CR4 project is medium.

HAZARD MITIGATION PRIORITY ALIGNMENT

Each state or territory must establish a FEMA-approved Hazard Mitigation Plan (HMP) to receive assistance via FEMA HMA, Public Assistance (PA), and other non-emergency disaster assistance. HMPs are updated every five years and outline a state or territory's local risks and hazards, mitigation capabilities, and mitigation strategy. It is important to consider how a potential CR4 project aligns with each jurisdiction's HMP. The goals and objectives outlined in the mitigation strategy prioritize the distribution of federal hazard mitigation funds sought and received by the jurisdiction. Each HMP mentions the importance of reefs in reducing wave energy; however, the plans simply state the role reefs play in hazard mitigation rather than explicitly connecting the potential benefits of reef ecosystems to risk reduction outcomes such as through incorporation of the Storlazzi et al. (2019)[4] results. Additionally, the plans all consider the impacts of climate change and sea level rise to the probability of future hazards and changes that may alter the state or territory's vulnerability. Still, none explicitly consider the impact of the potential (or expected) loss of coral reef habitats on the extent of hazards such as flooding, storm surge, and sea level rise.

Guam and Hawai'i have the highest alignment between HMP priorities and a potential CR4 project. For example, Guam's HMP explicitly names coral reefs as Guam's living breakwaters and identifies them as natural infrastructure[19]. Hawai'i's HMP mentions coral reefs in every hazard that poses risks to the State and highlights the opportunity to harness ecosystem function to meet mitigation goals through NBS[20]. Guam's HMP directly links the territory's hazard mitigation priorities to their coral priorities by prioritizing the implementation of adaptive management interventions from the 2018 Guam Coral Reef Resilience Strategy within the mitigation strategy[19].

On the other hand, CNMI and American Samoa's HMP priorities have medium alignment with a potential CR4 project. Within CNMI's HMP, there is no explicit mention of coral health, submerged breakwaters as a mitigation tool, flood-specific mitigation projects, or NBS[21]. American Samoa's HMP identifies the importance of coral reefs in reducing shoreline erosion and mentions breakwaters as a strategy for coastal protection, but none of the priority projects involve NBS[22]. In general, the mitigation priorities for CNMI and American Samoa emphasize gray approaches and the hardening of critical facilities rather than green approaches like NBS.

Political Buy-in

Legislative recognition of coral reefs as critical natural infrastructure is important to direct activities and funding towards CR4 projects. In all Pacific U.S. coral jurisdictions, coral reef ecosystems are recognized officially and unofficially as cultural treasures that provide millions of dollars in annual benefits through tourism, fisheries, and coastal protection. The political atmosphere throughout FEMA Region IX is highly favorable for coral reef conservation. Several federal policies set up a CR4 project for success in all four jurisdictions examined. In April 2022, President Biden signed an Executive Order that supports the detailed valuation of natural capital through the first U.S. National Nature Assessment and the subsequent implementation of effective NBS that promote resilience[23]. Further, President Biden's Bipartisan Infrastructure Law (Infrastructure Investment and Jobs Act), passed in 2021, allows for major investments tailored to resilience in all U.S. states and territories[24]. Some of these funds can be used specifically for NBS, while other aspects of the law support the next green workforce, advance environmental justice, and promote resilient infrastructure. In addition to these federal policies, several jurisdictions actively pursue concrete legislation to prioritize measures for implementing NBS and active restoration of reef ecosystems. We describe the state- or territory-specific policies supporting coral reef protection, restoration, or NBS below.

American Samoa and CNMI have broad territory-specific policies that recognize the increasing impacts of climate change, such as sea-level rise and ocean warming. In 2012, the Governor of American Samoa implemented Executive Order 03-2012, which identifies climate change as an imminent threat to American Samoa's industries and natural resources and establishes rules to limit greenhouse gas emissions via vehicles and appliances[25]. Executive Order 03-2012 also established the Territorial Climate Change Adaptation Advisory Group, but it does not specifically mention NBS or coral restoration. CNMI has established similar strategies for climate change mitigation, including developing the CNMI Climate Change Working Group in 2012. While these working groups and policies support the mitigation of threats due to climate change, they do not explicitly mention coral reefs or natural ecosystems for their role in climate resilience and adaptation.

Guam and Hawai'i have established explicit policies that highly align with a potential CR4 project. The Government of Guam has established plans for prioritizing coral reef ecosystems as natural infrastructure through formal and informal agreements. In February 2020, the Government of Guam and NGO agencies signed a formal agreement to establish the Guam Reef Restoration and Intervention Partnership. The partnership seeks to fulfill the restoration priorities outlined in the Guam Coral Reef Resilience Strategy. The University of Guam Center for Island Sustainability and Sea Grant program recently highlighted the importance of coral reefs and restoration to protect coastlines at the University of Guam Conference on Island Sustainability[26]. Additionally, the Tumon Bay Insurance Task Force is actively investigating the use of parametric insurance to fund post-storm repairs of the Tumon Bay reef system, including the potential of establishing a Coral Reef Trust[27].

The state of Hawai'i explicitly recognizes the importance of nature in reducing risks due to climate change impacts and natural disasters. In 2020, Hawai'i's Senate Concurrent Resolution No. 187: "Supporting a feasibility assessment for reef insurance and recommendations for nature-based solutions to protect Hawai'i's coastlines and coastal infrastructure from natural disasters," highlighted coral reefs as critical infrastructure that reduces risks to property and people, and the need for novel funding streams to support the restoration of these critical ecosystems[28]. Senate Resolution No. 187 tasks several cooperative agencies, including TNC, the Department of Land and Natural Resources, the Department of Transportation, and the Climate Change Mitigation and Adaptation Commission, to investigate novel funding for NBS[28]. In Maui County, Mayor Alan Arakawa signed a 2018 proclamation that directs county departments to use the Sea Level Rise Vulnerability and Adaptation Report in their plans, programs, and capital improvement decisions[29]. Protecting and enhancing nature and implementing effective coastal adaptation measures are at the forefront of climate and natural hazard strategies throughout Hawai'i.

Coral Restoration Capacity

Coral restoration efforts in all four Pacific U.S. coral jurisdictions are still in the early stages, especially compared to coral restoration capacity in Florida and the Caribbean. Several factors contribute to this such as the more advanced degradation of coral reefs in Florida and the Caribbean with little signs of natural recovery, and challenges in accessing supplies and materials in the Pacific. Coral restoration operations throughout the Pacific include land-based facilities and ocean-based coral nurseries. Techniques utilized primarily include coral gardening, where coral pieces are collected in the ocean, fragmented further, and placed in nurseries to grow to an outplantable size. Some jurisdictions also utilize microfragmentation techniques where corals are cut into 1-2 cm pieces and grown in nurseries close to each other to facilitate fusion of the coral tissue. Microfragmentation allows for faster growth rates and the potential to cover larger surface areas in much less time than it would take an individual coral fragment to grow a similar size.

Here, we evaluate current and planned coral restoration capacity based on the coral restoration action plans developed in 2021 by each Pacific U.S. coral jurisdiction. This planning effort was led by TNC and funded by the National Oceanic and Atmospheric Administration (NOAA) to help guide states and territories through the planning and development of climate-resilient restoration goals and the identification of priority restoration sites and methods[30].

American Samoa currently has the lowest capacity for coral restoration operations compared to the other Pacific jurisdictions. American Samoa has near-term plans for a pilot-scale restoration project to test direct coral transplantation, coral gardening, and substrate stabilization techniques[15]. This pilot project includes establishing three ocean-based nurseries followed by outplanting to stabilized rubble fields and subsequent monitoring of survival rate. Besides this planned pilot project, active coral restoration in American Samoa has only occurred in response to vessel groundings[15].

Guam has medium alignment for a CR4 project within their current and planned coral restoration capacity, and CNMI has high alignment for a CR4 project. Guam and CNMI have similar restoration nursery capacities and plans to expand operations and incorporate innovative restoration techniques. However, their initial priority goals defined for the 2021 coral restoration action plans are slightly different. Guam's priority goal is restoring reefs to enhance resilience to thermal stress or bleaching. Planned actions to support this goal include genotyping coral stock in nurseries and outplant sites, expanding the existing ocean-based coral nursery, and increasing community-based coral restoration throughout the territory[16]. On the other hand, the priority goal defined by CNMI is to restore or enhance the reef structure on the western side of Saipan to reduce wave energy that threatens coastal infrastructure. CNMI plans to utilize artificial reef structures to propagate and outplant corals and expand nursery capacity to meet this goal[18].

Hawai'i is the Pacific jurisdiction with the highest current and planned restoration capacity. In Hawai'i, governmental and non-governmental agencies lead several coral restoration operations. These include the Division of Aquatic Resources' land-based nursery on Sand Island, the Hawai'i Institute of Marine Biology's (HIMB) floating nursery in Kaneohe Bay, and Kuleana Coral Restoration, a community-led coral restoration program on O'ahu. The Coral Resilience Lab at HIMB is also leading the Restore with Resilience project, a statewide initiative to collect, test, identify, and propagate thermally resilient corals for use in all restoration outplanting efforts. Nonprofit, governmental, and community leaders are interested in supporting and scaling up restoration efforts throughout Hawai'i. TNC has plans to support Hawai'i through the permitting, implementation, and piloting stage of their coral restoration action plan priority goal of stress-testing coral fragments, identifying areas of refugia with temperature-resilient coral populations, and building community partnerships to lead coral nursery and outplanting efforts[30].

Case Study:

A PRELIMINARY FEMA HMA BENEFIT-COST ANALYSIS OF A HYPOTHETICAL CORAL REEF RESTORATION FOR RISK REDUCTION PROJECT IN MAUI, HI

Overview

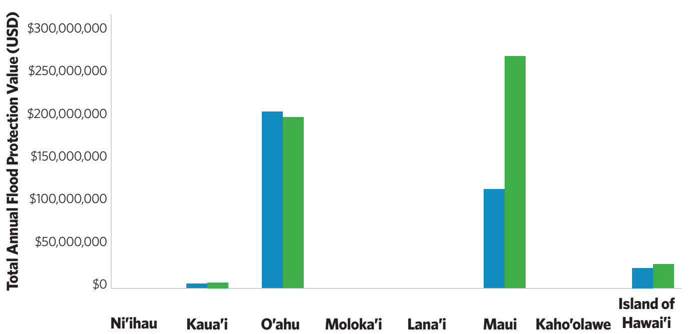
Hawai'i was determined as the most suitable U.S. coral jurisdiction within FEMA Region IX to examine whether a CR4 project could be funded using hazard mitigation dollars. This determination was based on the availability of NSI 1.0 structure-level valuation data, strong alignment between coral management plan and HMP priorities, state-wide policies that support NBS, and plans to expand restoration capacity throughout the state. We selected sites within the island of Maui to analyze because of the high flood protection value of Maui reefs, strong alignment between the Maui County HMP and CR4, and long-standing demonstrated community buy-in for NBS.

Maui's coral reef ecosystems support the island's tourism industry, maintain subsistence, recreational and commercial fishing industries, and are critical to local culture and community identity. Maui County contains the most considerable portion of the state's entire reef system, with over 55 km^2 of the total 142 km^2 [31]. Coral reefs in Maui protect over $112 million worth of buildings and $264 million in economic activity from flooding each year[4,5]. Maui's coral reefs' high value of flood risk reduction benefits encourages coral reef restoration as an effective hazard mitigation strategy.

The primary consideration in assessing the feasibility of applying for FEMA HMA with a CR4 project is whether a BCA determines the project is cost-effective. The benefits of a CR4 project are the avoided flood damages provided by coral reefs, and the costs are the capital, permitting, monitoring, and maintenance costs associated with the restoration project. To meet the eligibility requirements of FEMA HMA programs, the BCR of a project needs to be greater than 1.0.

To conduct a rigorous BCA, we selected potential sites on Maui to design a hypothetical CR4 project. We wanted to choose an area where the flood risk reduction benefits of coral reefs were high and where a CR4 project was

ANNUAL VALUE OF PROTECTION PROVIDED BY CORAL REEFS FROM FLOODING



	Ni'ihau	Kaua'i	O'ahu	Moloka'i	Lana'i	Maui	Kaho'olawe	Island of Hawai'i
Buildings	0	5,854,742	200,942,259	42,071	53,732	112,716,317	0	23,997,824
Econimic activity	1,066	6,466,170	194,404,235	73,122	1,359	264,474,795	0	26,686,848

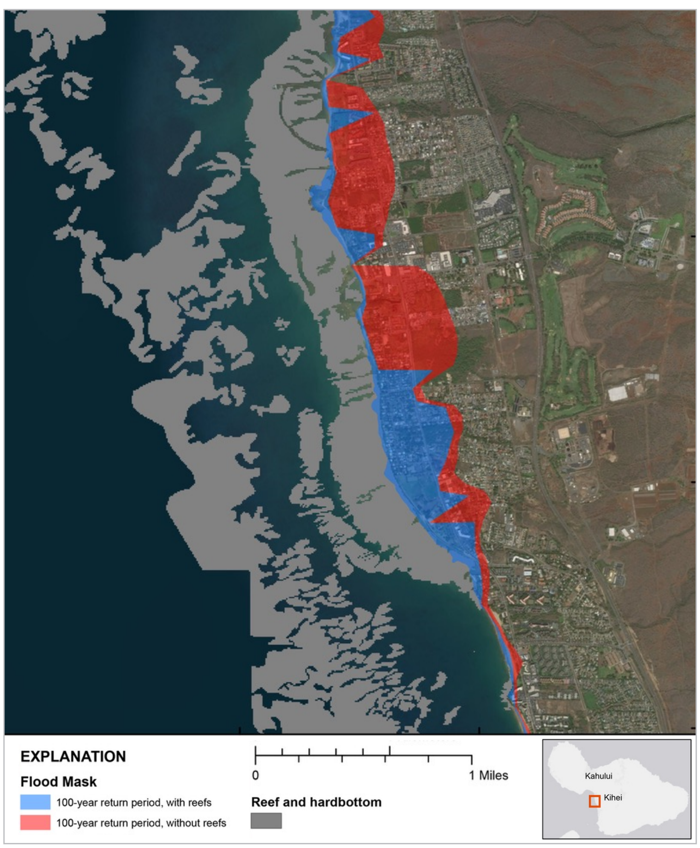
Source: Storlazzi et al. 2019.[4]

likely to be successful environmentally and socially. We identified an initial list of fifteen sites for a hypothetical CR4 project with the help of local stakeholders. Then, we assessed reef characteristics and existing conditions that would facilitate the effectiveness of a CR4 project. After assessing the reef condition at each site, we approximated the design of an effective CR4 project, isolated the predicted area that would receive benefits, and calculated the associated benefits and costs to run the BCA and determine site-specific BCRs.

Site Selection in Maui

FLOOD RISK REDUCTION ASSESSMENT

To assess where reefs provided flood risk reduction benefits to people and infrastructure we used the data from the 2019 U.S. Geological Survey (USGS) study "Rigorously Valuing the Role of U.S. Coral Reefs in Coastal Hazard Risk Reduction"[4]. This study provides flood maps that visualize the coastal flooding extent from multiple storm events with and without coral reefs. This initial assessment allowed us to select sites where reefs provide significant flood risk reduction benefits (e.g., the flood extent with reefs is considerably less than the flood extent without reefs) and protect the highest number of people



Source: Storlazzi et al. 2019.[4]

and properties, setting us up for a high BCR. We selected sites based on places where the AEB from coral reefs was high, mostly based on the dollar value of infrastructure protected from flooding in the "with reef" scenario. Sites with few properties were excluded because a CR4 project in that area was unlikely to have benefits that outweigh the costs (i.e., be cost effective). This initial assessment of flood extent and infrastructure protection allowed us to develop an initial list of seven sites to move forward with for the feasibility study.

COMMUNITY BUY-IN

The purpose and scope of this study assessed community buy-in based on general interest in a hypothetical CR4 project. We held two days of stakeholder meetings involving local and regional NGOs, local coastal engineers, local and regional resource management agencies, the Maui and Hawai'i Emergency Management Agencies, and community leaders/project proponents. Input from local stakeholders on our initial list of CR4 project sites allowed us to assess community support, potential barriers, and sociocultural considerations associated with each site. We subsequently prioritized eight additional sites with high community buy-in to further examine CR4 project development. Consultation with stakeholders interested in CR4 also highlighted characteristics of potential sites where we would conduct the next steps of the feasibility study. Some sites with high-value reefs for flood risk reduction based on the Storlazzi et al. (2019)[4] data did not have high stakeholder interest or had planned coastal projects that would interfere with a future CR4 project. For example, the state has plans to implement large-scale beach renourishment at the Ka'anapali Marriott site, which could result in sedimentation or scouring of corals outplanted offshore. Overall, there are many competing priorities for coastal resources on Maui, and the meetings revealed that erosion is a peak concern for Maui stakeholders. While the coastal risks from flooding and erosion often co-occur, the benefit valuation numbers we used in the BCA for this study are associated with flood damages. Thus, we were careful to identify hazards of concern, competing priorities, and reef characteristics for each site, along with the preliminary results of the BCA (see full BCA results link).

CORAL REEFS AND COMMUNITIES

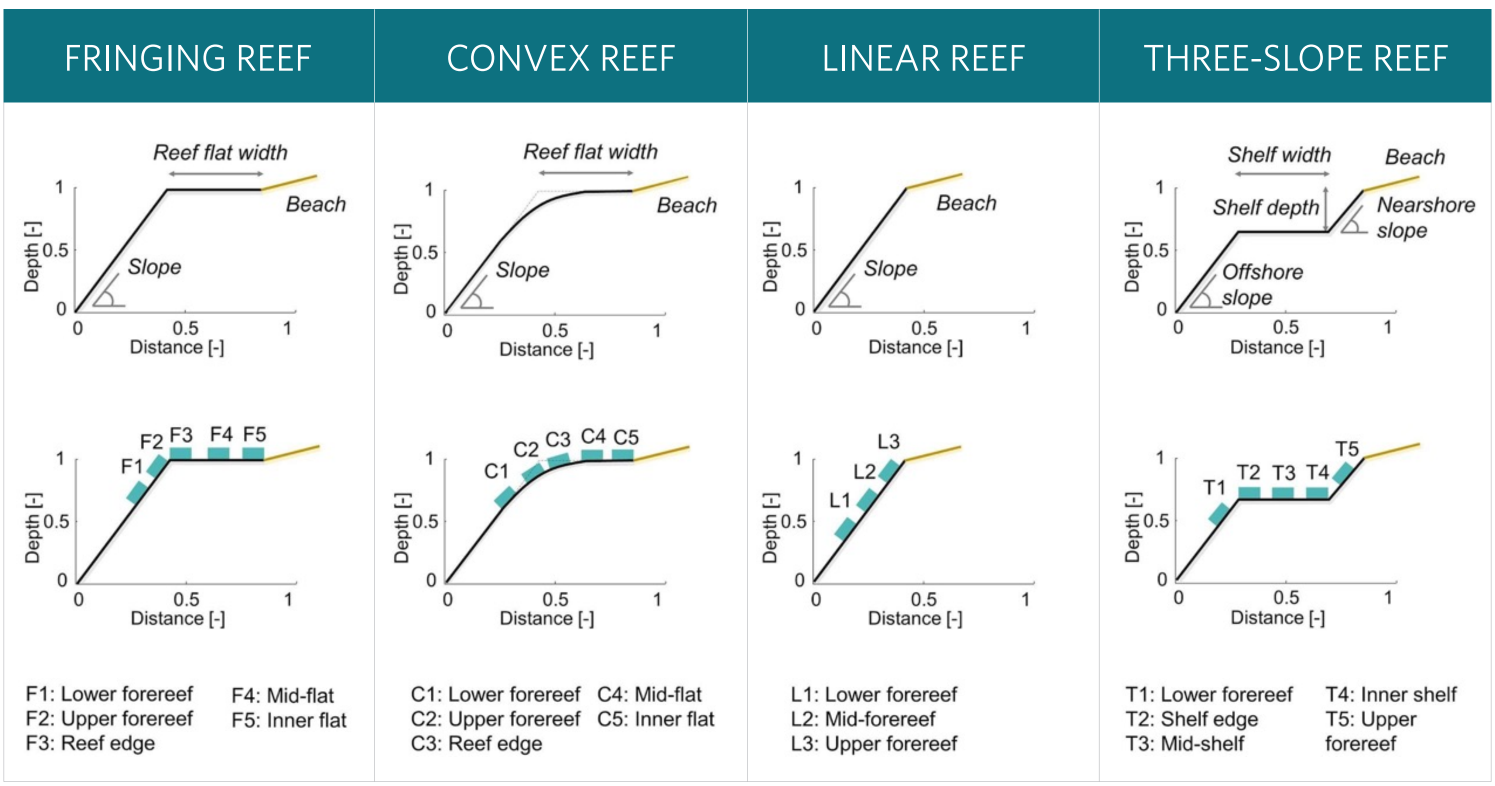
Assessing community support is critical for any hazard mitigation project, especially for coral restoration. Coral reef ecosystems are often intimately linked to cultural identity, community livelihood, and traditional values.

In Hawaiian culture, coral is referred to as the first life created through the Hawaiian creation chant, "Born was the coral polyp, born was the coral, came forth." Communities on Maui depend on and care for reefs as part of their inherent ownership of the island's natural resources. Active restoration interventions can benefit adjacent communities through the creation of jobs, education, stewardship, recreation, and satisfaction[32,33]. Trust is also an essential component of the long-term success of restoration projects because it establishes community expectations and allows for communication between communities and project managers[33]. Project perception and satisfaction by a community are directly tied to the level of their involvement from project ideation through implementation[34].

REEF CONDITION AND PROFILE

The reef condition, or health, affects whether a site can support a CR4 project. Extenuating stressors like land-based sources of pollution, sedimentation, and scouring impact the success of a restoration project by smothering coral outplants, introducing toxins that impact growth, and promoting the overgrowth of competitive algae. The level of reef degradation is important because a more degraded reef allows for the implementation of restoration with less risk to healthy coral colonies. For example, we did not consider a CR4 project at sites with exceptionally high coral cover because both restoration approaches we considered could have a potentially negative impact on a healthy existing reef. We also did not consider sites where coral survivability is low due to intense extenuating stressors like land-based sources of pollution or high human impact.

Furthermore, some reef profiles are more responsive to a CR4 project because reef width, height, and slope influence the extent of coastal flooding due to wave run-up[35]. We can characterize reefs into several major profile types, but for this study we focused on four profile types: fringing, convex, linear, and three-slope. Fringing and convex reef profile types have a wide reef flat that provides natural wave attenuation. As a result, CR4 projects on these profiles would result in few additional benefits to their natural flood reduction characteristics. Restorations placed on fringing or convex reef profiles must be carefully sited (preferably at F1, F2, or C1) to maximize run-up reduction because placement near the current breakpoint (F3 and C2) can increase wave height and exacerbate coastal flooding[35]. Linear and three-slope reef profiles are the most responsive to CR4 projects because they lack natural breakwater capabilities, making adding structure through a restoration project anywhere along these profiles relatively effective in reducing coastal flooding.



Source: Roelvink et al. 2021.[35]

Finally, depth and existing reef habitat also limit the placement of a restoration project. The coastal flooding potential decreases for three-slope and linear reefs as restorations are placed shallower and closer to shore[35]. Restoration projects sited in shallower water have more direct interaction with incoming waves and thus have more influence on friction, slowing wave speed, and reducing wave run-up onshore. There are also operational considerations for selecting the appropriate depth to conduct a restoration project. We want to site a restoration project deep enough to not interfere with local boat traffic but in shallow water where divers can perform restoration without the influence of surge and breaking waves. As a result, we followed similar studies in siting restorations within a depth range of 2 to 7 m[36]. Finally, more risk reduction benefits are realized as restoration project dimensions are increased because the increased surface area of the project better dissipates and reflects incoming wave energy, reducing wave height and onshore flooding[35]. Thus, we focused on sites with 100 m or greater continuous linear reef, allowing us to maximize project dimensions and effectiveness.

All placement considerations described above informed the design of a hypothetical CR4 project, thus determining site-specific benefits and costs for the BCA.

Benefit-Cost Analysis and Benefit-Cost Ratio

FEMA requires that all hazard mitigation projects are cost-effective, as determined by a BCA. A BCA measures a mitigation effort's short- and long-term benefits while accounting for the upfront and ongoing project costs. The result of the BCA is a BCR, which divides the sum of project benefits by the project's costs. A BCR of 1.0 or greater means the project's benefits are greater than its costs, and the project is cost-effective. We outline the benefit-cost methodology used in this study below.

DETERMINATION OF COSTS

A reduction of wave energy and subsequent wave run-up is a function of reef size and complexity of the underlying reef[3]. FEMA prioritizes projects that capture hazard mitigation benefits as early as possible within the project lifetime to provide near-immediate protection to people and properties. Thus, a CR4 project should utilize restoration methods that increase reef size and complexity as quickly as possible.

Restoration Approaches

The most common method utilized for coral restoration projects is a technique called coral gardening. Coral gardening involves collecting, fragmenting, and growing pieces of coral in a nursery in the ocean or tanks on land and then outplanting those fragments back to the reef. With growth rates up to 12cm/year, this technique has proven to be a reliable and effective method for coral restoration, especially for branching corals in the Caribbean and Florida[37]. However, for Hawaiian corals, the very slow growth rate (1-2 cm/year) means that outplanted corals will not provide significant risk reduction benefits immediately after outplanting, and full benefits are not realized for many years (assuming 100% survival it will take 50-100 years for corals to grow 1 m in height). Therefore, we also considered a hybrid reef approach as an alternative restoration method that provides risk reduction benefits sooner in the project implementation timeline. This method involves placing a structure constructed of artificial materials onto or near a reef and attaching nursery-grown coral fragments to the structure. Hybrid reefs are comparable to subtidal submerged breakwaters in that they provide an immediate reduction in wave energy from the artificial structure. At the same time, they also provide ecological co-benefits via the addition of the live coral fragments.

Capital Costs

Capital costs are fixed one-time costs incurred at the start of a project. Because no Maui-specific coral gardening costs are available, we utilized an average cost derived from global coral restoration projects and adjusted it to Hawai'i-cost levels. Coral gardening costs represent the cost to collect, rear, and outplant a coral fragment, including staff time, nursery cleaning and repairs, and materials. We estimated capital costs for the coral gardening approach at $200/m^2 ($811,015/acre) for biological repair efforts conducted by academic or agency organizations.

The hybrid reef approach includes the same coral gardening capital costs as well as capital costs for materials, design, and installation of a submerged breakwater. Industry experts in Hawai'i provided estimates for a submerged breakwater project at $650/m^3 ($801,762/acre-foot). This estimate is based on the typical design of submerged breakwater with a trapezoidal shape made of precast concrete. Coral outplants are assumed to be attached to the concrete in the same manner as the coral gardening method attaches outplants to the reef substrate (typically using marine epoxy, concrete, or nails and zip ties). We estimated the total capital costs for the hybrid reef approach at $400/m^2

($801,762/acre-foot for the structure and $811,015/acre for the corals*).

We also estimated site preparation costs based on the Florida Mission Iconic Reefs project, the largest ecological coral restoration effort in the U.S. to date, for both restoration approaches at a one-time expense of $12/m^2 ($47,578/acre)[38]. This estimate includes activities such as pre-project monitoring and site evaluation, removal of invasive species, relocation of sensitive species, and cleaning of reef substrate. This addition brings the total capital costs to $212/m^2 ($858,593/acre) for the coral gardening approach and $412/m^2 ($1,660,355/acre) for the hybrid reef approach.

We determined site-specific restoration project dimensions to align with the adjacent site on land receiving flood risk reduction benefits from the hypothetical project. The project length was defined by the shoreline length of the site receiving benefits, and the project width was set to 5 m based on the restoration scenarios in Storlazzi et al. (2021)[36]. The average total restoration area for restoration projects at sites throughout Maui was 1,902 m^2 (0.47 acres). The smallest restoration project area was 647 m^2 (0.16 acres) (Maui Sands), and the largest restoration project area was 5,342 m^2 (1.32 acres) (South Kihei). We estimated site-specific project costs by multiplying the per acre capital costs by the area of the proposed restoration project at each site.

For this study, we are assuming 100% survivability of outplants. Since estimated maintenance costs are on the high end for this study, we assume that those costs could help mitigate the loss or death of coral outplants to equal about 100% survivability overall.

Monitoring & Maintenance Costs

Based on the Florida Mission Iconic Reefs, we estimated monitoring costs at $9/m^2/year ($37,216/acre/year) for the first five years and $5/m^2/year ($18,608/acre/year) after that[38]. We based these estimates on an average of two monitoring events per year in the first five years after the project is complete. After five years, monitoring decreases to once per year. Monitoring activities include divers conducting surveys on outplanted coral health, including evidence of bleaching, disease, or coral predators. Maintenance activities include visits to the site once a month for divers to reattach damaged or disconnected corals, remove nuisance species or coral predators, and clean up marine debris. We estimated maintenance costs at $30/m^2/year ($120,096/acre/year) for the first five years. After five years, we expect maintenance interventions to decrease from twelve times per year to two times per year at the cost of $5/m^2/year ($20,016/acre/year). We examine opportunities for further developing and refining CR4 monitoring and maintenance requirements, techniques, and costs below.

Because monitoring and maintenance are ongoing project costs, we have to discount these costs using FEMA's standard discount rate of 7% over the project's life. We then summed the discounted costs to get a present value (PV) of monitoring and maintenance costs. Upfront capital costs varied based on the restoration approach and the size of the restoration project. We then added the standard PV of monitoring and maintenance costs which was the same for both restoration approaches but differed based on the size of the restoration project. This calculation provided the total PV of costs for each site.

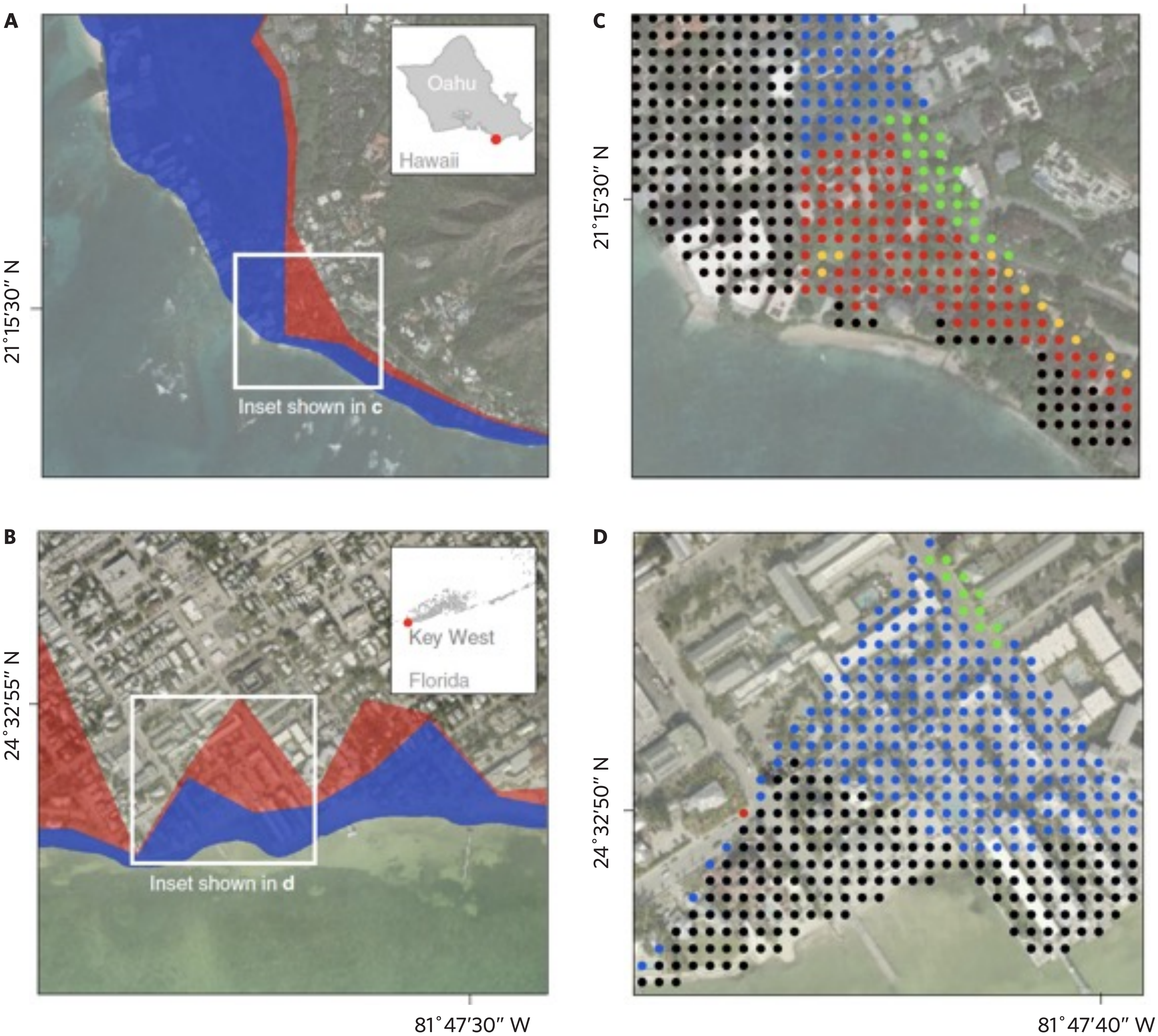
DETERMINATION OF BENEFITS

We calculated the AEB provided by coral reefs by comparing the expected annual losses in each flooding scenario (with and without reefs) from Storlazzi et al. (2019)[4]. To do this, we used FEMA FAST to calculate the damages associated with the 10-, 50-, 100- and 500- year storms in each scenario. Next, the expected losses associated with each event were multiplied by the probability of the event to inform an annual damage amount. The summation of annual damages across all events provides the expected annual losses. The difference between expected annual losses with the reef and expected annual losses without the reef is considered the AEB of the reef. This calculation gives the building-level AEB provided by the top 1 m of coral reefs for the entire Maui region. We estimated site-specific benefits by selecting benefit-recipient sites on land to encompass the AEB values attributable to the site-specific restoration project.

WITH/WITHOUT REEF BENEFITS CALCULATION:

Expected annual losses without reef − Expected annual losses with reef = Potential AEB gained with 1m 'reef' 'added'

* Note: One cubic meter assumes a square meter project of one meter fixed height. Thus, we add the m2 costs to the m3 costs assuming the height of the project is constant and cost only increases with an increase in horizontal area.



Changes in the 100-year flood hazard zones with current coral reefs and with the loss of the top-most 1m of reefs. a, South Oahyu, Hawaii. b, Key West, Florida. The blue regions denote the flooding extebt from a 100-year storm with present coral reefs and the red regions denote the additional flooding extent with 1m of coral reef loss (beyond the blue region) such that the region protected by coral reefs from a 100-year storm is the red band. c, South Oahu, Hawaii. d, Key West, Florida. The black dots denote the grid cells flooding during the 100-yr storm with coral reefs at present. The coloured dots show the damage prevented by coral reefs from a 100-year storm, at 10-m2 scale. The maps were created using ESRI ArcGIS v.10.7.1. The satelite images were sourced from World_Imagery from ESRI with transparency added in ArcGIS.

100-year flood with current reefs

100-year flood with 1-m loss in reefs

Flooded damages

- With current reefs
- With 1-m loss in reefs
- US\$0.01-US\$2,000.00
- US\$2,000.01-US\$5,000.00
- US\$5,000.01-US\$10,000.00
- US\$10,000.01-US\$35,000.00

Source: Reguero et al. 2021.[5]

Ideally, we would estimate benefits from a restoration project based on the specific placement and dimensions of an actual project. For example, Storlazzi et al. (2021)[36] examined the potential flood risk reduction benefits of hypothetical reef restoration projects in Florida and Puerto Rico. Those same hydrodynamic analyses have not yet been conducted in Hawai'i. Thus, in this study, we assumed that the flood protection benefits from adding 1 m of reef (through restoration) are equivalent to the flood protection benefits from avoiding the loss of the top 1 m of existing reefs (through degradation). In reality, a restoration project can never restore an ecosystem to its exact original state, but CR4 projects can be designed to enhance the reef characteristics that reduce coastal hazards.

Coral Growth Rate Adjusted Benefits

Both the coral gardening approach and the hybrid reef approach do not immediately add 1 m in reef height. Thus, the full benefits associated with 1 m of reef height cannot be attributed to either restoration approach on day one of project completion. The benefits of both approaches would increase over time as outplanted coral fragments grow. Based on the average growth rate of corals in Hawai'i, we assumed a linear growth of 1.5 cm of height and associated benefits each year for both restoration approaches. For the coral gardening approach, it was assumed that corals are 1 cm high when first outplanted. For the hybrid reef approach, it was assumed that the artificial structure is 30 cm high, with 1 cm tall coral fragments attached to it. As a result, the hybrid reef approach provides greater day one benefits since the structure's height immediately attenuates more wave energy than solely outplanted coral fragments. Over the project's life, the hybrid approach results in greater net benefits because more benefits can be claimed earlier in the life of a hybrid reef project than a coral gardening project.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A NOTE ABOUT RESTORATION CAPACITY ON MAUI

Currently, there is limited restoration capacity on the island of Maui, however, there are active plans to expand operations and implement pilot studies throughout West Maui.

Total Present Value of Benefits

To compare a CR4 project's benefits to costs over the lifetime of a project, the present value is calculated by adjusting future benefits to equate to present-day values through discounting. The PV is the sum of those discounted values. We calculated the PV of coral-growth-rate-adjusted benefits using FEMA's standard discount rate of 7% over the project's useful life. While the project will likely provide benefits in perpetuity, a conservative 50-year project useful life was chosen because it is standard for FEMA HMA flood mitigation project applications.

Ecosystem Service Benefits

In the FEMA BCA Tool, FEMA provides a list of pre-calculated ecosystem service benefits for applicants to use for nature-based mitigation projects. Currently, pre-calculated benefits are limited to land-type use defined by FEMA as green open space, riparian, wetlands, forests, or marine and estuary. FEMA developed these pre-calculated benefits based on a review of academic literature regarding the economic valuation of four ecosystem service categories: provisioning services, regulating services, supporting services, and cultural services.

Coral reef ecosystem services are not currently included in FEMA's BCA Tool options for pre-calculated benefits. However, FEMA has stated that subapplicants can develop their own ecosystem service values for their hazard mitigation subapplications (although they encourage subapplicants to use pre-calculated benefits where possible). Since FEMA has not published any pre-calculated benefits for coral reefs yet, Earth Economics developed a per-acre per-year value of $6,801 ($1.68 per-m² per-year). This value is based on a selection of studies from the ecosystem services literature, deemed a representative value.

BENEFIT-COST RATIO RESULTS

To obtain the BCR for each study site, we compared the PV of flood risk reduction benefits and ecosystem benefits to the PV of the costs for the coral gardening and hybrid reef restoration approaches.

		Coral Gardening Approach	Hybrid Approach	Earth Economics' Pre-calculated Benefits for Reefs
SITE NAME	RESTORATION AREA (ACRES)	PV OF BENEFITS (AVOIDED FLOOD DAMAGES AND ECOLOGICAL)	PV OF BENEFITS (AVOIDED FLOOD DAMAGES AND ECOLOGICAL)	ECOLOGICAL BENEFIT CONTRIBUTION
Ka'anapali Beach Club	0.34	$5,070,358	$14,418,105	$2,312
North Kihei	0.5	$4,593,867	$13,161,076	$3,401
Lahaina	0.41	$6,953,682	$19,784,033	$2,788
Kahana	1.15	$1,769,435	$4,839,329	$7,821
South Kihei	1.32	$25,124,420	$71,511,972	$8,977
Ka'anapali Ali'i	0.47	$5,078,910	$14,418,299	$3,196
Ka'anapali Marriott	0.46	$18,326,313	$52,256,161	$3,128
Kahana Sunset	0.43	$264,831	$676,231	$2,924
Napili Bay	0.4	$629,796	$1,724,203	$2,720
Kahanaiki Gulch	0.37	$841,266	$2,333,774	$2,516
Kuleana Resort	0.2	$607,369	$1,697,430	$1,360
Maui Sands	0.16	$826,737	$2,331,426	$1,088
Westin Ka'anapali	0.2	$164,481	$432,495	$1,360
Kauaula Stream	0.39	$1,989,423	$5,609,308	$2,652
Olowalu Beach	0.7	$503,642	$1,307,971	$4,761

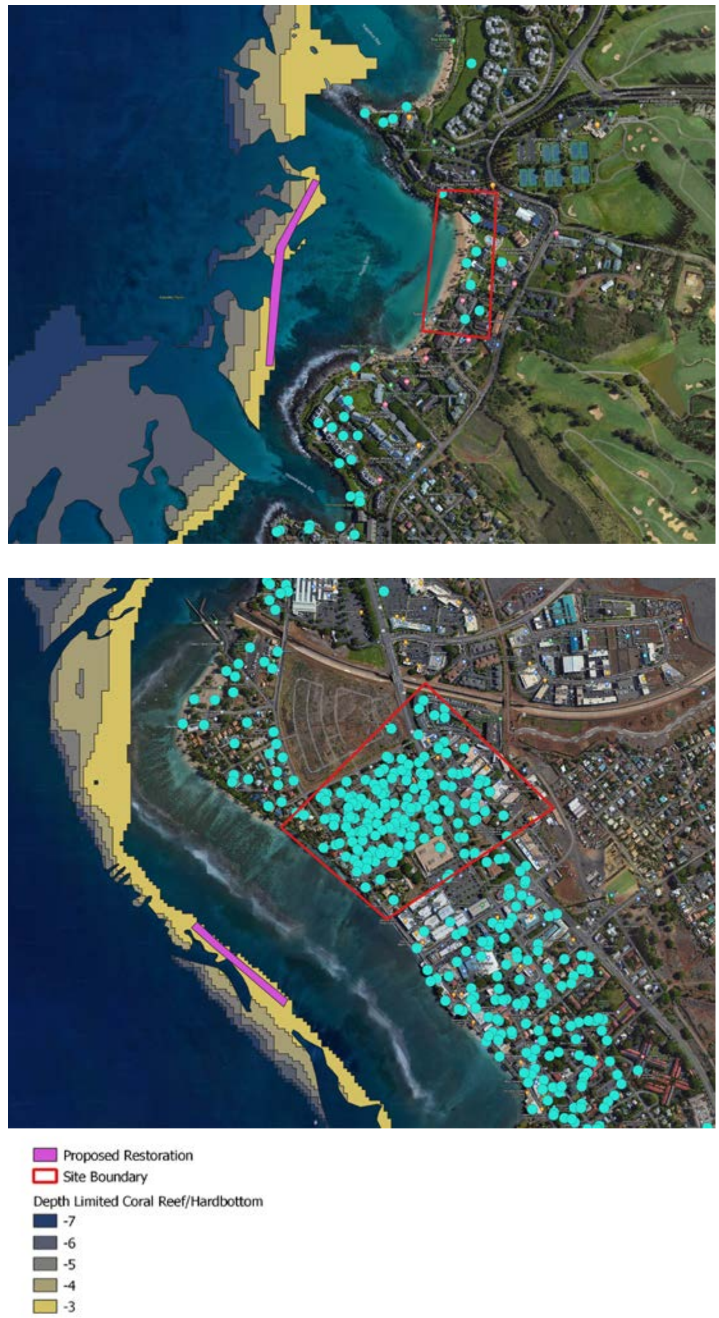
BENEFIT-COST RATIO		
SITE NAME	CORAL GARDENING	HYBRID REEF
Ka'anapali Beach Club	4.69	10.65
North Kihei	2.89	6.61
Lahaina	5.33	12.11
Kahana	0.48	1.06
South Kihei	5.98	13.60
Ka'anapali Ali'i	3.40	7.70
Ka'anapali Marriott	12.52	28.52
Kahana Sunset	0.19	0.39
Napili Bay	0.49	1.08
Kahanaiki Gulch	0.71	1.58
Kuleana Resort	0.95	2.13
Maui Sands	1.62	3.66
Westin Ka'anapali	0.26	0.54
Kauaula Stream	1.60	3.61
Olowalu Beach	0.23	0.47

The BCR is influenced by how much flood protection reefs provide at a site, the value of properties protected, and the restoration approach evaluated. For example, two sites with similar-sized coral gardening restoration projects, Lahaina (0.41 acres) and Napili Bay (0.40 acres), resulted in very different BCRs of 5.33 and 0.45, respectively.

The flood maps from Storlazzi et al. (2019)[4] for the Lahaina site show a significant difference in flood extent with reefs versus without reefs indicating that coral reefs in this area provide a high level of flood protection. In contrast, the flood maps for Napili Bay, a site important to local stakeholders, does not show significant flood protection provided by coral reefs. This is likely because the reef offshore of Napili Bay considered for restoration is not a continuous linear reef, as seen in the benthic layer on the flood maps, and does not provide as much flood protection.

The larger flood zone area protected by reefs in Lahaina translates to higher benefits as more buildings and people are protected. This results in a much higher BCR at Lahaina compared to Napili Bay, despite restoration projects for both sites being of similar size and thus cost.

The exceptionally high BCR at the Ka'anapali Marriott site results from a relatively small restoration project protecting high-value properties on shore.



Key Takeaways and Recommendations

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Coral reef restoration for risk reduction is a cost-effective hazard mitigation strategy.

The results of the preliminary BCA demonstrate that when sited carefully, coral reef restoration can be a cost-effective hazard mitigation strategy (BCR >1.0). Twelve out of the fifteen sites evaluated had a BCR >1.0 for at least one of the restoration approaches. For the seven sites with BCR <1.0 for the coral gardening approach, four demonstrate cost-effectiveness for the hybrid reef approach. It is important to note that a hybrid reef approach may not be acceptable or appropriate for every site and needs to be assessed carefully with input from local communities. The coral gardening approach might be more acceptable in many places, and we demonstrate that such a restoration project can be highly cost-effective even though the full benefits of the project will take longer to accrue. To determine the BCR ratio of a proposed CR4 project and its eligibility for FEMA HMA, project proponents should consider the following: flood protection benefits provided by coral reefs based on the Storlazzi et al. (2019)[4] flood maps, reef condition, reef profile, community buy-in, and proximity to restoration operations.

The benefit-cost ratio is one part of a comprehensive FEMA application.

The BCR is just one component of a rigorous FEMA application. A low BCR will not disqualify a project if the actual FEMA application is thorough, creative, and backed up by the best available science. There are many other factors and benefits that FEMA might consider when deeming a project/site favorable. For our preliminary BCA, we only considered the benefits of avoided flood damages to individual structures provided by coral reefs. However, other avoided losses could be included as benefits in a BCA or qualitative benefits within the application's project narrative. Benefits from additional categories that could be included in a CR4 project BCA are loss of road/bridge service, loss of utility services, loss of non-residential building services, recreational opportunities, displacement costs, loss of rent, debris removal, and disruption of life costs. Inclusion of these benefits will require sufficient documentation from reliable sources.

The scope of work and project narrative are application components that allow the subapplicant to further detail the proposed project's strengths. The scope of work is essential for outlining the project timeline, including detailed cost budgeting and project responsibilities. The project narrative allows the subapplicant to detail qualitative or ancillary benefits not included in the BCA. For example, the BRIC program application can include technical and qualitative criteria to make the best case for the proposed mitigation action. While the technical criteria include more standard requirements like building code rating requirements, the qualitative criteria allow applicants to explain the strengths and thoroughness of the proposed project.

Alignment between hazard mitigation and coral management priorities is critical.

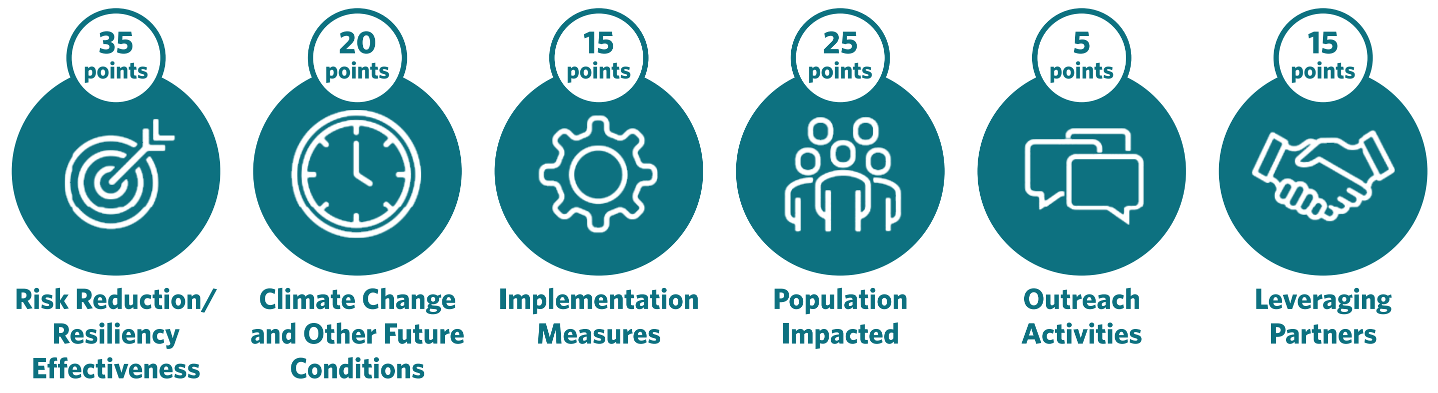
For HMA, alignment with the relevant HMP is a critical requirement that all proposed projects must meet. In general, a specific project type prioritized in the state or local HMP shows that the project has existing support that is more likely to lead to a project's success. For CR4 projects, the coral resource management agency or coral restoration lead will be a key player in developing a project's timeline, planning and supplying coral stock for outplanting, and reviewing and distributing required local permits. Officially established priorities prove that a project has extensive buy-in from multiple government agencies and resource managers. Based on our review of the coral management and HMPs for the coral jurisdictions in FEMA Region IX, the jurisdictions have extensive opportunities to align priorities better. This includes including CR4 projects as priorities in both planning documents and better incorporating the hazard protection value of coral reefs in local HMPs. Further, legislative support for coral reefs as critical natural infrastructure can allow for dedicated funding for CR4-related projects and prioritized protection and restoration of coral reef ecosystems to build community resilience.

Coral restoration operations will need to establish CR4 best practices and techniques.

In the Pacific, coral restoration operations will need to scale up significantly to provide enough coral fragments for outplanting at restoration sites of a large area. At an outplanting density of 3-4 corals/m^2 [39,40], the smallest site examined in this study would require about 2,265 corals (Maui Sands, 647 m^2, 0.16 acres), and the largest site would require 6,657 corals (South Kihei, 1,902 m^2, 1.32 acres). As such, coral restoration facilities should prioritize restoration techniques to scale-up outplant capacity to implement large-scale risk reduction-focused projects. Additionally, continued research and development of faster, cheaper, and more resilient coral restoration techniques have the potential to make CR4 projects even more cost-effective.

For each site, the BCR increases from the coral gardening approach to the hybrid reef approach because we can account for the earlier reception of flood reduction benefits provided by the height of the artificial structure for the hybrid reef approach. While the costs for the hybrid reef approach are almost double the coral gardening costs, the

BRIC NATIONAL COMPETITION QUALITATIVE CRITERIA AND POINT VALUES



greater reception of benefits on day one outweighs the additional costs. This difference makes hybrid reef projects cost-effective when coral gardening projects are not. Still, hybrid reef restoration projects have not been widely implemented or examined to understand the ecological and socioecological associations fully. For this study, we assumed the ecological benefits of the coral gardening and hybrid reef approaches were equal. There is a strong likelihood that the similar growth of corals outplanted directly to the reef versus outplanted onto a structure will result in similar ecological co-benefits. However, a hybrid reef approach could have a negative impact on the surrounding environment. This possibility makes it critical to carefully site hybrid reef restoration projects to ensure minimal negative externalities and maximum risk reduction benefits. Moreso, introducing an artificial structure into the ocean environment is often met with community concern or pushback. Thus, pursuing a hybrid reef restoration approach will need to include substantial community involvement, from planning through implementation.

Finally, there is an opportunity to reexamine the monitoring and maintenance costs and practices associated with CR4 projects. For the BCA, we included monitoring and maintenance costs associated with monitoring and maintenance activities for an ecological coral restoration project. However, the measured outcomes of a CR4 project are often more similar to a submerged breakwater project (i.e., reduction of wave run-up/coastal flooding) than an ecological coral restoration project (i.e., coral survivability or increased genetic diversity). Thus, there is potential to decrease monitoring and maintenance costs to the estimates for submerged breakwater monitoring and maintenance. This shift would require coral restoration permit requirements for CR4 projects to be distinct from ecological coral restoration permit requirements. The cost savings have the potential to be quite significant. For example, industry experts in Hawai'i estimated monitoring costs associated with a standard submerged breakwater at \$3.71/m^2/year (\$15,000/acre/year). This represents a reduction of about \$3/m^2/year (\$12,912/acre/year) compared to ecological coral restoration monitoring average estimates. The maintenance costs for a standard submerged breakwater are estimated at \$1.48/m^2/year (\$6,000/acre/year), an estimated reduction of \$11/m^2/year (\$64,056/acre/year) compared to ecological coral restoration maintenance average costs. The difference in monitoring activities would include less intensive fate-tracking of individual coral outplants and more presence/absence monitoring of groups of outplants intended to provide wave attenuation services. Submerged breakwater monitoring and maintenance costs are likely an

underestimation of the costs associated with an actual CR4 project; however, they indicate the potential for cost savings if better CR4 monitoring and maintenance practices are established.

THE LACK OF RIGOROUS DATA WILL BE A LIMITING FACTOR FOR SEVERAL JURISDICTIONS.

The most widely recognized building valuation data that aligns with the requirements of FEMA FAST are the NSI 1.0 data developed by FEMA and the USACE. Hawai'i's NSI 1.0 database was easily accessible and was completed at a high resolution allowing the calculation of losses to be rigorous enough for FEMA's BCA standards. However, NSI 1.0 data are not reliably available for American Samoa, CNMI, or Guam due to a lack of detailed U.S. census block-level demographic data, which are what NSI 1.0 data are built on. This will likely be a critical limiting factor for developing any future HMA applications involving coral restoration projects designed for flood risk reduction within U.S. small island territories.

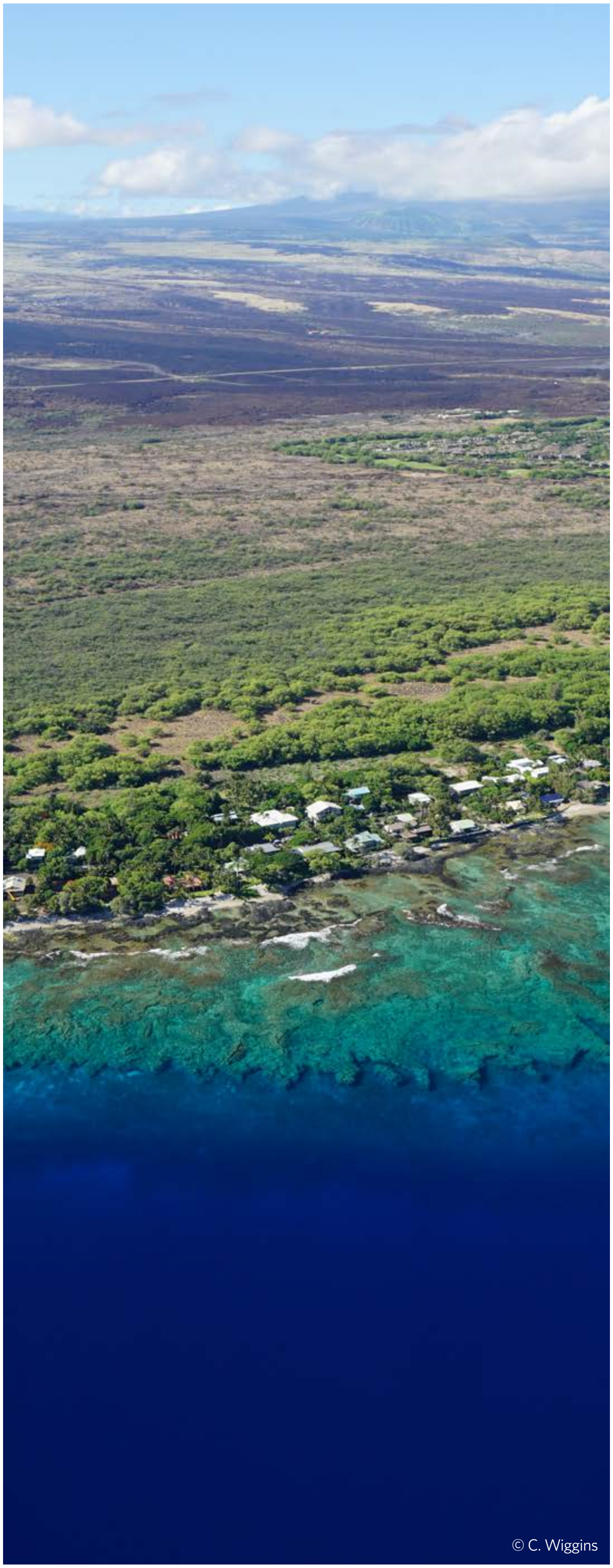
Additionally, hydrodynamic flood maps, like those developed by USGS/UCSC[4,5], will be the most time-consuming element to replicate for future reef and nonreef NBS projects. Developing these maps will also take additional time and money and will likely require outside expertise. For a CR4 project closer to actual implementation, hydrodynamic modeling of coral restoration projects can provide greater specificity about priority restoration sites and resulting benefits. Further, FEMA allows for and encourages the incorporation of sea-level rise in HMA project applications, so flood maps that account for the cumulative flood impacts due to sea-level rise should be considered soon.

UNANTICIPATED PROJECT COSTS MAY LIMIT THE TERM AND SCALE OF FUTURE PROJECTS.

FEMA requires the BCA to include all costs throughout the life of a project. However, an HMA grant from FEMA will not cover all of the costs included in the BCA. For example, monitoring and maintenance costs are included in the BCA to determine a project's cost-effectiveness, but a FEMA award will not cover these costs. FEMA grants cover a 3-year project implementation phase but do not cover additional operational expenses after the project is complete. However, local permits for coral restoration projects often have requirements for monitoring ecological restoration projects for 2-5 years after implementation. Any monitoring and maintenance costs required by local or federal coral restoration permits will be an additional cost burden to the CR4 project applicant.

Significant costs will also be associated with project planning and design that are not covered by an HMA grant. FEMA offers planning and assistance grants to support the project planning and design process because this often increases the likelihood of long-term success for any project.

Finally, mitigation grant programs require a cost-share where at least 25% of any awarded funds are to be paid by the project applicant. This cost will need to be budgeted for well before submitting an HMA application. If appropriate, community-based reef restoration projects involving volunteer divers performing some part of the project implementation could be used for cost-sharing purposes since volunteer or in-kind contributions can be considered as project match. Official prioritization of CR4 projects within local and state coral management plans or HMPs could allow subapplicants to more easily make a case for set-aside funding within state/municipal budgets to support cost-share requirements.



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COMMON TERMS & ACRONYMS	
AEB	Annual Expected Benefit
BCA	Benefit-cost Analysis
BCR	Benefit-cost Ratio
BRIC	Building Resilient Infrastructure and Communities
CTP	Cooperating Technical Partners
CNMI	Commonwealth of the Northern Mariana Islands
CR4	Coral Reef Restoration for Risk Reduction
FAST	Flood Assessment and Structure Tool
FEMA	Federal Emergency Management Agency
FMA	Flood Mitigation Assistance
HIMB	Hawai'i Institute of Marine Biology
HMA	Hazard Mitigation Assistance
HMGP	Hazard Mitigation Grant Program
HMP	Hazard Mitigation Plan
NBS	Nature-based Solution
NGO	Non-governmental Organization
NOAA	National Oceanic and Atmospheric Administration
NSI	National Structure Inventory
PA	Public Assistance
PDM	Pre-disaster Mitigation
PV	Present Value
SHMO	State Hazard Mitigation Office/Officer
TNC	The Nature Conservancy
TNC-CA	The Nature Conservancy of California
UCSC	University of California Santa Cruz
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey

Thank you!

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SUGGESTED CITATION:

A.E. Stovall, M.W. Beck, T. Bieri, A.N. Mann, J. Mojica, R. Schmidt. 2022. Unlocking FEMA's Hazard Mitigation Funding for Coral Reef Restoration: A Feasibility Study in Maui, Hawaii. The Nature Conservancy, Sacramento, CA. scienceforconservation.org