Coastal Habitats
4. Coral Reef Restoration

DEFINITION

Coral reefs are the skeletons of marine invertebrates called *coral*, which form large underwater structures comprised of colonies. Coral reefs are built by hard corals that extract calcium carbonate from the ocean to create an exoskeleton (Ross 2018). Coral polyps, which are individual corals, begin building reefs by attaching themselves to submerged rocks or hard surfaces near the ocean floor (CRA 2018). In most cases, coral reefs are constrained to shallow waters and latitudes between 30° north and south of the equator (NOS n.d.). In the United States, corals are concentrated in the Pacific Islands, the Caribbean, and the Gulf Coast, with a few isolated deep-sea corals off the Pacific and Carolina coasts (Necaise et al. 2022; Oceana n.d.). Coral reefs are sensitive ecosystems facing many threats, including ocean acidification, increases in water temperatures, pollution, and physical damage (EPA 2023). Coral reef restoration strategies include direct transplantation, coral gardening, invasive species removal, micro-fragmentation and building artificial reefs (Boström-Einarsson et al. 2020).

TECHNICAL APPROACH

Because coral grows slowly, innovative techniques are needed to restore coral reefs at a large scale (Dullo 2005). Coral restoration techniques include methods for removing stressors to existing reefs, enhancing the reef structure, and supplementing the coral population. These techniques are often used in conjunction with each other and none of the methods are mutually exclusive.

1. **Removing stressors to existing reefs:**
    - **Predator removal:** Native predators of coral, such as the crown-of-thorns starfish (*Acanthaster planci*) and the burrowing urchin (*Echinometra mathaei*), have proliferated because of the overfishing of their natural predators and increases in nutrient runoff, which aid starfish in their planktonic stages. Excess numbers of these predators have deleterious effects on corals and can wipe out entire colonies (Goldberg and Wilkinson 2004). Removal strategies include physically removing or chemically injecting the animals (KSLOF n.d.).
    - **Algae removal:** Significant algae buildup can occur in coral reefs that are inundated by nutrient pollution. Algae shade coral, transmit pathogens, and release chemicals that block coral growth, all of which degrade coral health. To remove excess algae, introduction of herbivorous fish and physical removal are the most established control methods (Ceccarelli et al. 2018).
    - **Disease management:** Multiple diseases plague coral, most notably black band disease in coral reefs in the Caribbean and the Gulf of Mexico. While research on

controlling coral pathogens is limited, two main treatment options are available: phage therapy and probiotics. Phage therapy uses bacteriophages that prey on coral pathogens while probiotics introduce mutualistic bacteria that compete with the pathogens (Teplitski and Ritchie 2009).

- **Invasive species removal:** Invasive species vary geographically across American coral reefs, with prominent invaders including corallimorphs (*Corallimorpharia*), and lionfish (*Pterois*). Treatments vary from species to species, with innovative approaches like toothpaste application and boiling seawater particularly effective at subduing noxious corallimorphs (Work et al. 2022).

2. **Enhancing reef structure:**

   - **Building artificial reefs (substrate enhancement):** Building artificial reefs adds additional hard substrates to a degraded reef, improving coral habitat and giving coral polyps something to latch onto. Building materials used include eco-friendly concrete, reef balls, construction rubble, and modular hexagonal structures called *spiders*. Artificial reefs help protect corals from harmful fishing practices like bottom trawling (Fadli et al. 2012), because artificial reefs can break nets used in bottom trawling, deterring fishing boats from entering the area (Liu et al. 2011).

3. **Supplementing the coral population:**

   - **Direct transplantation:** *Coral transplantation* refers to the relocation of coral fragments or colonies from a healthier donor reef to a reef experiencing significant stress or degradation (Figure 1; Ferse et al. 2021). Donor reefs are often planned to be destroyed by construction projects and the corals are salvaged to aid other reefs (Boström-Einarsson et al. 2020). Direct transplantation is a controversial restoration strategy because virtually all coral reefs globally are in distress, making it difficult to find donor reefs. Transplantation should be used as a last resort when the reef fails to recruit juvenile corals (Edwards and Clark 1999).

   - **Coral gardening:** Coral gardening involves taking coral recruits and raising them in protected nurseries, which helps increase coral survival rates (Figure 2). Nurseries can either be in the open ocean or closed holding tanks. Once the corals have grown to a size where their survival rates are higher, they are placed at the degraded reef site (Rinkevich 2005)

   - **Microfragmentation:** Microfragmentation involves breaking up corals into tiny pieces, which helps them grow faster. This allows for a greater amount of coral to be available for restoration projects without taking more coral from natural reefs. Microfragmentation must occur in a controlled environment because coral fragments are much more vulnerable to predation (Page et al. 2018). Microfragmentation is often paired with coral gardening (Boström-Einarsson et al. 2020).

Figure 4.1 Transplanted elkhorn coral near Puerto Rico

Photo courtesy NOAA's National Ocean Service

Figure 4.2 A coral nursery growing staghorn coral on a tree structure

Photo courtesy NOAA's National Ocean Service

- **Larval enhancement:** Corals produce millions of offspring, but few corals make it to adulthood (Boström-Einarsson et al. 2020). There are multiple pioneering methods of larval enhancement, including the use of harvested gametes to raise embryo corals in a protected environment and then releasing the corals to degraded sections of a reef (dela Cruz and Harrison 2017).

OPERATIONS AND MAINTENANCE

Invasive species removal using the techniques described previously is often required on an ongoing basis after coral reef restoration. Additional repairs to the restored reef may be needed after severe storms, and the metallic tools and dive equipment used for maintenance must be cleaned. If a coral nursery is used to supply the project with new coral recruits, it must be maintained as well.

FACTORS INFLUENCING SITE SUITABILITY

✓ **Adequate room to accommodate colony expansion:** Once a coral colony becomes established, it should be able to naturally expand over time. Selecting a site with adequate room will help facilitate this process (Johnson et al. 2011).

✓ **Near existing wild populations:** Wild coral populations serve as a proxy for ideal conditions for coral growth. Additionally, wild coral populations can help increase genetic diversity in restored coral colonies (Johnson et al. 2011).

✓ **Ample sunlight:** Corals rely on photosynthetic algae for survival. Sunlight needs to penetrate down to the reef to provide energy for the whole ecosystem (Johnson et al. 2011).

✓ **Hard and stable substrates:** Hard substrates reduce sedimentation (which lowers turbidity and allows sunlight to filter deeper into the water) and competition from other species. Stable substrates give corals a secure surface to latch onto (Johnson et al. 2011).

✓ **Historical presence of coral reefs:** Corals reefs are limited to particular areas due to their specific requirements for water depth, temperature, and pH. Choosing a site where historic coral populations once thrived increases the likelihood that a site will be suitable for coral restoration (Tsang et al. 2020).

✗ **High temperature variability:** Mass coral die-offs are often associated with rapid fluctuations in temperature. Choosing areas with stable year-round water temperatures will reduce the stress on corals.

✗ **High human impacts that won't be reduced as part of the project:** Sites that are frequented by boats, industry, and dredging are not ideal for coral reefs. Most coral restoration projects occur inside marine protected areas (MPAs) or in remote areas (Shaver et al. 2020).

✗ **High levels of coral predation:** Unless coral predators are being removed as a part of the restoration project, it is a waste of resources to restore a coral reef without addressing the cause of its degradation. Predation is one of the key determinants of coral survivorship. Few corals are likely to survive unless predator populations are first reduced (Shaver et al. 2020).

- **High water movement:** Corals thrive in areas where the water is relatively calm. Corals will struggle to establish themselves in areas with strong currents (Johnson et al. 2011).
- **Near areas with excessive pollution discharges:** Nutrient and sediment pollution from terrestrial sources limit coral growth. Limiting the sources of pollution is necessary before engaging in coral restoration.

TOOLS, TRAINING, AND RESOURCES FOR PLANNING AND IMPLEMENTATION

						Resource Includes			
Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Coral Reef Restoration as a Strategy to Improve Ecosystem Services	Guidebook	2021	UN Environment Programme	Global	This guidebook gives a broad overview of coral reef restoration and the situations for which it is applicable. The resource contains recommendations for implementing a project as well as six case studies of successful projects.	✓	—	✓	✓
A Manager's Guide to Coral Reef Restoration, Planning and Design	Guidebook	2020	National Oceanic and Atmospheric Administration	National	This guidebook helps restoration managers choose suitable sites for restoration and develop effective restoration strategies. The authors put an emphasis on matching the applicable restoration strategies with an appropriate site for that strategy.	✓	✓	✓	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Caribbean *Acropora* Restoration Guide: Best Practices for Propagation and Population Enhancement	Guidebook	2011	Nova Southeastern University	Caribbean and Gulf of Mexico	Focused on reefs dominated by *Acropora* corals, this guidebook covers coral gardening and other restoration techniques. A special emphasis is given to increasing genetic diversity within coral colonies.	✓	✓	—	✓
Coral Reef Restoration Toolkit	Guidebook	2018	Nature Seychelles	Designed for Seychelles but most of the information is more broadly applicable	This practical guide explains the nuances of coral reef restoration, providing details about the equipment and resources needed to complete a project. The authors also enumerate successful practices for coral gardening and coral transplantation.	✓	✓	✓	—
Training Guide for Coral Reef Restoration	Guidebook	n.d.	Mesoamerican Reef System Reef Rescue Initiative	Designed for the Caribbean and Gulf of Mexico but most of the information is more broadly applicable	Designed to aid specialists with coral restoration, this guide describes procedures associated with asexual and sexual coral rearing techniques. The authors also weigh the trade-offs of different coral gardening methods and discuss coral fragmentation.	✓	✓	—	—
Hawaii Division of Aquatic Resources Coral Restoration Implementation Guide	Guidebook	2019	Hawai'i Division of Aquatic Resources	Designed for Hawai'i but most of the information is more broadly applicable	This resource focuses on mitigating risks associated with coral transplantation. Topics covered include disease transmission, ecological concerns, and genetic considerations.	✓	✓	—	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Coral Reef Restoration Monitoring Guide	Guidebook	2020	National Oceanic and Atmospheric Administration (NOAA)	National	Monitoring is an integral component of every coral restoration project, making this guide especially valuable to coral restoration project managers. This resource lays out metrics for environmental, ecological, socioeconomic, and coral health.	—	—	✓	—
Coral Reef Restoration: The Rehabilitation of an Ecosystem under Siege	Book chapter	2005	William Precht and Martha Robbart	National	This guide focuses on identifying the agents of coral reef degradation and developing a plan to mitigate these drivers of decline. The authors provide information on identifying signs of reef decline to inform the creation of relevant restoration goals.	✓	✓	✓	—
Coral Reef Restoration for Risk Reduction (CR4): Guide to Project Design and Proposal Development	Guidebook	2022	University of California Santa Cruz	National	Containing information about designing coral reef restoration projects specifically for reducing flood risk, this guide provides the key components needed to make a project successful. The authors outline federal funding available for coral reef restoration projects, including advice about the application process.	✓	✓	—	—

Name and Link	Resource Type	Year	Authors/ Authoring Organization	Geography	Description	Resource Includes: Design/Construction Guidance?	Site Selection?	Monitoring Guidance?	Example Projects?
Handbook on Coral Reef Impacts: Avoidance, Minimization, Compensatory Mitigation, and Restoration	Guidebook	2016	US Coral Reef Task Force	National	This guide encompasses a variety of coral reef damage mitigation strategies, including ways to remediate the impacts of oil spills, dredging, sedimentation, and pollutant-laden stormwater runoff. The guide also contains a comprehensive list of all federal statutes that apply to coral reefs.	✓	✓	✓	—

GRAY INFRASTRUCTURE ALTERNATIVES

Coral reef restoration can be an alternative to gray infrastructure approaches that address coastal flooding and erosion: artificial breakwaters, riprap/revetments, seawalls, bulkheads, and groins. The ability of a coral reef restoration project to replace or supplement one of these gray infrastructure types depends strongly on the project's location and whether it is designed to create the necessary outcomes. Certain environmental conditions may require gray infrastructure rather than coral reef restoration. See the gray infrastructure alternative tables in Section 1 for a comparison of coral reef restoration to these alternatives.

LIKELY BENEFITS AND OUTCOMES

Primary objectives for each strategy are highlighted.

Climate Threat Reduction

- **Storm protection:** As severe storms become more frequent with climate change, coral reefs provide vital protection to coastal communities, preventing billions of dollars in storm damage. During intense storms, shallow coral reefs and those near the coast were found to be the most effective at mitigating storm damage, meaning that these reefs should be prioritized for restoration (Beck et al. 2018).

- **Reduced flooding:** Corals reefs are highly effective at wave attenuation, dissipating wave energy before the water reaches the coast. This reduces coastal flooding because as large waves cross coral reefs, their height rapidly decreases, preventing water from penetrating inland (Roelvink et al. 2021).
- **Sea level rise adaptation and resilience:** Historically, coral reef expansion was limited by sea level, with corals not able penetrate water's surface. Presently, sea level rise has allowed coral reefs to expand vertically. Coral reef growth can keep pace with moderate sea level rise as long the reef remains healthy, providing a bulwark of protection to vulnerable coastal communities (van Woesik et al. 2015). Coral growth may not be able keep up with very rapid sea level rise, which causes coral decline resulting from the lack of sunlight for photosynthetic algae that aid coral survival (Sanborn et al. 2017).
- **Carbon storage and sequestration:** Corals serve as carbon sinks, storing carbon via the process of calcification. Corals build their skeletons with calcium carbonate, which stores carbon for long periods of time. Coral restoration hastens the pace of calcification, enhancing a reef's ability to serve as a carbon sink (Platz et al. 2020).

Social and Economic

- **Recreational opportunities:** Coral reefs are key locations for recreational activities including scuba diving, snorkeling, and kayaking.
- **Tourism:** Tour companies have been the drivers behind coral reef restoration projects in many regions, especially the Caribbean. Because tour companies rely on healthy reefs to continue attracting tourists, they are willing to expend significant capital on coral reef restoration. Furthermore, tour companies can have greater financial resources than government agencies or nongovernmental organizations, which help underwrite the hefty costs of coral reef restoration (Blanco-Pimentel et al. 2022). While the impacts of tourism can degrade coral reefs, sustainability measures can help mitigate these downsides (Cowburn et al. 2018).
- **Reduced erosion:** Coral reefs help reduce shoreline erosion by attenuating waves and protecting and retaining sand for beach nourishment. Intact coral reefs are necessary to stabilize shorelines, with areas of significant reef degradation also experiencing high rates of erosion (Reguero et al. 2018).
- **Property and infrastructure protection:** Because of their ability to shield coastal properties, the coastal protection value of coral reefs is estimated at $9 billion worldwide (van Zanten et al. 2014). This protection is especially valuable in the Caribbean and Pacific Islands, where many industries depend on access to the water and need to be located on a waterfront property.
- **Food security:** Many subsistence fisheries rely on healthy coral reefs, meaning that coral reef restoration can boost local nutrition.
- **Resilient fisheries:** Studies have shown that restored coral plots host increased species richness than degraded plots. Fish colonization of degraded areas occurs rapidly after restoration, meaning fish harvesting can resume soon after a plot has been restored (Opel et al. 2017).

- **Jobs:** Coral reef restoration is a labor and equipment intensive process. Local workers will need to be hired to perform the restoration, stimulating the local economy.
- **Mental health and well-being:** Healthy coral reefs help enhance greenspace for the public to enjoy, improving mental health and psychological wellbeing.
- **Cultural values:** Coral restoration helps improve public knowledge of coral reefs, boosting awareness and connection to the ecosystem.
- **Scientific research:** Because corals are particularly vulnerable as stationary animals, they have developed a repertoire of chemical defenses to protect themselves. Species that reside in coral reefs are a source of medicines for cancer, Alzheimer's, and heart disease (NOS 2023).

Ecological

- **Enhanced biodiversity:** Coral reefs are the most biodiverse marine habitat, hosting 32% of all marine biodiversity despite only covering 0.1% of the ocean's surface area (UNEP n.d.). Despite the steep decline in biodiversity among the world's coral reefs, properly managed coral reef restoration has been shown to slow the loss of biodiversity (Rinkevich 2021).
- **Supports wildlife:** Coral reefs support fish species that spend most of their life cycles in the open ocean, having an outsized impact on marine biodiversity. Coral reefs provide protection for young fish, making them ideal spawning grounds. Fish abundance in restored coral reefs increases exponentially as the site ages, highlighting the effectiveness of coral restoration in fish conservation (Seraphim et al. 2020). More than 83 species of coral are listed as endangered under the Endangered Species Act and many other endangered animals reside in coral reefs as well (Gregg 2021). Coral reef restoration can help reverse this pervasive decline by facilitating the recruitment of endangered corals and restoring the reef structure to provide habitat for endangered animals (Lirman and Schopmeyer 2016).
- **Increased primary productivity:** Coral reefs have high rates of primary productivity because of their efficient nutrient cycling. Coral restoration helps maintain these biogeochemical processes, increasing primary productivity (Davis et al. 2021).
- **Improved water quality:** While coral reefs cannot tolerate poor water quality, corals can improve water quality via filtration. Corals feed on particulate matter, helping remove pollutants from the ocean (UNEP 2020).

BARRIERS AND SOLUTIONS FOR PRACTITIONERS

Common Barriers

Several barriers are common across many of the nature-based solutions strategies; these are described in more detail in Section 1 of the Roadmap. Additional notes about these barriers specific to coral reef restoration are included here.

- **Expense:** Coral reef restoration is one of the most expensive habitats to restore, with restoration costs of up to $2,879,773 per hectare ($1,165,900 per acre) (Bayraktarov et al. 2016). Coral reef restoration requires high upfront investment capital, such as boats and nurseries to host coral gardening. However, the cost of restoration can vary widely depending on the technique used and location of the restoration site.

- **Capacity**
- **Public opinion**
- **Conflict with other land uses:** Many coral reefs have been degraded from bottom trawling, which destroys the structure of the coral reef. Most coral reef restoration sites are in MPAs, which limit or completely ban fishing (Armstrong et al. 2014). While healthy coral reefs can boost fish stocks, many fishermen may be opposed to increased regulations related to coral restoration projects. Coral mining, where coral is harvested for construction materials or as a source of calcium, is also detrimental to reef health. While the total economic value of a reef is far more than the economic gains from coral mining, mining is a vital source of income for many workers in developing areas (Guzmán et al. 2003).
- **Regulation:** There are many statutes, regulations, and policies to be cognizant of when planning a coral reef restoration project. These include the Abandoned Shipwreck Act, the Coastal Barriers Resources Act, the Coral Reef Conservation Act, and the Lacey Act, all at the federal level (EPA 2016). States, territories, and local authorities may have their own additional requirements. It is vital to line up all the necessary permits before construction begins because many grants will only support projects that have been fully approved (Stovall et al. 2022).
- **Lack of effectiveness data**

Community

- **Encroachment on the reef:** Local residents and tourists alike visit coral reefs for their aesthetic value. However, frequent visitation to reefs, especially during the restoration process, can kill corals. Therefore, local communities must be involved in the project planning process to encourage them in aiding the restoration process by temporarily refraining from visiting the reef (Hein et al. 2019).
- **Equitable access to coral reefs:** Many local communities often feel that coral reef restoration projects are meant to attract more tourists and not to help local residents. This sentiment often stems from no-take zones within parks and the high costs of coral restoration. Incorporating local knowledge and goals into the restoration project is vital to increasing compliance with park rules (Cinner et al. 2012).

Ecological

- **Challenges of mimicking natural reefs:** Artificial reefs struggle to mimic the original substrates that support a successful coral reef ecosystem. Because artificial reefs are large structures, substantial quantities of material must be found and transported out to sea to create an artificial reef. To defray these high costs, many projects have used construction rubble or other waste materials as a reef substrate, which often contains toxic materials (Svane and Petersen 2002).

- **Susceptibility to nutrient pollution:** Nutrient pollution reduces both calcification and production rates of coral reefs, reversing coral growth. Nutrient pollution reduces the metabolism of corals and alters the pH of reef waters, meaning that terrestrial fertilizer runoff must be reduced before a reef can achieve full health (Silbiger et al. 2018).
- **Ocean acidification:** Ocean acidification is caused by anthropogenic CO_2 emissions. About 25% of CO_2 emissions are absorbed by the ocean, where the excess CO_2 becomes carbonic acid. Through a chain of chemical reactions, the surplus carbonic acid creates more bicarbonate, which diminishes the amount of carbon that is available to corals, reducing calcification (Hoegh-Guldberg et al. 2007). In other words, as long as humans emit large quantities of CO_2, coral reefs will be at risk.

EXAMPLE PROJECTS

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
Palmyra Atoll and Kingman Reef Coral Restoration Project	Palmyra Atoll and Kingman Reef National Wildlife Refuges, HI	**US Fish and Wildlife Service (USFWS)**, The Nature Conservancy, NOAA, US Environmental Protection Agency, US Coast Guard	Invasive species removal, shipwreck removal, coral transplantation	1	5.5 million	One month for debris removal, but ongoing invasive species treatment	The iron from shipwrecks fueled the growth of invasive species in the coral reef, particularly corallimorphs and algae. USFWS and partners removed the shipwrecks and invasive species, and transplanted corals to help the reef regenerate.	No	Corallimorph control must be incorporated into long-term management strategies, as treatment occurred for many years after the initial shipwreck removal.
Eastern Dry Rocks Coral Reef Restoration Project	Florida Keys National Marine Sanctuary, FL	NOAA, National Fish and Wildlife Foundation, Coral Restoration Foundation, Mote Marine Laboratory & Aquarium	Invasive species and debris removal, coral outplanting	69	5 million	Still ongoing—started in 2021	The project removed invasive species and other debris at the site. Then, divers planted more than 60,000 corals, mostly staghorn and elkhorn corals.	Sea level rise, increased storm severity, coastal flooding	NA
Carysfort Reef Restoration Project	Key Largo, FL	NOAA, Ocean Reef Club, Coral Restoration Foundation	Coral outplanting	31	4 million	5 years	Carysfort Reef was once one of the most vibrant reefs in the Florida Keys but succumbed to disease. Coral outplanting occurred on artificial reef structures.	Sea level rise, increased storm severity, coastal flooding	Artificial reef barriers and buoys are important to deter ships from entering the restoration site.

Name and Link	Location	Leading Organizations	Techniques Used	Size, acres	Cost, $	Duration	Project Description	Climate Threats Targeted	Lessons Learned or Adaptive Management
T/V MARGARA Ship Grounding Site	Bahia de Talloboa, PR	NOAA, Puerto Rico Department of Natural and Environmental Resources	Coral outplanting, reattaching loose corals, stabilizing corals	2	4.5 million	5 years	Coral outplanting occurred in the affected area, with corals supported by masonry nails, cable ties and epoxy. Corals that survived the incident were stabilized with stakes or wire cages.	No	Rubble needs to be completely cleared before the mortality rates of coral recruits will decrease.
Columbus Iselin Coral Reef Restoration Project	Florida Keys National Marine Sanctuary, FL	NOAA	Shipwreck removal, substrate remediation, artificial reef made with rebar and limestone boulders, coral outplanting	1	3.75 million	6 weeks	Debris, rubble, and damaged coral were removed from the site. Then, coral outplantings were placed on a new substrate of rebar and limestone boulders.	Increased storm severity	Coral restoration must occur all at once, as partially completed restoration projects are vulnerable to further degradation from hurricanes.

Bolding indicates DOI affiliates.

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