Received: 29 August 2022 | Revised: 13 March 2023 | Accepted: 17 March 2023

DOI: 10.1002/ecs2.4517

SYNTHESIS & INTEGRATION

Coastal and Marine Ecology

ECOSPHERE
AN ESA OPEN ACCESS JOURNAL

Coral restoration for coastal resilience: Integrating ecology, hydrodynamics, and engineering at multiple scales

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Funding information
NOAA Coral Reef Conservation Program, Grant/Award Number: 31237

Handling Editor: Debra P. C. Peters

Abstract

The loss of functional and accreting coral reefs reduces coastal protection and resilience for tropical coastlines. Coral restoration has potential for recovering healthy reefs that can mitigate risks from coastal hazards and increase sustainability. However, scaling up restoration to the large extent needed for coastal protection requires integrated application of principles from coastal engineering, hydrodynamics, and ecology across multiple spatial scales, as well as filling missing knowledge gaps across disciplines. This synthesis aims to identify how scientific understanding of multidisciplinary processes at interconnected scales can advance coral reef restoration. The work is placed within the context of a decision support framework to evaluate the design and effectiveness of coral restoration for coastal resilience. Successfully linking multidisciplinary science with restoration practice will ensure that future large-scale coral reef restorations maximize protection for at-risk coastal communities.

KEYWORDS
coastal protection, coral reef, engineering, hydrodynamics, restoration

INTRODUCTION

Increasing coastal hazards and protective role of coastal habitats

Coastal hazards are increasing significantly worldwide due to climate change (Marsooli et al., 2019). Climate-related threats, including sea-level rise (Church et al., 2013), a more powerful global wave climate (Reguero, Losada, et al., 2019), and increased hurricane intensity (Knutson et al., 2010), are increasing the frequency and magnitude of disasters in coastal communities (Hallegatte et al., 2013; Reguero et al., 2015). As coastal zones continue to increase in assets, infrastructure (e.g., cities, ports, and airports), value, and human populations, so does the risk to life and property caused by flooding and storm damage (Peduzzi et al., 2012; Woodruff et al., 2013). Coastal hazards and the associated risks are accentuated by loss of natural coastal habitats, many of which are being restored to help maintain critical ecological functions. Resilience of coastal socioecological systems in a changing climate will depend in part on the advancement of restoration science and practice. Here we examine the advances necessary in coral reef restoration to enhance the resilience of tropical latitude coastlines.

Coastal habitats, including salt marshes, mangroves, oyster reefs, vegetated dunes, seagrasses, and coral reefs, provide protection from coastal flooding during storms and inundation due to sea-level rise (Spalding, McIvor, et al., 2014). The economic value of storm protection provided by natural coastal habitats is substantial (Costanza et al., 2008; Narayan et al., 2017); however, the degradation of coastal habitats continues (Beck et al., 2011; Lotze et al., 2006). Although vulnerability to coastal hazards and the importance of habitats for protection vary geographically, it is estimated that the complete loss of these habitats would increase the economic risk to imperiled human life and property by 67% in the United States (Arkema et al., 2013). Preserving and restoring natural habitats is necessary so that they continue to deliver ecosystem services to coastal communities.

Coral reefs serve as natural, highly efficient submerged breakwaters that reduce wave energy reaching shorelines (Ferrario et al., 2014; Monismith, 2007), where most storm-related damage occurs. This service provides important flood protection to coral reef-lined coastlines: coral reefs avert flood losses valued at US $1.8 billion per year in property damages along 3100 km of the US shorelines with coral reefs (Reguero et al., 2021); whereas, globally, the annual global economic cost of coastal flooding could increase by 91% to US $272 billion (Beck et al., 2018). Approximately 325 km of reefs in the United States provide annual flood protection benefits valued at over US $1 million per kilometer (Reguero et al., 2021), which indicates that maintaining this service through active management and restoration could be a cost-effective strategy.

Coastal protection provided by coral reefs is progressively more at risk as reefs are degraded or destroyed by global and local stressors (Burke et al., 2011; Hughes et al., 2018). Declines in living coral and reef structure reduce reef elevation and hydrodynamic roughness, which reduce reef capacity to attenuate waves and wave-driven water levels. The interplay of coral reef degradation and coastal hydrodynamic and geologic processes results in a negative feedback loop: coral reef degradation increases the negative impacts of coastal hydrodynamics (Harris et al., 2018; Quataert et al., 2015; Sheppard et al., 2005), which in turn increases the risk of coastal flooding and erosion (Beck et al., 2018; Osorio-Cano et al., 2019), which again enhances the local degradation of coral reefs (Storlazzi et al., 2011). Declines in reef structural complexity can also increase the potential for sediment transport away from beaches (Sheppard et al., 2005), further reducing coastal protection. All of these mechanisms reduce the capacity of reefs to protect coastlines against wave impacts and flooding, which will add to the existing hazards and rising threats of climate change that coastal communities face.

Nature-based coastal defense

The increasing threats in coastal zones from sea-level rise, storm surge, and storm-induced waves are galvanizing governments to undertake large investments to adapt and reduce risks. The majority of these hazard mitigation and adaptation funds are used to create man-made, "gray" infrastructure (McCreless & Beck, 2016), which can provide wave attenuation upon implementation. However, as structures degrade over time, services are lost without costly maintenance or replacement. The structures also do not self-adapt and are increasingly challenged by rising sea levels (Sutton-Grier et al., 2015). Conventional engineering approaches can also have adverse effects, including further loss of important coastal habitats (Rangel-Buitrago et al., 2018), as in the case of sea walls and embankments that replace biogenic habitat and often enhance erosion (Jones et al., 2012). Management strategies that rely on conventional gray engineering require costly initial investment and maintenance over time (a major challenge in developing regions) and have finite life spans, becoming unsustainable as climate risk increases (Temmerman et al., 2013).

Coastal ecosystems can contribute effectively to coastal protection (Narayan et al., 2016; Spalding, Ruffo, et al., 2014). Management approaches now seek to build coastal resilience, defined as "the capacity of the socioeconomic and natural systems in the coastal environment to cope with disturbances, induced by factors such as sea-level rise, extreme events and human impacts, by adapting whilst maintaining their essential functions" (Masselink & Lazarus, 2019), using nature-based solutions (NBS) to adapt to climate change impacts (Bridges et al., 2021; FEMA, 2021; Hobbie & Grimm, 2020; Seddon, 2022). NBS incorporate natural habitats, often termed "green" infrastructure, and can be a sustainable and cost-effective approach to contribute to coastal protection, either as a fully green approach or hybridized with gray infrastructure (i.e., "gray-green," "hybrid"; Jones et al., 2012). NBS for coastal resilience have been implemented in coastal habitats, including salt marshes, oyster reefs, and mangroves (Spalding, Ruffo, et al., 2014; Sutton-Grier et al., 2018; Temmerman et al., 2023).

Restoration of degraded coral reefs is increasingly proposed as a strategy to provide coastal protection. To date, however, few projects have implemented coral reef restoration specifically for wave attenuation (but see Brathwaite et al., 2022; Reguero, Beck, Agostini, et al., 2018). Many questions remain about how to design, engineer, and plan coral reef restoration to provide tangible and effective coastal protection in the face of global climate-change-induced stressors, such as sea-level rise and increased wave activity. Achieving such protection requires scaling up reef restoration and aligning environmental benefits with engineering goals by fully considering hydrodynamics and ecological sustainability along rapidly changing coastlines.

Most efforts to plant corals or seed coral recruits have focused on ecological rehabilitations to promote population enhancement of native species or aspects of ecosystem functioning, such as habitat quality and reef aesthetics, to support tourism and fisheries (Bayraktarov et al., 2019). Restorations that strive for partial or holistic native ecosystem recovery of functioning and self-sustaining coral reefs would likely be more effective in the long term (Vardi et al., 2021). Successful ecological restorations demonstrate self-organization, are resilient to disturbances, and are able to recover from perturbations (Gann et al., 2019). For long-term sustainability, restored reefs must be resilient to disturbances and able to recover unaided from even major perturbations (Spalding, Ruffo, et al., 2014). These goals present considerable planning, design, implementation, and evaluation challenges; currently, there is no standardized approach.

Here we provide an interdisciplinary synthesis of the ecological, hydrodynamic, and engineering principles to be considered for coral reef restoration for coastal protection. Within this context, we utilize a coastal engineering framework that incorporates relevant spatial and temporal scales for coral restoration and is focused on coastal protection. To protect vulnerable coastlines in a rapidly changing climate, an interdisciplinary approach to coral reef restoration is needed to leverage existing knowledge as well as identify and fill key knowledge gaps.

CORAL RESTORATION FOR COASTAL PROTECTION

Implementation of coral reef restorations that successfully contribute to coastal protection over long time periods would benefit from a quantitative approach to restoration design and assessment. Coastal engineering projects commonly use a decision support framework that consists of sequential stages including (1) inception, (2) design analysis and strategy, (3) implementation, and (4) evaluation (Figure 1; Bridges et al., 2021; McDonald et al., 2016; Whelchel & Beck, 2016), and this framework is beginning to be applied to coral restoration design (National Academies of Sciences, Engineering, & Medicine, 2019; Shaver et al., 2020). In this framework, each successive stage is reliant on the development of previous stages, and multiple evaluation steps and feedback loops allow for dynamic adjustment. Here, the project inception includes the goal of coral restoration for coastal protection, and success criteria are measured by (1) the effectiveness in reducing wave energy and

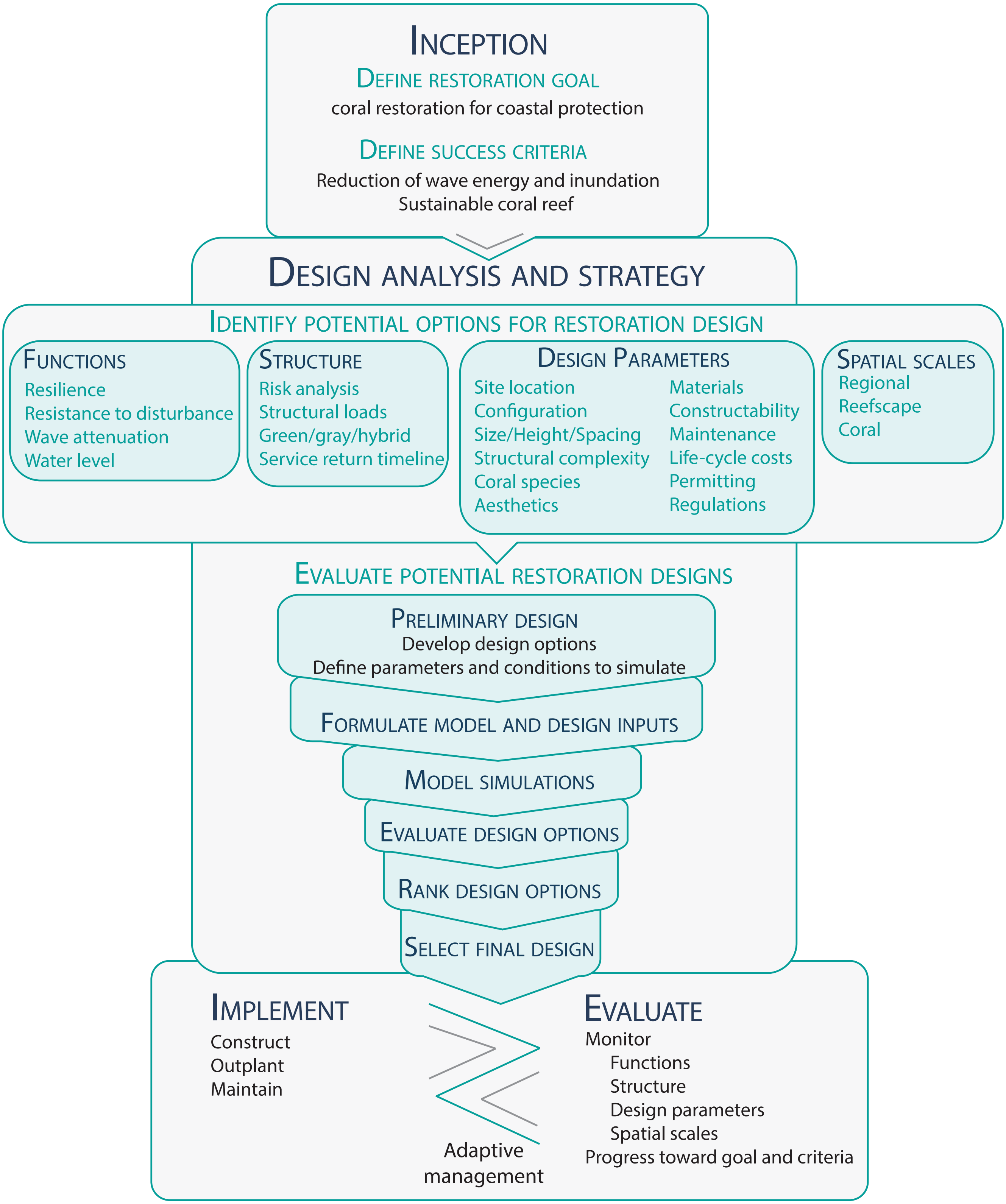

FIGURE 1 Decision support flowchart for implementing coral restoration with the goal of coastal protection (modified from National Academies of Sciences, Engineering, & Medicine, 2019; Whelchel & Beck, 2016). In the design analysis and strategy stage, a range of potential options for inclusion in restoration design are identified. Potential design options are then quantitatively modeled at multiple spatial and temporal scales to inform the ranking of options and selection of the final restoration design. The implemented restoration is evaluated to quantify progress toward meeting the project success criteria identified early in the design process: reduction of wave energy and inundation, and sustainable coral reef. Monitoring data can be used to evaluate recovery, inform adaptive management for implementation, and post hoc test model designs, including the implemented design.

inundation onshore and (2) the sustainability, resilience, and resistance to disturbance of the restoration project as a fully functioning coral reef (Figure 1).

Restoration design analyses and strategy

In the restoration design analyses and strategy phase of project planning, potential design options that relate to the intended functions and structure are first identified and then evaluated to inform selection of the final design (Figure 1). As potential restoration projects scale up in spatial scale, temporal scale, and cost (such as the large-scale, long-term restorations needed for functioning, sustainable coral reefs to provide coastal protection), a priori quantitative evaluations of design options are particularly important to rank potential options in terms of forecasted performance. Evaluating potential project designs should include the intended functions, structures, and design parameters at multiple spatial scales. Functional metrics address the provision of reef services, which for the specific goal and success criteria (Figure 1) include both ecological and hydrodynamic (e.g., wave attenuation) services. Structural design options address the engineering of the restoration and can include gray, green, and hybrid approaches, how these relate to risk analyses, and structural sustainability, such as ensuring structural integrity in the face of ongoing stressors and extreme events. Design parameters can relate to ecology and hydrodynamics (e.g., restoration siting, reef, and coral outplanting options) as well as engineering (e.g., restoration materials, constructability, life-cycle costs, and availability of construction and maintenance materials for both corals and other materials, aesthetics, and regulatory requirements). Potential designs should be quantitatively evaluated for their likelihood to meet the restoration project goals and functions over time. Design evaluations include model analyses and simulations at multiple spatial and temporal scales and lead to the selection of the final design for implementation (Figure 1).

Implementation and evaluation

The restoration implementation and evaluation stages are closely linked (Figure 1). The implementation stage of coral restoration for coastal protection consists of two components: (1) construction and outplanting, which includes addition of corals (green) and, if applicable, engineered structure (gray), and (2) maintenance. Implementation may be repeated through the course of the project to add additional corals or structure as needed, depending on the evaluation of progress toward meeting restoration goals and need for adaptive management actions.

Evaluation of restoration progress toward meeting the design goals is critical (Bostrom-Einarsson et al., 2020; Gann et al., 2019), particularly for large, long-term projects such as those needed for effective coral restoration for coastal protection and including ecological resilience and sustainability. Restoration in general can result in many different outcomes, and for coral reefs, outcomes can span a range from no recovery where corals and reef structure continue to decline, to coral recovery specific to individual species, and full recovery of the coral reef community and biogenic reef structure. Given this broad spectrum of potential outcomes, evaluations of restoration performance should be used to inform the need for adaptive management for implementation (McDonald et al., 2016; Suding, 2011). Empirical data from monitoring changes through time from baseline conditions in restoration sites relative to reference sites are critical (Goergen et al., 2020; McDonald et al., 2016). Monitoring data can also be used to test and validate quantitative modeling from the design analysis and strategy stage and to determine whether current and forecasted progress toward returning services is on track. These comparisons of actual performance to designed performance can be used to inform potential adaptive management of the restoration design. For example, if restored corals from a given species do not survive or grow, the design may need to be re-evaluated to include different coral species.

Scales for design and evaluation

Healthy coral reefs are complex, diverse ecosystems in which key processes are interdependent and occur at multiple spatial and temporal scales. Ecological and oceanographic processes are scale-dependent (Levin, 1992; Stommel, 1963), and reef restoration is inherently multiscale. Restoration design and evaluation can be assessed at two temporal scales (Figure 2). Temporal scales that are important for coral restoration include (1) the timeline for restoring services and (2) the longevity of services (Figure 2). The timeline for restoring services is the length of time needed to achieve the restoration objectives and success criteria. Restoration design (e.g., details from gray, green, or hybrid approaches) directly influences the timeline for returning services and the restoration longevity, and these forecast projections should be included in design analyses (Figures 1 and 2). After implementation, the progress over time toward providing services to the designed level is measured in restoration evaluation (Figures 1 and 2).

Coral restoration also spans three intrinsic spatial scales, with interactions between coastal hydrodynamics, ecology, and related processes occurring at regional,

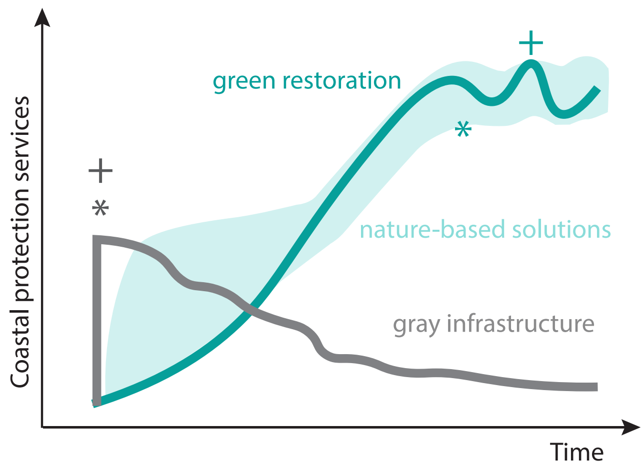

FIGURE 2 Schematic illustration of temporal return of services for risk reduction for engineered reef restoration (gray line), ecological reef restoration (dark green line), and a hybrid nature-based approach (light green line). Plus symbols (+) illustrate maximum levels of services provided. Star symbols (*) illustrate inflection points when services decline. The slope of the lines and locations of inflection points are not to scale and vary depending on the specific coral reef restoration context. Services are provided by engineered structure immediately but decline over time as the structure degrades. Risk reduction services provided by ecological reef restoration take time to develop and fluctuate in response to stressors and disturbances. Nature-based structures may provide services available more immediately (from the engineered structure) that develop over time (from the ecological restoration).

reefscape, and colony spatial scales (Figures 1 and 3). At each spatial scale, the success of the restoration will therefore be conditioned by the interdependency and decisions made at other scales. For example, the selection of the site for a coral reef restoration may be based on regional scale factors, such as potential for coastal risk reduction, and the selection of coral species used in a restoration may be based on reefscape scale factors, such as habitat zonation. Below, we describe how relevant hydrodynamic and ecological processes can be incorporated into the design and evaluation of coral restoration for coastal protection at each spatial scale.

Regional scale (10–100 km)

Overview

At the regional spatial scale, planning for habitat restoration for coastal resilience can incorporate an assessment of current and potential ecosystem functioning that includes (1) risk to coastal communities and (2) potential for protection from flooding and erosion (Figure 3). Risk assessments include information on the hazards and the vulnerability of the exposed infrastructure and social demographics, including vulnerable populations (Kron, 2013). These can be combined with forecasts of how habitat restoration may reduce risk over time as services are returned. Spatial planning for risk reduction integrates ecological data, physics-based models of coastal flooding under past, current, and future climate scenarios, and models of hazards and risk (Reguero, Secaira, et al., 2019; Ruckelshaus et al., 2020; Storlazzi et al., 2019). Social metrics of coastal infrastructure valuation, restoration cost–benefit comparisons, and vulnerable human populations are also included (Reguero, Beck, Bresch, et al., 2018). Risk assessments inform restoration design through evaluation of the applicability of restoration to contribute to coastal protection and effectiveness of potential designs (e.g., Storlazzi et al., 2021). Metrics used in risk assessments can also be used to evaluate the progress that a restoration is making toward meeting restoration goals.

Fluid dynamics

Assessing risk and the potential for coastal protection requires environmental data on bathymetry, wave conditions, and sea levels. In restoration design, these can be evaluated first at the regional scale. In reef environments, periodic and episodic variation in water levels in reefs and shorelines due to astronomical tides, wind setup, and other influences are also relevant (Figure 3; Firing & Merrifield, 2004). Restoration can reduce risk from wave-driven flooding more when implemented in shallower, more energetic locations than in deeper reef habitats (Roelvink et al., 2021). Furthermore, the restoration design needs to encompass not only the normal range of conditions (i.e., expected loads) but also extreme events (e.g., large wave heights that can damage the project). Therefore, the expected intensities and frequency of extreme events (e.g., cyclones, waves, and heat) within a region will affect the expected longevity of services derived from restoration and therefore need to be factored into the design and evaluation (Figures 2 and 3). Hindcast and forecast models can be used to estimate normal and extreme conditions in a region (Callaghan et al., 2020; Reguero et al., 2012).

Habitats

Regional assessments also include the physical, chemical, and biological properties of water that moves across reefs (e.g., flow, temperature, nutrient concentrations, turbidity, plankton, and pollution) and are limiting environmental constraints for coral reefs (Figure 3). These water properties are influenced by coastal current circulation, driven by large-scale water level gradients, density gradients, and winds that control exchange between the reef and open ocean (Lowe et al., 2012). Poor land-use practices and coastal development can drive watershed runoff

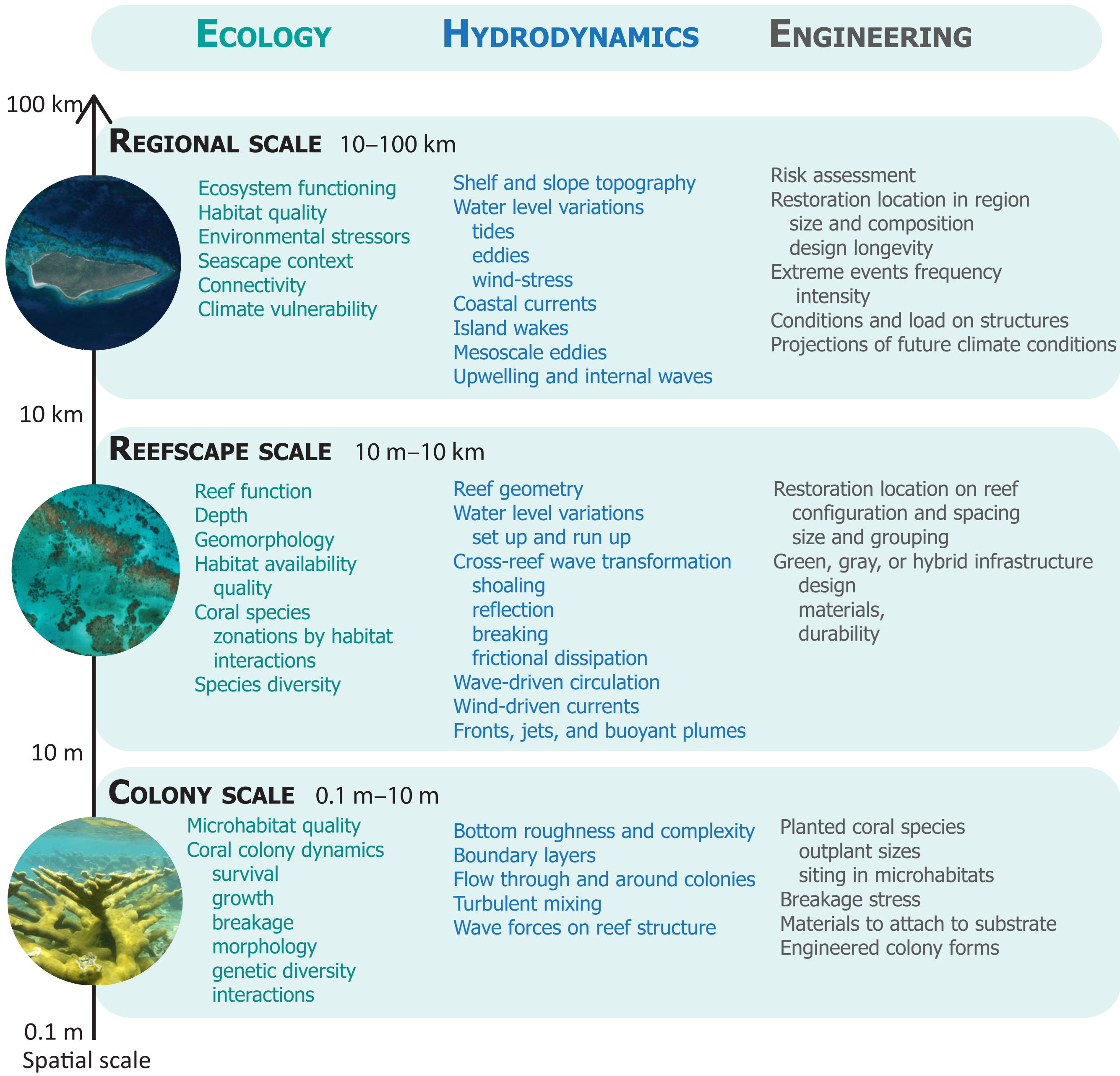

FIGURE 3 Description of key ecological, and hydrodynamic processes and criteria for coral restoration for coastal protection at multiple spatial scales (i.e., regional, reefscape, and colony-scale). Image credits: (regional) CNES/Airbus DS, Maxar Technologies, USGS, (reefscape) UAS imagery from the Oregon State University in collaboration with NOAA and the National Park Service; (colony) NOAA.

and high nutrient and sediment levels (Koop et al., 2001; Sakamaki et al., 2022) that damage reefs and limit potential restoration habitat (Jones et al., 2016). Local causes and consequences of historic and current reef degradation should be identified and remediated prior to restoration (Spalding, Ruffo, et al., 2014), for implementation of restoration in unsuitable habitat has a high risk of failure (Gann et al., 2019).

The seascape structure and function of habitats and geomorphological features within a region are additional considerations for restoration (Figure 3; Gann et al., 2019; Gilby et al., 2018; Spalding, McIvor, et al., 2014). Coral reefs have the potential to work together with mangroves and seagrass beds to provide positive reciprocal interactions for wave attenuation (Gillis et al., 2014). In addition, coral reefs and coastal dune habitats work together to provide coastal protection for many reef-lined coasts (Reguero, Secaira, et al., 2019), and coral reefs can mitigate beach coastal erosion (Escudero et al., 2021). Although these seascape interactions affect the potential for reef restoration to contribute to coastal protection and adapt to changing climate conditions, there are as yet few examples of their application.

Species

Sustainable, resilient coral reef restoration is facilitated by the potential of a restoration site for ecological connectivity at a regional scale with adjacent coral populations as well as the retention of locally produced larvae at the restoration site (Frys et al., 2020). These are both facilitated by regional circulation patterns and the spatial orientation of a reef (Holstein et al., 2014; Leichter et al., 2013). Recruitment is a primary driver of coral reef recovery from disturbance (Holbrook et al., 2018), and connectivity is an important input into selection of restoration sites and species composition of coral outplants (Figure 3; King et al., 2023). Some potential restoration sites may be more likely to consistently attract and retain larvae (or sustain local coral species that have short pelagic durations) than other sites, increasing the probability of self-sustaining coral populations. Influx of new corals via regional connectivity between restored reefs and populations of climate-resilient coral populations will be critical for the long-term viability of reef restoration, especially given the additional stressors of climate change conditions that can lead to increased coral mortality. Furthermore, the degree of resilience and longevity exhibited by a restored coral reef will directly affect the magnitude and frequency of needs for additional coral restoration implementation over time at a restoration site (Figures 1 and 2).

Climate change

Finally, regional-scale restoration planning and evaluation also need to incorporate regional projections of future climate conditions (Figure 3; Gann et al., 2019; Suding et al., 2015). Sea-level rise will exacerbate the flood vulnerability of low-lying tropical coastlines, and if reef accretion cannot keep up with sea-level rise, larger waves will be able to pass over the reef and increase coastal flooding (Storlazzi et al., 2011; Storlazzi, Gingerich, et al., 2018) and erosion (Grady et al., 2013). Severe loss of coral cover has already compromised the carbonate budgets of coral reefs, and many reefs are bioeroding rather than accreting (Morris et al., 2022; Perry et al., 2013). Future ocean acidification and reduced aragonite saturation state conditions may compromise the calcification of living coral (Pandolfi et al., 2011), and the expectation of reef accretion through restoration may not be realistic everywhere (Toth et al., 2022; Webb et al., 2023). Restorations may therefore require gray or hybrid elements to provide wave attenuation (e.g., engineered structures) to meet restoration goals in the timeframe needed (Figure 2). Alternatively, reefs may change in their taxonomic and therefore morphological characteristics in response to acidification (van Woesik & Jordán-Garza, 2011). Coral "winners" are often predicted to be mounding corals that grow relatively slowly but also provide structure that is most resistant to wave energy (Hench & Rosman, 2013). Coral restoration planning is beginning to consider active intervention strategies to create or enhance coral reefs' resilience to current and projected climate stressors (National Academies of Sciences, Engineering, & Medicine, 2019; van Oppen et al., 2017).

Reefscape scale (10 m–10 km)

Overview

Regional-scale assessments can identify potential locations for coral restoration; however, to restore a functional coral reef system, additional evaluation at finer spatial scales is needed. Reefscape-scale processes are key components of the coastal protection service provided by coral reefs. The reefscape scale includes the patch scale (e.g., patch reefs and reef spurs; 10–100 m), as well as the reef scale of multiple patches within one or more reefs (100 m–10 km). Although most restorations are currently implemented at the patch scale, some are beginning to be implemented at the larger scale of multiple reefscapes (e.g., NOAA, 2019). Restoration siting at reefscape scale incorporates reef width, depth, profile, structure, and roughness, all of which impact both hydrodynamics and ecology.

Fluid dynamics

As waves propagate from offshore toward the shoreline, their properties change as they interact with the sloping seafloor and reef structure. Wave shoaling, refraction, breaking, and dissipation from bottom friction cause changes in wave height, wave direction, and distribution of wave energy across different frequencies, collectively termed wave transformation. The intent of coral restoration for coastal protection is to modify reef shape and roughness, and thereby change wave transformations. Coral reefs primarily dissipate wave energy through wave breaking and bottom friction (Lentz, Churchill, Davis, & Farrar, 2016; Lowe, Falter, Bandet, Pawlak, et al., 2005; Monismith et al., 2015). Wave breaking occurs when the ratio of wave height to water depth reaches a critical value (Battjes & Janssen, 1978; Thornton & Guza, 1983). The location of the breaker zone and the wave energy dissipated by breaking varies with incoming wave properties, mean water level (e.g., tides and storm surge), and local bathymetry. Under large wave conditions, energy is primarily dissipated through breaking (Osorio-Cano et al., 2019). Enhanced frictional energy dissipation provided by restored reefs may be more important for moderate (smaller but more frequent) wave events, in which less energy is dissipated by breaking (Storlazzi et al., 2019), than major events, although the cumulative benefits of restoration over many small to moderate events could be significant. The effect of a restoration project on wave transformation can change over the course of the restoration as engineered structures are added or as corals grow large and complex. Furthermore, restoration at one site can influence levels of wave energy at another site, such as a restored reef crest sufficiently reducing wave energy to enhance the potential for restoration in back-reef habitat.

Water levels at the shoreline are another important design consideration for reef restoration projects for coastal protection. Water level variability at the reefscape scale is determined by a combination of regional-scale processes (e.g., astronomical tides, mesoscale eddies, and wind stress) and local physical processes largely associated with wave transformation. The rapid decay in wave height caused by wave breaking on a reef crest results in an increase in mean water level, referred to as the wave-induced setup (e.g., Vetter et al., 2010). At the shoreline, residual wave energy is converted into runup, the upward swash of waves on the shoreline (Svendsen, 2006), which is a major contributor to flooding in reef-lined coats, particularly for steep, narrow, and smooth reefs (Quataert et al., 2015). When sets of waves break, long-period (in minutes) waves, termed infragravity waves, can propagate shoreward, and these also substantially affect water levels at the shoreline (Cheriton et al., 2016; Pomeroy et al., 2012). Restoration actions that modify wave breaking or dissipation have the potential to change water level variability at the shoreline, and these impacts must be considered in the design and evaluation of the project.

Circulation (currents) at the reefscape scale determines the length of time that water spends on reefs (residence time, flushing; Hench et al., 2008; Storlazzi, Cheriton, et al., 2018), which affects water properties that affect coral survival and growth, such as temperature, concentrations of nutrient and other terrestrial inputs, and materials that are modified as water passes across the reef (e.g., plankton, dissolved gases, and carbon). Sedimentation and larval transport on reefs are also strongly influenced by circulation; therefore, understanding the impacts of restoration design on circulation at a site is important for restoration project success (Figure 1). Currents across reefs are driven by water level gradients due to wave transformation and larger scale processes (tides, mesoscale eddies; Figure 1), together with wind (Lentz, Churchill, Davis, Farrar, Pineda, et al., 2016; Lowe, 2009; Monismith et al., 2013). The relative importance of these processes varies within and across reef systems (Lowe & Falter, 2015). Currents across a reef are typically determined by a balance between these forces that drive the flow and bottom friction from the rough reef, which opposes the flow. Water level variations due to tides and large-scale processes also have an indirect effect on currents by modulating wave breaking, bottom friction, and the rate at which water is transported over the reef crest (Herdman et al., 2015). Reef-ocean exchange can also be influenced by density differences due to freshwater inflows and differential heating on the reef (Herdman et al., 2015), jets through reef passes, and fronts that form between water masses with different densities. Restoration actions that change the water depth and geometry of the reef lagoon system and the bottom roughness can affect the circulation by modifying wave processes (Lindhart et al., 2021; Lowe et al., 2010), wind-driven currents, and bottom friction.

To quantify the success of restoration projects for coastal protection, indicators can include changes in wave properties (height, energy spectra) across the restored reef and measures of water level at the shoreline (Figure 3). Measurements using cross-shore arrays of wave and water level sensors (e.g., Cheriton et al., 2016; Péquignet et al., 2014) can inform parameter values (e.g., bottom friction coefficient and wave breaking criteria) for wave modeling at a site. The impacts of restoration on wave transformation can be assessed with spectral wave models (e.g., Pomeroy et al., 2021; Quataert et al., 2015). The wave model can then be used to predict how potential changes in reef elevation and roughness from a restoration translate to changes in wave energy and water levels on the reef and at the shoreline. Model simulations can incorporate a range of environmental conditions, from normal conditions at the restoration site in the near term and over the forecasted life of the project to forecasted conditions for multiple storm scenarios (e.g., 100-year storm and 500-year storm). Coupled wave-circulation modeling (e.g., Lowe et al., 2009) along with measurements of currents, waves, and water levels at key locations may be needed to understand current patterns at a site and predict how a restoration will impact circulation. Circulation models can be used in combination with transport models to predict how changes in circulation due to the restoration affect water temperatures, concentrations of dissolved materials, and larval transport on the reef. Model sensitivity studies can inform how changes in reef elevation and roughness from a restoration will translate to changes in wave energy and currents on the reef and at the shoreline. This type of wave and current modeling is a valuable part of restoration design. Site-specific studies can be used to identify the most effective locations within reef systems to site coral restorations for optimal attenuation of wave energy across the range of water levels experienced at a site and to relate effects of restored corals (e.g., size, spacing, and morphology) to changes in bottom roughness and wave breaking.

Reef structure

For a reef restoration to contribute to wave attenuation in the near term, gray or hybrid structures may be required to add physical reef structure that would otherwise take decades to centuries for corals to produce (Figure 2). Green restoration, such as planting corals on natural reef substrate, may be insufficient to significantly change wave breaking or the wave energy that reaches the shoreline in the short term (Figure 2). Gray engineered structures, such as artificial reefs, can provide immediate structure upon implementation as well as services related to structure, such as wave attenuation (Figure 2). However, engineered structures degrade over time, and services may be lost without maintenance or replacement (Figure 2; Sutton-Grier et al., 2015). A gray-green hybrid approach to reef restoration can encompass a broad spectrum of options, the most common of which is engineered reef structures (or group of structures) with corals planted onto them (Jaap, 2000; Reguero, Beck, Agostini, et al., 2018). Gray or hybrid approaches have been used to replace localized loss of reef structure from impacts including ship groundings, dredging, and blast fishing (Jaap, 2000; Williams et al., 2019). Engineered structures to replace or create hard-bottom habitats by stabilizing large extents of rubble (e.g., rubble removal, revetment mats, and artificial structures) can be effort-intensive and have had mixed success (Jaap, 2000; Williams et al., 2019). The hybrid approach has the potential to combine benefits of both gray and green approaches: the immediate reduction of wave energy, the long-term potential for continued coral growth, and to support other critical ecosystem services, such as biodiversity, fisheries, and tourism (Figure 2); however, hybrid approaches are not universally applicable. These efforts demonstrate the challenges of meeting simultaneous engineering and ecological objectives, such as structural stability, aesthetics, functionality, and expense, and the provisioning of suitable substrate for coral settlement, growth, and reef accretion (Figure 1; Abelson, 2006; Masucci et al., 2020).

Species and habitats

Species composition is considered a key restoration design and evaluation indicator for ecological restorations (Gann et al., 2019). At reefscape scales, restoration persistence is predicated on reef habitat suitable for viable coral recruitment, survival, and growth of coral species to be restored (Figure 3). Restoration siting and species selection can follow natural zonation patterns of distinct coral community patterns relative to depth, reef orientation, and local patterns in waves and circulation, accounting for specific ecological requirements of different coral taxa (Figure 3). For example, a restored reef crest requires different composition and abundances of restored coral species than a reef flat. Restoration at sites with unstable reef substrate that can degrade into unconsolidated rubble could reduce coral recruitment, growth, and survival (Ceccarelli et al., 2020; Viehman et al., 2018), and substrate stabilization may be required for successful restoration. Depth is also an important factor in restoration design, not only for hydrodynamic reasons but also because many coral species grow more slowly at depth (Baker & Weber, 1975), yet also find refuge from thermal extremes (Glynn, 1996; Storlazzi et al., 2020) and wave forces. Coral bleaching can be less severe or frequent on reefs with high structural variability (Teneva et al., 2011), sites with strong currents (Lenihan et al., 2008), and sites where temperatures are modulated by internal waves (Wyatt et al., 2019).

Inclusion of diversity can incorporate a degree of ecological resilience into restoration (Gann et al., 2019) and is a clear need for coral restoration (Vardi et al., 2021). Diversity can be represented in restoration design and evaluation at reefscape scales by using multiple coral species in appropriate habitats (Cabaitan et al., 2015; Ladd et al., 2018), where some species can survive higher stress while others have faster recovery (Baskett et al., 2014). Planting different coral species in a reefscape can cause interspecific interactions (Shaver & Silliman, 2017). For example, reefs with high cover and diversity can support more herbivores and fish within the community, which can increase coral survivorship and growth (Huntington et al., 2017; Ladd & Shantz, 2020). Interactions between species and within species can be considerations in restoration design and evaluation at the reefscape scale. More work is needed to relate species diversity and interactions to restoration design in terms of size, spacing, and groupings of corals.

Climate change

Restoration in the context of climate change can incorporate diversity by including multiple genotypes that are resilient to ongoing stressors such as bleaching and disease (Baums et al., 2019). Potential active interventions to increase resilience, such as assisted gene flow (National Academies of Sciences, Engineering, & Medicine, 2019), are currently conceptualized at a small spatial scale and have yet to be incorporated into reef-scale production.

Colony scale (0.1–10 m)

Overview

The primary focus of coral reef rehabilitation to date has been the survival and performance of individual corals (Bostrom-Einarsson et al., 2020; Goergen et al., 2020). The survival and growth of planted (or seeded) corals and new coral recruits collectively control the temporal trajectory of the forecast for restoration recovery (Figure 2) and provide the foundation for reinstating ecosystem functions and services at larger spatial scales (Figure 3). Survival and growth of individual corals (or thickets or branching corals) are influenced by biotic and abiotic factors acting at the colony scale.

Species and habitats

Growth and survival of individual restored corals are influenced by the size, spacing, and density of planted corals, as well as species, genotypes, and compatibility with the reef habitat and stressors at the restoration site (Figure 3; Goergen et al., 2020). The projected change over time in coral size depends on realized growth, which includes both calcification and linear extension, and varies by species, morphology, colony density, geography, habitat, and biological drivers, such as predation, competition, and facilitation (e.g., Kopecky et al., 2021; Kuffner et al., 2017; Shantz et al., 2011), that can be evaluated in site selection and monitoring (Goergen et al., 2020). Planted corals can also show positive or negative density dependence that affects survival and growth (Griffin et al., 2015), and effects may vary with coral size (Ladd et al., 2016). Restoration may promote persistence via larval dispersal or down-current fragmentation of branching corals (Goergen & Gilliam, 2018; Lirman & Fong, 1997). These complex ecological dynamics illustrate the need for coral reef monitoring to include metrics, beyond simply coral cover, to measure population and community dynamics important to restoration (Edmunds & Riegl, 2020; Goergen et al., 2020).

The survival and growth of individual corals are also dependent on abiotic factors, such as flow, light, temperature, and sedimentation (Anderson et al., 2017; Baker & Weber, 1975; Lough & Cantin, 2014), which can be evaluated in site selection and monitoring (Goergen et al., 2020). Depth is also an abiotic factor in restoration siting because many coral species grow more slowly at depth (Baker & Weber, 1975), yet also find refuge from thermal extremes (Bongaerts et al., 2010) and wave forces. In addition, reef microhabitats affect light availability (Anthony & Hoegh-Guldberg, 2003), habitat use by reef fish (Wehrberger & Herler, 2014; Wilson et al., 2016), and local environmental cues for coral recruitment on natural substrates (Gleason et al., 2009; Ritson-Williams et al., 2010, 2020) and on engineered substrate (Chamberland et al., 2017; Randall et al., 2021). More information is needed on how microhabitats may factor into colony-scale coral recruitment, survival, and growth for restoration.

Fluid dynamics

Restoration design and evaluation can include the impacts of hydrodynamic flow patterns (Figure 3). At the coral colony scale, flow patterns are dominated by interactions of waves and currents with individual corals and groups of corals and vary depending on colony size, spacing, shape, and water depth. Flow affects coral growth, mainly through controlling mass transfer of metabolites in and out of coral tissue (Edmunds & Lenihan, 2010; Mass et al., 2010). Pumping of water past colonies by waves greatly enhances mass transfer to/from coral tissue and varies with colony size and spacing and wave properties (Lowe, Koseff, & Monismith, 2005; Lowe, Koseff, Monismith, & Falter, 2005). Waves and turbulence can also influence coral growth and mortality indirectly by controlling the incidence and severity of corallivory (Lenihan et al., 2015), as well as rates and impact of sedimentation (Lenihan et al., 2011). Experimental evidence also indicates that bleaching severity declines and recovery from bleaching increases with flow velocity (Nakamura et al., 2003), and this is thought to be related to enhanced transfer of metabolites away from coral tissues in faster flows (Mass et al., 2010). In the boundary layer above corals, dissolved materials are mixed vertically by turbulence, and this mixing is also greatly enhanced by waves (Reidenbach et al., 2006). Further efforts are needed to relate colony-scale flow patterns (Chang et al., 2014; Hench & Rosman, 2013) and biological processes to restoration design and evaluation.

Most coral reef restoration occurs in relatively shallow water (Bostrom-Einarsson et al., 2020), where oscillatory water motion due to waves is appreciable at the bottom and can far exceed the flow due to currents (Nielsen, 1992). Wave orbital motion and currents exert hydrodynamic forces on coral structure that can affect the potential for colony breakage and are influenced by colony size and morphological geometry (Madin, 2005; Madin et al., 2014), both of which will change as corals grow. These forces can be estimated as the sum of an inertial force associated with the fluid acceleration and a drag force due to flow separation (Morison et al., 1950). Estimates of forces can be used to estimate internal forces (stresses) in corals with given dimensions and hence their susceptibility to breakage.

In addition, force estimates enable estimation of the torque around the coral base; this is important for designing the attachment to the coral substrate. Cement, epoxy, wire, nails, and cable ties are commonly used materials for attachment of corals to substrate (Goergen & Gilliam, 2018; Okubo et al., 2005). In hybrid approaches, engineered coral forms can be attached to the substrate, and coral fragments transplanted onto it to sheet together as they grow (Mostrales et al., 2022; Page et al., 2018). Additional work is needed to quantify benefits and limitations of different engineered materials used in coral restorations, as well as breakage stresses of corals and attachment materials.

Cross-scale integration

The final restoration design and implementation is therefore a complex interplay between processes at different spatial and temporal scales (Figures 1–3). Many of these multiscale processes have been qualitatively acknowledged by the coral reef management community. However, forecast modeling can help quantify the influence of each design decision and provide insight under current and projected future climatological conditions (Figures 1 and 3; Bodner et al., 2021). Quantitative tools, such as models, to characterize them exist but are not yet commonly used in restoration design and evaluation. Quantitative interdisciplinary models are a critical approach for evaluating restoration designs (Figure 1) because they provide the ability to systematically vary design and evaluate different simulations of restoration scenarios at the multiple spatial and temporal scales needed for restoration planning. Monitoring data can then be used to test model accuracy and quantify model uncertainty (Figure 1).

Quantitative models can be used to inform marine spatial planning decisions (Lester et al., 2020), such as restoration siting; that is, to identify degraded reefs that are valuable for coastal protection and suitable for restoration, and to identify current or historical species ranges. Modeling historical changes in the shoreline and marine habitats can help link the health of coral reefs with wave energy and shoreline change (Reguero, Beck, Agostini, et al., 2018). Wave and circulation patterns at regional scales can be quantified and predicted using coupled wave and circulation models, or coupled with biogeochemical and sediment transport models to provide information about sediment movement on the shelf, and nutrient and phytoplankton concentrations in water arriving at reefs. The hydrodynamic outputs of these models can be used with larval dispersal and connectivity models to provide information about coral larval sources and sinks.

Ecological population and community models can be used to forecast how restoration may improve populations and communities over multiple spatial and temporal scales. These forecasts can be incorporated into design modeling (Figure 1) in terms of what restoration targets would be needed to enact changes and how environmental and climate conditions may affect coral survival and growth. Ecological models can be tested using monitoring data that spans multiple spatial scales, such as from large-area imagery. Although progress has been made in application of population models to forecasting the restoration success of individual species (Kayal et al., 2018), further work is warranted on this topic to explore impacts of variable input parameters such as climate change conditions.

Despite the use of these tools for single applications, quantitative models have had limited applications in coral restoration. As restorations continue to scale up spatially, new approaches will be needed to evaluate changes in ecosystem functions and services at larger spatial scales. In coral reef systems, the applications of explanatory and predictive models for both ecology and hydrodynamics have increased over the past several decades (e.g., Chen et al., 2020; Elahi et al., 2022; Madin et al., 2020; Yu et al., 2018). Considerable expertise and many tools have been developed for ecological, hydrodynamic, and engineering processes specific to coral reefs. Many of these can also be applied to restoration needs. The largest challenge will be to combine interdisciplinary approaches to implement comprehensive design and evaluation of coral reef restorations at the temporal and spatial scales needed to affect coastal resilience.

CONCLUSIONS

Increasing human population, associated development of coral reef coasts, and climate change will increase coastal risk, necessitating innovative solutions to maintain or increase coastal resilience. There is much uncertainty in scaling coral reef restoration up to the extent needed to meet current challenges; however, given continued coral reef decline, continued restoration efforts are needed. Here, we show the need for multidisciplinary integration if restorations are to meet the challenge of scaling up coral restorations for coastal protection and for a resilient, self-sustaining reef.

Large-scale coral reef restoration for coastal protection is a nascent field. As such, establishing best practices for design, implementation, and evaluation is critical. Defining metrics that capture the restoration design, hydrodynamic and ecological factors, functions, and restoration trajectory will be essential to expanding our knowledge base. Field studies will need to be carefully designed to address data gaps, provide inputs needed for model simulations, and generate data that can be used to improve models of reef processes. Models are needed that include interactions between hydrodynamics and ecological processes on coral reefs at multiple scales to provide predictions of reef restoration trajectories, services, and resilience. Science advances and recommendations should be accessible to nonspecialists and shared with the restoration community.

The decision support framework described here (Figure 1) will help connect the ecological, hydrodynamic, and engineering sciences of coral reefs with restoration, and lead to more holistic scientifically grounded restoration design, implementation, and evaluation.

Implementing this framework will require constructive partnerships between ecologists, physical oceanographers, coastal engineers, restoration practitioners, and managers.

AUTHOR CONTRIBUTIONS

T. Shay Viehman conceptualized the original workshop and organized it with James L. Hench; T. Shay Viehman, Borja G. Reguero, Johanna H. Rosman, Hunter S. Lenihan, Curt D. Storlazzi, James L. Hench prepared the first draft; all authors contributed to idea development at the workshop, writing, editing, and approved the final version of the manuscript.

ACKNOWLEDGMENTS

This work was funded by the U.S. National Oceanic and Atmospheric Administration's Coral Reef Conservation Program Project 31217. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of NOAA or the U.S. EPA. This document has been peer reviewed and approved for publication consistent with USGS Fundamental Science Practices (https://pubs.usgs.gov/circ/1367). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. The authors would like to thank Alejandra Ortiz, Greg Piniak, Carolyn Currin, Jenny Davis, Miles McGonigle, Phanor Montoya-Maya, and anonymous reviewers for helpful feedback.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

No data were collected for this study.

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How to cite this article: Viehman, T. Shay, Borja G. Reguero, Hunter S. Lenihan, Johanna H. Rosman, Curt D. Storlazzi, Elizabeth A. Goergen, Miguel F. Canals Silander, et al. 2023. "Coral Restoration for Coastal Resilience: Integrating Ecology, Hydrodynamics, and Engineering at Multiple Scales." *Ecosphere* 14(5): e4517. https://doi.org/10.1002/ecs2.4517