23

MAKING RESTORATION MEANINGFUL: A VISION FOR WORKING AT MULTIPLE SCALES TO HELP SECURE A FUTURE FOR CORAL REEFS

Les Kaufman, Ilsa B. Kuffner, Tom Moore, and Tali Vardi

INTRODUCTION

If coral reefs continue to decline, society will lose important ecosystem services worth billions of dollars (Costanza et al. 2014), including coastline protection, food security, and economic (e.g., tourism) opportunities. There is hope, though. Many reefs around the world are doing okay, and even when degradation is pronounced, pockets and patches of reef remain where hard coral cover and individuals or populations of threatened coral species and other reef creatures survive despite continuing deterioration in ocean conditions (Guest et al. 2018). Right now, humans have a fleeting opportunity to intervene directly. While we mitigate climate change and coastal disturbances, active restoration of coral populations can, along with more advanced interventions that are currently in development, help corals sexually reproduce and successfully recruit to reefs, buying time and encouraging adaptation to changing conditions. In order to enact this vision, we need to work at multiple scales simultaneously. The concept of restoring reefs was developed years ago (Precht 2006), but in the past, efforts were mostly local-scale operations with a more focused purpose such as recovering reefs from boat groundings or other assaults. Currently, small scale, single-species restorations, mainly using coral fragmentation, continue to help floundering reefs hold on and keep valuable, endangered species alive until more significant investments can be made. Simultaneously, investment on the scale of thousands of kilometers is underway to intervene in the future of the Great Barrier Reef. There are restoration projects in progress at all levels of spatial scale, complexity, and investment in between those two extremes (Boström-Einarsson et al. 2020). Each of these levels is important to continue. We are making progress toward increasing the number and scale of reef stewardship and restoration projects. There is a chance to make a difference on regional and global scales, with the simple goal of ensuring that coral reefs still exist at the end of this century.

We stress that coral reef restoration is not a panacea. Of course, restoration must be couched in the context of, and not in lieu of, continuing global threat reduction and local management efforts to reverse the human impacts that are causing reef decline. Some areas of the world may not yet need, or be ready for restoration because local management actions have not yet been tried, nor have other interventions such as predator removal (e.g., crown-of-thorns starfish in the Indo-West Pacific) been recognized as a necessary prerequisite. However, after four decades of attempting to reverse coral reef ecosystem decline, focusing mostly on fishery regulations and marine spatial planning—for example, creating marine protected areas (MPAs)—the time has come to try new tactics (Anthony et al. 2017). While MPAs have shown success in rehabilitating fish stocks (Halpern and Warner 2002), positive effects on coral populations have not been realized (Toth et al. 2014; Bruno et al. 2019). The use of active coral restoration techniques, as outlined in this book, has gained recognition and validity throughout the world (van Oppen et al. 2017; National Academies of Sciences 2019). This chapter offers a vision of what coral restoration can look like along a continuum of increasing investment, spatial scale, and payoffs in the currency of ecosystem services.

Climate Predictions

The first question that people usually ask when they ponder the usefulness of coral-reef restoration is: "Why restore reefs if the ocean conditions that killed them in the first place have not been mitigated, and in fact, are getting worse?" This is a valid concern. Earth's climate is changing in ways that were set in motion centuries ago at the dawn of the industrial revolution, and humans continue to perturb the global carbon cycle at rates and on a spatial scale that is unprecedented in Earth's history (Mackenzie and Lerman 2006). Humans have moved hundreds of gigatons of carbon from where it was locked away in the Earth's crust as fossil fuels to the atmosphere, hydrosphere (oceans), and biosphere (land-bound vegetation) in nearly equal thirds. The consequences of this added carbon in the atmosphere (as carbon dioxide) and the ocean (as dissolved inorganic carbon) have direct impacts on coral reefs. Coral bleaching, the separation of dinoflagellate symbionts from their cnidarian hosts—most often in association with ocean warming—is now recognized as a primary cause of coral mortality around the globe (Hoegh-Guldberg 1999; Eakin et al. 2010; Hughes et al. 2017b). Ocean acidification is projected to accelerate dissolution and erosive processes on reefs (Enochs et al. 2016), cause declines in coral growth (Gattuso et al. 1998), and weaken reef framework (Wisshak et al. 2012; Fang et al. 2013). The combined effects of bleaching and ocean acidification that are projected for this century bring into question the future of coral reefs as geologic formations (Kleypas et al. 2001; Kuffner and Toth 2016), along with the survival of reef populations and associated species (Hoegh-Guldberg et al. 2007), which comprise at least 25% of all marine species (Fisher et al. 2015). Human activities have already contributed to warming the planet 1°C (1.8°F) (IPCC 2018). Because of lag times inherent in perturbations of the global carbon cycle and oceanic thermal inertia, humans have committed the Earth to an additional one degree centigrade of warming (for a total of 3.6°F) even if carbon emissions were stopped 20 years ago (Meehl et al. 2005; Wigley 2005; IPCC 2018). Coral reef persistence through these changes will require acclimation, adaptation, and reassembly by individuals, species, and communities, respectively. While suboptimal conditions for reefs presently pervade the globe and are predicted to persist, the occurrence of reefs doing unexpectedly well in pockets across the seascape offers hope that it is not too late to act (Guest et al. 2018). Restoration actions can multiply, expand,

and extend the lifetimes of these pockets. The result would be added value to people in the short term, and a more rapid rebound of the global coral reef estate in the future.

Sexual Reproduction and Adaptation

The demise of many of the world's coral reef ecosystems is due primarily to individual coral colonies dying en masse from bleaching and disease (Aronson and Precht 2006; Hughes et al. 2017a). Most reef-building corals reproduce via mass spawning, where colonies all release gametes together during specific times and seasons (Page, Fogarty, and Vaughan, Chapter 8 in this book). In a healthy population during mass spawning, there are enough individuals to ensure cross fertilization among different genetic strains (genets). When populations decline, sexual reproduction becomes more uncertain because compatible colonies are spread too far apart for gametes to meet and successfully fertilize (i.e., the *Allee effect*, Knowlton 2001). By intervening (Koch, Chapters 9 and 10 in this book) and increasing the number of genetically different corals of a particular species on a reef, restoration can help rebuild genetically diverse populations to maximize the potential for successful sexual reproduction in that species or population. This is an essential step in establishing self-sustaining populations of key framework-building corals (Randall et al. 2020). Further, recombination of genetic material is necessary for species to adapt to changing ocean conditions (Baums et al. 2019)(Koch, Chapter 10 in this book).

THE VALUE OF RESTORATION EFFORTS AT VARIOUS SCALES

Because of the lag in time between carbon emissions and subsequent climate impacts, there will be a gap—even with concerted efforts to lower greenhouse gas release—between the present when existing coral populations are threatened with extinction, and a future ocean that is once again hospitable to corals. The chapters of this book illustrate that the restoration of coral reef habitat is possible and the spatial scale of success is steadily increasing (Section III, Chapters 11–21 in this book). All of this is embedded in the larger context of arresting anthropogenic climate change while making local environments more conducive to coral reef recovery (Hughes et al. 2017a). Even considering climate change, it is critical for restoration to continue at the current (albeit small) scale, while other management actions continue—such as water quality and fisheries management—and large-scale coral reef ecosystem restoration is being investigated and planned for (Vaughan and Nedimyer, Chapter 22 in this book). This final chapter outlines the multiple steps along the way. We must maintain success at the local level while aiming for maximum impact at the ecosystem level. This is the trajectory we are suggesting for the coral reef restoration community, and the vision that we encourage for those who are new to the field.

A Continuum of Valuable Objectives

A comprehensive review of published literature, gray literature, and a survey of practitioners reveals that almost 70% of current restoration practice consists of coral gardening techniques or transplantation (Boström-Einarsson et al. 2020). Most of these efforts are directed to restoring local coral populations—usually of only one or a few species. However, restoration is steadily becoming much more than merely reattaching a limited number of asexually produced coral fragments of a limited set of one or two species (Precht 2006; Johnson et al. 2011; Rinkevich 2017; Boström-Einarsson et al. 2020), (Section II, Chapters 5–10, and Section III, Chapters 11–21 in this book). Restoration programs today exist along a continuum of objectives from supporting tourism to bringing back self-sustaining and functioning ecosystems (Shaver and Silliman 2017; Bayraktarov et al. 2019). The continuum of objectives or benefits relate to three basic parameters—spatial extent, complexity of the intervention (i.e., number of species or genotypes restored, substratum manipulations, genetic interventions—Chapter 9 in this book), and overall investment in terms of money and resources (Figure 23.1). The aim of this chapter is to leave the reader with confidence that thoughtful restoration can render critical ecosystem-service benefits all along the continuum. The benefits begin with even modest efforts, but then increase exponentially as the restoration increases in scope. Furthermore, an economy of scale can be achieved when practicing coral restoration at a larger scale because establishing the infrastructure is usually the most expensive and time-consuming element. Helping coral reefs to persist through the end of the century requires that we work at all scales simultaneously. Achieving many successes at a smaller scale will, in summation, contribute to the attainment

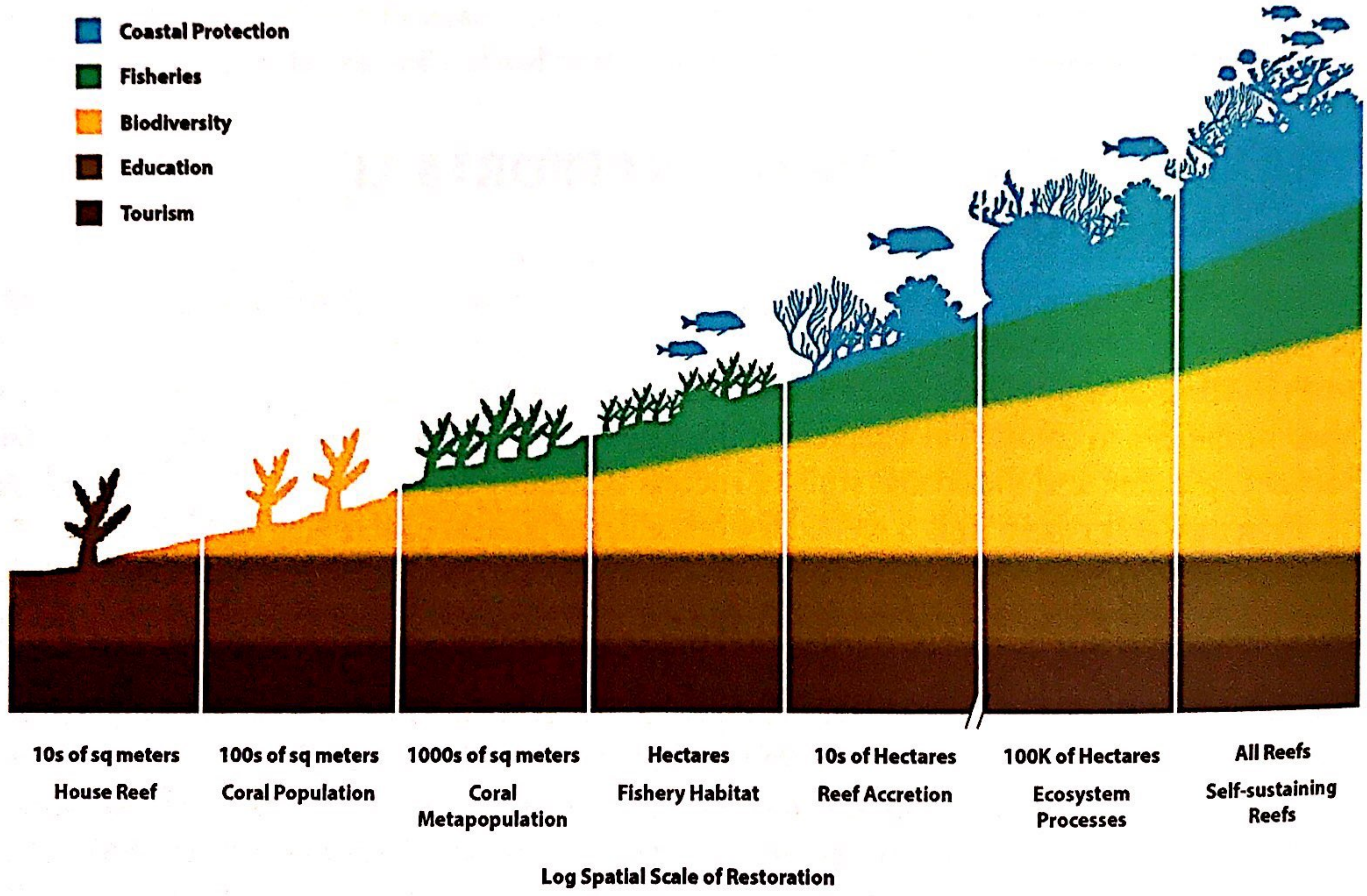

Figure 23.1 A conceptual representation of the increasing ecosystem service benefits that are accrued as the (log) spatial scale of restoration increases. The x-axis could have been represented by any number of other variables (e.g., cost, duration); but spatial scale was chosen as it probably represents the tightest correlation and it is easiest to visualize. The drawings at the top of each column hint at the level of effort (single species to full reef restoration) that is necessary for achieving the benefits. A more detailed explanation of what is needed can be found in the text and in Table 23.1, later on in this chapter. The first two columns represent the scale of current practices. Restoration projects or programs can fall anywhere along the continuum. Note that a fishery habitat restoration project would not necessarily be smaller than that for reef accretion. The primary difference between these two are the goals—fisheries/biodiversity accumulation versus the accumulation of reef structure for coastal protection. (Conceptual illustration by George Boorujy.)

of the end goal of restoring self-perpetuating, functioning reef ecosystems. We are not and cannot be doing all of this by ourselves. We have a powerful and resilient partner working with us: *nature*.

Baseline Conditions

Each restoration program's path depends on the starting baseline conditions of the particular reef ecosystem and the chosen objectives. Baseline conditions encompass considerations such as reef area, number of habitat zones represented, presence/absence of reef-associated habitats (seagrass, mangroves), island geography (low-island versus high-island), geologic makeup (carbonate atoll versus continental crust versus sedimentary), hydrologic setting (arid versus monsoon, etc.), and others aspects of the biophysical setting of a reef. Modern tropical reefs are complex systems that vary greatly in space and time. Any single coral reef at a given time represents one point on the spectrum of species composition and functional configuration that reefs in that location can express. Consequently, coral reef restoration might be able to consistently achieve certain broad goals, but the specifics of what is achievable will vary greatly according to baseline conditions. It may be impossible to restore most of what one reef was or can be, but some level of success is nearly always possible with clarity of purpose and scale (Figure 23.1).

Examples

Next, we provide seven examples of objectives that possess such clarity of purpose and scale for restoration programs. In general, the value of restoration increases exponentially with spatial scale, complexity, duration of effort, as well as time and money invested. In Figure 23.1, spatial scale is used as a proxy for all of these categories. Note that there are infinite intermediate steps along the spatial-scale axis where a restoration program could fit. These examples are made to complement and illustrate, not supersede, the objectives identified in other guides (e.g., Shaver et al. 2020). In each example, we outline the minimum of what is needed to achieve the specific goals (Table 23.1) and payoffs in terms of ecosystem services that success at this level should achieve (Figure 23.1).

1. House Reef

Vacationers traveling to tropical coastlines, as well as local people, seek beach and marine-related forms of relaxation. Snorkeling or diving to see brightly colored fishes and corals is an important part of these experiences. Many coastal hotels and resorts boast a *house* reef, a place where visitors can slip into the water without fuss and lavish in a blast of tropical marine diversity. Loss of a house reef portends serious economic impact if a resort's reputation rests on the environmental quality and recreational opportunities afforded by its setting. Publicly accessible reefs are also a great source of pride for communities that live near reefs, and local governments are increasingly interested in restoring habitats for enjoyment by their own citizens.

A restoration project to bolster a house reef or reinvigorate a local community's care and appreciation of their natural resource are examples of the smallest scale at which coral restoration is likely to deliver significant value in the short term. This type of restoration could be done with the least amount of effort by collecting *fragments of opportunity* and reattaching them to the substratum of a degraded reef. The next level of effort would be building a small in-water nursery for branching corals, fragmenting those corals, and attaching the fragments to the reefs.

Table 23.1 Rough guidelines of the *minimum* components that are needed to achieve the primary objective for each of the seven example objectives for restoration. This table is in no way a substitute for restoration planning and design-critical processes that would take place with local stakeholders, local ecological conditions, and local regulatory contexts in mind (as in Shaver et al. 2020)

	CORAL					
Objective	**Species**	**Genetics**	**Propagation Strategy**	**Morphology**	**Herbivores**	**Structural Augmentation**
House Reef	minimum 1 species	3+ putative genotypes per 100 m^2	asexual	branching	N/A	N/A
Coral Population	minimum 1 species	10+ putative genotypes per species				
Coral Meta-population	minimum 1 species	20+ putative genotypes per species		multiple	0–1 species	
Fishery Habitat	minimum 2 species	25+ known genotypes per species with broodstock rotation	asexual with larval augmentation		1–2 species	if necessary to achieve goals
Reef Accretion	10% of native mix	50+ known genotypes per species with a genetic management plan and selection for diversity and conditions		native mix	multiple species	
Ecosystem Processes	20% of native mix	75+ known genotypes per species with a genetic management plan and selection for diversity and conditions	asexual and larval			likely
Self-sustaining Reefs	50% of native mix	100+ known genotypes per species with a genetic management plan and selection for diversity and conditions	asexual, larval, and natural recruitment			

The resulting habitat quality is likely to depend on the availability of other healthy reef habitats that are reasonably close by, since many of the charismatic fishes and other animals (e.g., sea turtles) that people want to see would be moving among coral patches spread across the local region rather than permanently restricted to one reef. Potential payoffs include enhancement of citizen and visitor experiences, education of a broad audience (local and foreign) on the plight of coral reefs, and increased revenue from enhanced value of the visitor experience. Even this smallest level of restoration can function as part of a *seedbank* reef—in other words, as a source of genetic material and broodstock—if the corals are healthy enough to produce gametes and larvae. It may also contribute to the prevention of coastal erosion, particularly for reefs that are close to the shore. In addition, once a beachhead of hard corals and other structure-builders has been established, this small oasis can become a population node and stepping-stone for myriad other reef-associated organisms.

2. Coral Population

The threshold for local-scale (demographic) restoration is that a species or group of species have reestablished a secure and persistent population. This means that reefs can recover from local-scale perturbations within an area of interest, both through the recovery of surviving fragments and by larvae settling in from nearby subpopulations within a few years. There may be a need or a wish to define secondary goals such as the size of subpopulations or the genetic diversity of a population that relates to its resilience through time. Demographic restoration would surpass biomass and distribution thresholds that are associated with such factors as the Allee effect and recovery from severe storms, bleaching, disease, or other mass-mortality events. As such, the minimum level of effort on a patch reef scale, ~100m^2, would consist of: (1) a small in-water nursery that houses at least four genotypes (or putative genets based on local phenotypic knowledge) of a primary reef-building coral and (2) clustering outplants in groups of four to six different genotypes (Baums et al. 2019, Koch, Chapter 10 in this book). Ecosystem services restored at this scale should include those at the previous scale as well as additional biodiversity conservation, *passion* tourism such as underwater photography and scuba diving, and possibly some fisheries benefits. In addition, the restoration of a self-sustaining population means that this reef can then serve to rescue other nearby populations by providing larvae or habitat for settling recruits.

3. Coral Metapopulation

Restoration at this scale would be in the form of a network of connected populations that can absorb even higher levels of disturbance without shifting irreversibly into noncoral-dominated systems (i.e., they have some level of ecosystem resilience). This level of restoration necessitates promoting climate-resilient reefs (National Academies of Sciences 2019) at the levels of species, community, and metapopulation. Progress is being made in our understanding of the population genetics and functional genomics of corals—including resistance and resilience to high temperatures (Dixon et al. 2015), diseases, and combined stressors (Muller et al. 2018). Restoration at this level will benefit from cutting-edge research that evaluates locally available sources of genets for their genetic diversity and functional plasticity. This is of particular interest with regard to the ways that phenotypic variability corresponds with environmental variability in the complex array of biophysical settings found on reefs (Kenkel et al. 2013). The *minimum* steps necessary for this objective would be similar to those previously mentioned, repeated at least three times. Thus, (1) an in-water nursery of at least one primary reef-building coral with at least twelve genets of various physiological traits sourced from both local and distant reefs and (2) clustered outplants of at least four genotypes on each of three patch reefs. Ecosystem services restored at this scale should include those at the previous levels as well as increases to some fisheries services, biodiversity from obligate coral-associated species, and the beginnings of a reduction in subsequent restoration costs. Of course, increasing the size of each patch, the number and variability of each genotype, the number of coral species, and the number of patches would result in greater benefits.

4. Fishery Habitat

A distinct step-up in minimum effort is required to provide habitat at a scale sufficient to enhance reef fisheries that are important to local communities. In essence, restoration at this level seeks to reboot an entire coral reef community—that is, providing the shelter and sustenance to support populations of reef fishes, lobsters, and other coral reef fishery targets. Restoration at this scale involves multiple species of coral, and possibly also the restocking (or culling of, e.g., crown-of-thorns starfish) of non-coral species, such as herbivorous sea urchins, predators of coral predators (e.g., lobsters and hogfish that eat corallivorous snails), or any organism that contributes to critical ecosystem functions like grazing, production of suitable settlement habitat, and coral colony survival. However, if restoration promotes a settlement of key species, additional restocking efforts may not need to be carried out. We do not yet understand how succession works on many reefs, but continued restoration experience will help reveal these unknowns. In reef regions where there is a generally healthy ecosystem to begin with, bolstering the populations of multiple species of coral may be sufficient to re-attract a full complement of fishes and other reef species. The topographical complexity of reefs is likely to increase with restoration at this scale, thereby attracting cryptic organisms that fill out trophic webs and add complexity and needed redundancy in ecological functions. Restoration at this scale would pay attention to the biophysical setting and enabling conditions necessary for a wide array of ecologically important coral reef taxa, such as crustose coralline algae that are settlement cues for coral and other invertebrate larvae. In this phase, it becomes possible to tolerate ecological players that may be intolerable in a scenario that is characterized by smaller patches of this or that coral. For example, at a very low density of branching acroporid corals, algal-gardening damselfishes can have a devastating impact on populations of their host corals. In extensive thickets of these same corals, however, algal gardeners might actually *benefit* their host corals by defending a larger area of live coral from coral enemies such as excavators and borers. Ecosystem services restored at this scale include those at the previous levels as well as gains in fisheries, a steeper rise in biodiversity from volunteer recruitment, and ecological processes such as larval export and the beginnings of shoreline protection returning. Note that research and development of restocking programs for non-coral species can be costly.

5. Reef Accretion

Restoration at this scale requires the reestablishment of net-positive carbonate-accretion budgets. This is accomplished when the amount of calcium-carbonate rock and cemented sediments produced by corals and other calcifiers outweighs the amount that is lost from dissolution, erosion, and transport off the reef (Perry et al. 2018). The most important metrics for justifying public funding for coral-reef stewardship, in all forms, is return on investment. The value of the shoreline protection by U.S. reefs in terms of human lives and dollar amounts to an annual flood-risk reduction of more than 18,000 lives and 1.8 billion dollars (Storlazzi et al. 2019).

Returning reefs to positive accretion rates is no easy task, may not be possible in all locations, and will be particularly challenging in subtropical areas, such as Florida, where reef building largely ceased several thousand years ago (Toth et al. 2018). However, considering that reefs attenuate, on average, 97% of wave energy (Ferrario et al. 2014) and protect human lives and infrastructure (Storlazzi et al. 2019), restoring reefs could be far less costly than rebuilding the human communities they protect. Bolstering reef accretion and coastal protection will necessitate work with multiple reef-building coral species at higher densities than in previous steps, and will require focused restoration at the top of the reef crest where the bulk of wave energy dissipation takes place; alas, a challenging reef setting in which to work! Restoration at this level will also challenge us to stage coral communities that, on their own, can then restore coral reef architecture and geomorphology—a daunting but noble pursuit.

In certain locations, adding artificial reef structure could be an important interim step in preventing coastal erosion (Reguero et al. 2018). However, for the longevity of the project and to ensure multiple, additional ecosystem benefits (fisheries, tourism, biodiversity), an artificial reef structure would be complemented by active coral restoration to form a living, and thus, self-sustaining coral reef and not simply a series of concrete structures on the seafloor. This type of restoration would be accompanied by specific monitoring tailored toward measuring increases in topographical complexity and reef elevation. Providing evidence that restoration can attain positive reef accretion, and thus, geological function (Kuffner and Toth 2016), and deliver decreased risk to coastal human communities is of major importance in making the case for the cost-effectiveness of restoration (Reguero et al. 2018). Ecosystem services restored at this scale include those at the previous levels as well as enhanced coastal protection through increased reef elevation (Alvarez-Filip et al. 2009) and roughness (Quataert et al. 2015), beach replenishment via net positive sediment production, and further increases in biodiversity as ecological complexity rises in concert with physical complexity.

6. Ecosystem Processes

By this scale of restoration, many major ecosystem components and ecosystem resilience are being reestablished. Processes such as sexual reproduction, herbivory, recruitment, trophic dynamics, competition, niche partitioning, and population connectivity are returning, at least in some part, on a scale of hundreds of hectares. This scale and level of coral reef ecosystem restoration is still aspirational; it has not yet been done. However, the Reef Restoration and Adaptation Program (RRAP) in Australia is developing plans to do this for the Great Barrier Reef (Hardisty et al. 2019). RRAP is a $500M (AUS dollars) program and the plan includes deployment of sexually-derived coral larvae on a massive scale, analyses of heat tolerance and gene flow among coral populations to allow for future reef processes to continue through the coming decades of warming, prevention of bleaching during warming events, researching additional highly scientific and technological advancements, modeling exercises, and then eventually implementation. Although such a comprehensive program does not yet exist elsewhere, others are beginning to emulate it (e.g., Florida’s Mission: Iconic Reefs, the UN Decade of Restoration, Blue Charter Program), and lessons learned from this program will be broadly applicable. Ecosystem services restored at this scale would include those at the previous levels, and these would now be, in part, self-sustaining systems. While these very large projects are exciting to think about, equal attention should be paid to efforts that are more modest in scale, but also more achievable and instructive in the short term, for the benefits of restoration in serving and educating local residents is not only necessary (Suding et al. 2015) but very valuable. The restoration of significant areas of Laughing Bird Caye National Park in Belize by Fragments of Hope (see Chapter 11 in this book), of large swaths of reef in Puerto Rico by NOAA and its partners, and other examples (see Chapters 14 and 18 in this book), are both illuminating and inspiring.

7. Self-Sustaining Reefs

This paragraph describes the level of restoration that should be the *ultimate and final goal*. Restoration of the global ecological-economic landscape in which coral reefs are embedded, including the whole human-biosphere system, is accomplished. All ecosystem services of coral reefs have been restored at this scale and restoration investments can cease. This level of restoration requires that fossil-fuel burning has arrested, global climate change is no longer primarily anthropogenic in nature, there is better fisheries management, water pollution is under control, there is more thoughtful coastal and watershed development, and region-wide ecosystem-scale restorations such as those described previously have been implemented in all reef regions (Hughes et al. 2017a). There is total and complete politico-economic restoration; that is, the Earth and all its human and nonhuman inhabitants are living in sustainable harmony. While this may sound like a pipe dream in the early to mid-21st Century, it could be possible to achieve in part, and any progress toward achieving it would be worth the resources expended.

CONCLUSIONS

Coral reef restoration is a very young but maturing set of tools with great potential in the fight to bridge the gap between the current phase of exponential anthropogenic climate change and a future when it has been arrested and reversed (Hoegh-Guldberg et al. 2008; van Oppen et al. 2017). Coral reef restoration can enable the species, relationships, and processes that constitute a coral reef system to cross this bridge from hostile to amenable ocean conditions for reefs, and to reassemble on the other side in some form capable of, once again, accreting calcium-carbonate edifices that keep pace with sea level and support the ocean's richest biological community. The methodical steps toward scaling up coral reef restoration are key to this grand vision of ecosystem repair and resurrection. Restoration cannot and will not solve all of the problems facing coral reef communities today, for it is not a substitute for the abatement of anthropogenic climate change—it is only an adjunct, but an important and legitimate one. Coral reef restoration can buy time—but it is *precious* time, and without it, we risk losing these systems.

DISCLAIMER

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. We thank J. A. Kleypas and I. M. McLeod for their critical and constructive reviews that greatly improved our manuscript.

REFERENCES

Alvarez-Filip, L., N. K. Dulvy, J. A. Gill, I. M. Cote, and A. R. Watkinson. 2009. "Flattening of Caribbean coral reefs: Region-wide declines in architectural complexity." *Proceedings of the Royal Society of London*, Series B 276:3019–3025.

Anthony, K., L. K. Bay, R. Costanza, J. Firn, J. Gunn, P. Harrison, A. Heyward, et al. 2017. "New interventions are needed to save coral reefs." *Nature Ecology & Evolution* 1:1420–1422.

Aronson, R. B. and W. F. Precht. 2006. "Conservation, precaution, and Caribbean reefs." *Coral Reefs* 25:441–450.

Baums, I. B., A. C. Baker, S. W. Davies, A. G. Grottoli, C. D. Kenkel, S. A. Kitchen, I. B. Kuffner, et al. 2019. "Considerations for maximizing the adaptive potential of restored coral populations in the western Atlantic." *Ecological Applications* 29:e01978.

Bayraktarov, E., P. J. Stewart-Sinclair, S. Brisbane, L. Boström-Einarsson, M. I. Saunders, C. E. Lovelock, H. P. Possingham, et al. 2019. "Motivations, success, and cost of coral reef restoration." *Restoration Ecology* 27:981–991.

Boström-Einarsson, L., R. C. Babcock, E. Bayraktarov, D. Ceccarelli, N. Cook, S. C. A. Ferse, B. Hancock, et al. 2020. "Coral restoration—a systematic review of current methods, successes, failures and future directions." *PLoS ONE* 15:e0226631.

Bruno, J. F., I. M. Côté, and L. T. Toth. 2019. "Climate change, coral loss, and the curious case of the parrotfish paradigm: Why don't marine protected areas improve reef resilience?" *Annual Review of Marine Science* 11:307–334.

Costanza, R., R. de Groot, P. Sutton, S. van der Ploeg, S. J. Anderson, I. Kubiszewski, S. Farber, and R. K. Turner. 2014. "Changes in the global value of ecosystem services." *Global Environmental Change* 26:152–158.

Dixon, G. B., S. W. Davies, G. A. Aglyamova, E. Meyer, L. K. Bay, and M. V. Matz. 2015. "Genomic determinants of coral heat tolerance across latitudes." *Science* 348:1460–1462.

Eakin, C. M., J. A. Morgan, S. F. Heron, T. B. Smith, G. Liu, L. Alvarez-Filip, B. Baca, et al. 2010. "Caribbean corals in crisis: Record thermal stress, bleaching, and mortality in 2005." *PLoS ONE* 5:e13969.

Enochs, I. C., D. P. Manzello, G. Kolodziej, S. Noonan, L. Valentino, and K. E. Fabricius. 2016. "Enhanced macroboring and depressed calcification drive net dissolution at high-CO_2 coral reefs." *Proceedings of the Royal Society of London*, Series B 283.

Fang, J. K. H., M. A. Mello-Athayde, C. H. L. Schönberg, D. I. Kline, O. Hoegh-Guldberg, and S. Dove. 2013. "Sponge biomass and bioerosion rates increase under ocean warming and acidification." *Global Change Biology* 19:3581–3591.

Ferrario, F., M. W. Beck, C. D. Storlazzi, F. Micheli, C. C. Shepard, and L. Airoldi. 2014. "The effectiveness of coral reefs for coastal hazard risk reduction and adaptation." *Nature Communications* 5:3794.

Fisher, R., R. A. O'Leary, S. Low-Choy, K. Mengersen, N. Knowlton, R. E. Brainard, and M. J. Caley. 2015. "Species richness on coral reefs and the pursuit of convergent global estimates." *Current Biology* 25:500–505.

Gattuso, J. P., M. Frankignoulle, I. Bourge, S. Romaine, and R. W. Buddemeier. 1998. "Effect of calcium carbonate saturation of seawater on coral calcification." *Global and Planetary Change* 18:37–46.

Guest, J. R., P. J. Edmunds, R. D. Gates, I. B. Kuffner, A. J. Andersson, B. B. Barnes, I. Chollett, et al. 2018. "A framework for identifying and characterising coral-reef 'oases' against a backdrop of degradation." *Journal of Applied Ecology* 55:2865–2875.

Halpern, B. S. and R. R. Warner. 2002. "Marine reserves have rapid and lasting effects." *Ecology Letters* 5:361–366.

Hardisty, P. E., C. H. Roth, P. Silvery, D. Mead, and K. Anthony. 2019. "Investment Case: A report provided to the Australian Government from the Reef Restoration and Adaptation Program." https://www.gbrrestoration.org/reports, downloaded on September 3, 2020.

Hoegh-Guldberg, O. 1999. "Climate change, coral bleaching and the future of the world's coral reefs." *Australian Journal of Marine and Freshwater Research* 50:839–866.

Hoegh-Guldberg, O., L. Hughes, S. McIntyre, D. B. Lindenmayer, C. Parmesan, H. P. Possingham, and C. D. Thomas. 2008. "Assisted colonization and rapid climate change." *Science* 321:345–346.

Hoegh-Guldberg, O., P. J. Mumby, A. J. Hooten, R. S. Steneck, P. Greenfield, E. Gomez, C. D. Harvell, et al. 2007. "Coral reefs under rapid climate change and ocean acidification." *Science* 318:1737–1742.

Hughes, T. P., M. L. Barnes, D. R. Bellwood, J. E. Cinner, G. S. Cumming, J. B. C. Jackson, J. Kleypas, et al. 2017a. "Coral reefs in the Anthropocene." *Nature* 546:82–90.

Hughes, T. P., J. T. Kerry, M. Álvarez-Noriega, J. G. Álvarez-Romero, K. D. Anderson, A. H. Baird, R. C. Babcock, et al. 2017b. "Global warming and recurrent mass bleaching of corals." *Nature* 543:373–377.

IPCC. 2018. "Summary for Policymakers." In: V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield, (eds.). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

Johnson, M. E., C. Lustic, E. Bartels, I. B. Baums, D. S. Gilliam, L. Larson, D. Lirman, et al. 2011. "Caribbean *Acropora* restoration guide: Best practices for propagation and population enhancement." p. 54. *The Nature Conservancy*, Arlington, VA.

Kenkel, C. D., G. Goodbody-Gringley, D. Caillaud, S. W. Davies, E. Bartels, and M. V. Matz. 2013. "Evidence for a host role in thermotolerance divergence between populations of the mustard hill coral (*Porites astreoides*) from different reef environments." *Molecular Ecology* 22:4335–4348.

Kleypas, J. A., R. W. Buddemeier, and J. P. Gattuso. 2001. "The future of coral reefs in an age of global change." *International Journal of Earth Sciences* 90:426–437.

Knowlton, N. 2001. "The future of coral reefs." Proceedings of the National Academy of Sciences of the USA 98:5419–5425.

Kuffner, I. B. and L. T. Toth. 2016. "A geological perspective on the degradation and conservation of western Atlantic coral reefs." *Conservation Biology* 30:706–715.

Mackenzie, F. T. and A. Lerman. 2006. "Carbon in the geobiosphere—Earth's outer shell." *Springer*, Dordrecht.

Meehl, G. A., W. M. Washington, W. D. Collins, J. M. Arblaster, A. Hu, L. E. Buju, W. G. Strand, and H. Teng. 2005. "How much more global warming and sea level rise?" *Science* 307:1769–1772.

Muller, E. M., E. Bartels, and I. B. Baums. 2018. "Bleaching causes loss of disease resistance within the threatened coral species *Acropora cervicornis*." *eLife* 2018:7:e35066.

National Academies of Sciences, Engineering, and Medicine. 2019. *A Research Review of Interventions to Increase the Persistence and Resilience of Coral Reefs*. The National Academies Press, Washington, DC.

Perry, C. T., L. Alvarez-Filip, N. A. J. Graham, P. J. Mumby, S. K. Wilson, P. S. Kench, D. P. Manzello, et al. 2018. "Loss of coral reef growth capacity to track future increases in sea level." *Nature* 558:396–400.

Precht, W. F. 2006. "Coral Reef Restoration Handbook." CRC Press Taylor & Francis Group, Boca Raton, Florida, p. 363.

Quataert, E., C. Storlazzi, A. van Rooijen, O. Cheriton, and A. van Dongeren. 2015. "The influence of coral reefs and climate change on wave-driven flooding of tropical coastlines." *Geophysical Research Letters* 42:6407–6415.

Randall, C. J., A. P. Negri, K. M. Quigley, T. Foster, G. F. Ricardo, N. S. Webster, L. K. Bay, et al. 2020. "Sexual production of corals for reef restoration in the Anthropocene." *Marine Ecology Progress Series* 635:203–232.

Reguero, B. G., M. W. Beck, V. N. Agostini, P. Kramer, and B. Hancock. 2018. "Coral reefs for coastal protection: A new methodological approach and engineering case study in Grenada." *Journal of Environmental Management* 210:146–161.

Rinkevich, B. 2017. "Rebutting the inclined analyses on the cost-effectiveness and feasibility of coral reef restoration." *Ecological Applications* 27:1970–1973.

Shaver, E. C., C. A. Courtney, J. M. West, J. Maynard, M. Hein, C. Wagner, J. Philibotte, P. MacGowan, I. McLeod, L. Boström-Einarsson, K. Bucchianeri, L. Johnston, J. Koss. 2020. A Manager's Guide to Coral Reef Restoration Planning and Design. NOAA Coral Reef Conservation Program. NOAA Technical Memorandum CRCP 36, p. 120. https://doi.org/10.25923/vht9-tv39.

Shaver, E. C. and B. R. Silliman. 2017. "Time to cash in on positive interactions for coral restoration." *PeerJ* 5:e3499 https://doi.org/3410.7717/peerj.3499.

Storlazzi, C. D., B. G. Reguero, A. D. Cole, E. Lowe, J. B. Shope, A. E. Gibbs, B. A. Nickel, et al. 2019. *Rigorously Valuing the Role of U.S. Coral Reefs in Coastal Hazard Risk Reduction*. U.S. Geological Survey Open-File Report 2019–1027.

Suding, K., E. Higgs, M. Palmer, J. B. Callicott, C. B. Anderson, M. Baker, J. J. Gutrich, et al. 2015. "Committing to ecological restoration." *Science* 348:638–640.

Toth, L. T., I. B. Kuffner, A. Stathakopoulos, and E. A. Shinn. 2018. "A 3000-year lag between the geological and ecological collapse of Florida's coral reefs." *Global Change Biology* 24:5471–5483.

Toth, L. T., R. van Woesik, T. J. T. Murdoch, S. R. Smith, J. C. Ogden, W. F. Precht, and R. B. Aronson. 2014. "Do no-take reserves benefit Florida's corals? 14 years of change and stasis in the Florida Keys National Marine Sanctuary." *Coral Reefs* 33:565–577.

van Oppen, M. J. H., R. D. Gates, L. L. Blackall, N. Cantin, L. J. Chakravarti, W. Y. Chan, C. Cormick, et al. 2017. "Shifting paradigms in restoration of the world's coral reefs." *Global Change Biology* 23:3437–3448.

Wigley, T. M. L. 2005. "The climate change commitment." *Science* 307:1766–1769.

Wisshak, M., C. H. L. Schonberg, A. Form, and A. Freiwald. 2012. "Ocean acidification accelerates reef bioerosion." *PLoS ONE* 7:e45124.