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STRATEGIC ISSUES ARTICLE

Six priorities to advance the science and practice of coral reef restoration worldwide

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Coral reef restoration is a rapidly growing movement galvanized by the accelerating degradation of the world's tropical coral reefs. The need for concerted and collaborative action focused on the recovery of coral reef ecosystems coalesced in the creation of the Coral Restoration Consortium (CRC) in 2017. In March 2020, the CRC leadership team met for a biennial review of international coral reef restoration efforts and a discussion of perceived knowledge and implementation bottlenecks that may impair scalability and efficacy. Herein we present six priorities wherein the CRC will foster scientific advancement and collaboration to: (1) increase restoration efficiency, focusing on scale and cost-effectiveness of deployment; (2) scale up larval-based coral restoration efforts, emphasizing recruit health, growth, and survival; (3) ensure restoration of threatened coral species proceeds within a population-genetics management context; (4) support a holistic approach to coral reef ecosystem restoration; (5) develop and promote the use of standardized terms and metrics for coral reef restoration; and (6) support coral reef restoration practitioners working in diverse geographic locations. These priorities are not exhaustive nor do we imply that accomplishing these tasks alone will be sufficient to restore coral reefs globally; rather these are topics where we feel the CRC community of practice can make timely and significant contributions to facilitate the growth of coral reef restoration as a practical conservation strategy. The goal for these collective actions is to provide tangible, local-scale advancements in reef condition that offset declines resulting from local and global stressors including climate change.

Key words: corals, coral interventions, coral reefs, coral restoration, reefs, restoration

Implications for Practice

- Coral reef restoration is a necessary tool for the persistence of tropical coral reef ecosystems and scientifically rigorous reef restoration methods are being developed quickly.
- Collaboration and communication among scientists and practitioners are essential to test methods in various conditions and regions, and to disseminate the results rapidly.
- The Coral Restoration Consortium is a clearinghouse of methods, ideas, and resources. The priorities outlined herein are designed to improve restoration research and practice within the next 5 years so that tropical coral reefs may persist to the end of the century.

Introduction

The degradation of coral reefs is escalating worldwide (NASEM 2019), with predictions of ecosystem collapses and keystone-species extinctions by 2050 (Bindoff et al. 2019) unless aggressive interventions are adopted to both protect key species

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and mitigate existing stressors. Tropical coral reef ecosystems are threatened by a variety of local factors, such as overfishing and pollution, that are exacerbated by the devastating effects of global climate change, which are damaging even the most remote reefs (Hughes et al. 2018). The increasing severity and frequency of tropical storms and coral bleaching are hindering the natural recovery of coral reefs between disturbances (Fabricius et al. 2017; Hughes et al. 2019). Decreases in local abundance of key species of coral have led to fragmented populations, impairing reproductive potential and increasing vulnerability to extirpation. With this unprecedented scale of decline, resource management priorities have shifted from passive interventions, which depend on natural recovery processes (e.g. marine protected areas), to active interventions, which emphasize increasing population sizes of key coral species while promoting resilience and adaptation to changing conditions (Possingham et al. 2015; Bay et al. 2019; Bindoff et al. 2019; NASEM 2019).

The long-term survival of tropical coral reef ecosystems depends on action taken on three levels: mitigating the stressors that have led to coral mortality, maintaining and rebuilding remnant coral populations until stressor abatement is achieved, and researching and implementing methods to help corals adapt to a changing ocean (Duarte et al. 2020; Hein et al. 2020). Addressing the stressors without investing in protection, management, and adaptation measures of and for coral populations is myopic; similarly, focusing exclusively on curating remaining individual corals without addressing stressors and the need to adapt to warmer seas is folly. Developed countries have the resources to lead climate change mitigation efforts so that the seas may be hospitable for corals in the long term (Hein et al. 2020). Researchers can pilot adaptation interventions to encourage a holistic, ecosystem approach to restoration. At local scales, active interventions such as coral restoration (eventually including other interventions such as stress hardening, assisted gene flow, etc.) are essential for delaying the loss of coral reefs while solutions for abating global and regional stressors are being developed and implemented.

Given the urgency to protect and save tropical coral reefs, the complexity of the required interventions, and the accelerating pace of academic publications, conservation actions, and management policies being developed, it became increasingly clear that a coordinated, information-sharing network could accelerate outcomes. In 2017 the Coral Restoration Consortium (CRC) was formed as a community of practice composed of individuals dedicated to using the best science and ingenuity to enable the persistence of coral reef ecosystems (Fig. 1). The CRC includes academic researchers, restoration practitioners, natural-resource managers, and policymakers, among others. The purpose of the CRC is to foster the communication of science and ingenuity that improves the efficacy and increases the scale of coral reef restoration, thus addressing the need to "maintain and rebuild remnant coral populations."

The leadership team of the CRC convened in March 2020 (Fig. 2) to define its working priorities for the upcoming years. The discussion was framed within the context of the UN Decade of Ecosystem Restoration and the set of standards and principles for the practice of ecological restoration defined in Gann

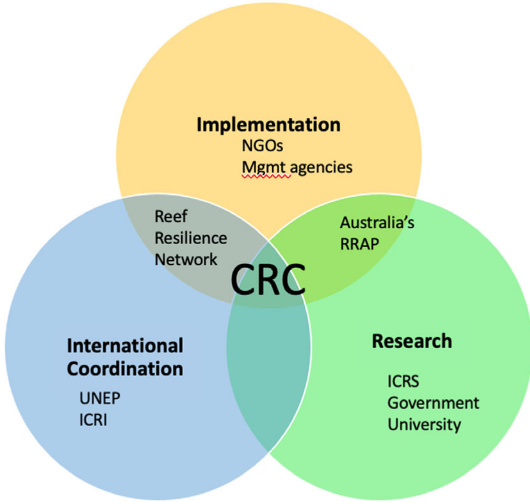

Figure 1. Venn diagram depicting how the Coral Restoration Consortium (CRC) intersects with organizations focusing on international coordination (blue), implementation (yellow), and research (green). Acronym decoder: UNEP, United Nations Environment Program; ICRI, International Coral Reef Initiative; NGO, nongovernmental organization; Mgmt, management; RRAP, Reef Restoration and Adaptation Program; ICRS, International Coral Reef Society. For reference, the CRC is a topic chapter of ICRS and a member of ICRI.

et al. (2019; Table 1). The result is six priorities to help guide and promote the scaling up of coral reef restoration efforts across the tropics. These priorities were not developed to be exhaustive of all possible needs, to be sufficient in scope to save coral reefs, or to dictate the priorities of other organizations. Rather, these priorities are topics where the CRC believes that its unique format and multidisciplinary membership can make timely and significant contributions to facilitate the growth of coral reef restoration as a viable, scientifically rigorous, and practical conservation strategy.

Six Priorities to Advance Coral Reef Restoration

Increase Restoration Efficiency, Focusing on Scale and Cost-Effectiveness of Deployment

Currently, a large majority of coral reef restoration projects worldwide employ asexual propagation techniques (Böstrom-

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Figure 2. The Coral Restoration Consortium leadership team. Playa Hermosa, Costa Rica—from back left: David Gulko, Valérie Chamberland, Joseph Pollock, Mikhail Matz, Tali Vardi, Elizabeth Shaver, Shay Viehman, Anastazia Banaszak, Petra Lundgren, Jennifer Moore, Petra MacGowan, Sandrine Pivard, Whitney C. Hoot, Chelsea Wolke, David Suggett, Les Kaufman, Margaux Hein, Scott Winters, Tom Moore, Bernardo Sanchez, Caitlin Lustic, Virginia Weis, Tatiana Villalobos, Jessica Levy, Michelle Loewe, and Samuel Suleiman. Missing from photo: Phanor Montoyo-Maya. Photo by our fearless facilitator Daphne Booth.

Einarsson et al. 2020) whereby fragmented colonies are grown in either an ocean-based or land-based nursery and then transplanted (or "outplanted") onto the reef. Asexual propagation techniques will not—nor are intended—to recover the world's coral reefs alone. However, various aspects (e.g. nursery rearing of coral, whether ocean- or land-based, and outplanting) are important restoration components regardless of whether new coral fragments are produced asexually or sexually, from natural populations or from genetically assisted strains. Therefore, large-scale success in coral reef restoration will require increases in efficiency and efficacy of these techniques. Additionally, asexual reproduction may serve as a platform for upscaling techniques and approaches such as ecological engineering (Horoszowski-Fridman & Rinkevich 2017) and augmentation of coral reproduction (Horoszowski-Fridman et al. 2020). Yet, simple increases in efficiency can significantly increase the number of corals returned to the wild, and thus offset declining coral cover and diversity. Finally, cost-effective, simple, and scalable techniques are essential because practitioners throughout the world, with varying access to resources, have pioneered and continue to fuel the majority of coral reef restoration activities. Objectives under this priority are to (1) increase diversity of propagated corals, (2) articulate the benefits of combining ocean- and land-based nurseries, and (3) increase outplant efficiency.

Scale up Larval-Based Coral Restoration With an Emphasis on Recruit Health, Growth, and Survival

Interventions using sexually propagated coral larvae are referred to as larval-based coral restoration. In contrast to asexual propagation, this approach generates large numbers of genetically unique individuals created from gametes caught during spawning events. This approach promotes genetic variability within restored populations, thereby increasing the adaptability of restored populations to a rapidly changing ocean. Despite the relative novelty of larval-based restoration, advances in assisted fertilization and husbandry techniques (Marhaver et al. 2017; Randall et al. 2020), alongside the development of mass-rearing and outplanting technologies (e.g. Chamberland et al. 2017; dela Cruz & Harrison 2017; Linden et al. 2019) have made this approach increasingly attractive to restoration practitioners.

However, the scale and effectiveness of larval-based coral propagation efforts remains limited by naturally low survivorship rates of outplanted recruits, as well as the often complex, time-consuming, and costly operations required for mass larval rearing and outplanting. Like asexual-based efforts, larval-based efforts are often too small (<1 ha) to address reef decline at relevant ecological scales (Böstrom-Einarsson et al. 2020); however, they hold great potential to be scaled up based on sheer numbers of individuals produced during spawning events. The CRC aims to accelerate the effective integration and

Table 1. This table delineates the CRC's six priorities to advance the scale, efficiency, and efficacy of coral reef restoration efforts around the world. Each priority is followed by objectives, and the relevant principle for ecological restoration as outlined by the Society for Ecological Restoration in Gann et al. 2019.

CRC Priority	*CRC Objectives*	*Principles for Ecological Restoration*
1. Increase restoration efficiency, focusing on scale and cost-effectiveness of deployment.	a. Increase diversity of propagated corals.	Principle 6. Ecological restoration seeks the highest level of recovery attainable
	b. Articulate the benefits of combining ocean- and land-based nurseries.	Principle 7. Ecological restoration gains cumulative value when applied at large scales
	c. Increase outplant efficiency.	
2. Scale up larval-based coral restoration with an emphasis on recruit health, growth, and survival.	a. Identify, prioritize, and publicize research needs. b. Increase the scale of larval-based restoration efforts. c. Develop criteria for conducting and monitoring larval-based restoration efforts	Principle 3. Ecological restoration practice is informed by native reference ecosystems, while considering environmental change
3. Ensure restoration of threatened coral species proceeds within a population-genetics management context.	a. Improve access to genetic profiling techniques. b. Develop phenotyping methods c. Develop a coral restoration genetics data repository d. Articulate methods to minimize risks during translocation	Principle 3. Ecological restoration practice is informed by native reference ecosystems, while considering environmental change
4. Support a holistic approach to coral reef ecosystem restoration.	a. Preserve coral species diversity	Principle 2. Ecological restoration draws on many types of knowledge
	b. Expand the use of noncoral organisms to facilitate reef ecosystem restoration	Principle 3. Ecological restoration practice is informed by native reference ecosystems, while considering environmental change Principle 4. Ecological restoration supports ecosystem recovery processes Principle 8. Ecological restoration is part of a continuum of restorative activities
5. Develop and promote the use of standardized terms and metrics for coral reef restoration.	a. Develop a coral reef restoration glossary b. Promote standardized metrics	Principle 5. Ecosystem recovery is assessed against clear goals and objectives, using measurable indicators
6. Support coral reef restoration practitioners working in diverse geographic locations.	a. Transfer of knowledge and technology	Principle 1. Ecological restoration engages stakeholders
	b. Build capacity	Principle 7. Ecological restoration gains cumulative value when applied at large scales

increase the geographic scale of larval-based coral propagation within coral reef restoration efforts, by combining sound scientific research with the use and development of ambitious technologies for larval mass-rearing and outplanting, while supporting access to tools and trainings. Three objectives under this priority are to identify, prioritize, and publicize research needs, increase the scale of larval-based restoration efforts, and develop criteria for conducting and monitoring larval-based restoration efforts.

Ensure Restoration of Threatened Coral Species Proceeds Within a Population-Genetics Management Context

Many reef-building, foundational coral species are suffering population declines that may necessitate strategic and thoughtful population management plans to achieve species recovery (Bindoff et al. 2019). Such plans would include protecting the remaining genetic diversity of degraded coral populations (Rinkevich 2019) and facilitating population recovery through enhancing opportunities for sexual reproduction that is necessary to foster natural selection and adaptation (Baums et al. 2019). Ideally, population management plans would be developed based on genetic (including epigenetic) and environmental considerations, as well as an understanding of existing and future reef states (Rinkevich 2020). That said, the CRC understands that in many areas highly susceptible to coral reef loss, management decisions may need to be made before genetic information is available. Until such time, the outplanting of genetically and phenotypically diverse corals can facilitate the ability of the population to endure environmental changes. Adopting outplanting strategies that enhance opportunity for larval dispersal and population connectivity can ensure that outplanted populations support long-term recruitment locally and at nearby sites. More specifically to meet this priority, the CRC has identified the following objectives: (1) improve access to genetic profiling techniques; (2) develop phenotyping methods; (3) develop a coral restoration genetics data repository and (4) articulate methods to minimize risks during translocation.

Support a Holistic Approach to Coral Reef Ecosystem Restoration

To date coral reef restoration has been dominated by coral-population enhancement using primarily asexual propagation (Böstrom-Einarsson et al. 2020). Even with great advancements in larval propagation and excellent management of coral genetics resulting in plentiful genotypic diversity, increasing the population sizes of key coral species is not equivalent to restoring a coral reef ecosystem—though it is a critical building block. As coral reef restoration evolves from outplanting activities to a rigorous conservation method, elucidating the mechanisms by which coral reef ecosystems are built, maintained, and exhibit resiliency will be essential. Important components of holistic coral reef ecosystem restoration may include enhancing the populations of noncoral keystone species (e.g. macro-herbivores), understanding the dependencies of trophic interactions and how they might be built sequentially, and defining when active intervention reaches a stable state for reef resiliency. All of the above will require intensive and long-term ecological monitoring. Although long-term data on performance of coral outplants (e.g. growth and survivorship) and subsequent ecological processes (e.g. coral recruitment) are not yet plentiful (see Montoya-Maya et al. 2016 for a counter example), new guidance has been developed to gauge ecological recovery at the reef scale following coral restoration projects (Goergen et al. 2020). Even though restoring ecological complexity requires a more intentional and extensive type of restoration beyond coral outplanting, small projects across regional scales can all contribute to this larger goal (Bayraktarov et al. 2020; Schmidt-Roach et al. 2020). Several recent publications are available to guide the community on holistic coral reef restoration approaches (Böstrom-Einarsson et al. 2020; Hein et al. 2020; Shaver et al. 2020). However, there is still a need for guidance on how to intentionally preserve community-scale biodiversity both on the reef and in land-based nurseries for eventual reintroduction, and how to promote restoration of other important reef organisms. This priority will focus on (1) preserving coral species diversity, and (2) expanding the use of noncoral organisms to facilitate reef ecosystem restoration.

Develop and Promote the Use of Standardized Terms and Metrics for Coral Reef Restoration

A lack of common definitions and standardized metrics slows the transmission of ideas and the adoption of new techniques, while limiting comparability across projects (Böstrom-Einarsson et al. 2020). To increase the scale and efficiency of coral reef restoration, we must be able to communicate effectively across regions, fields of study, and varying levels of technical expertise. To this end, the CRC is drafting a glossary of terms to facilitate communication among restoration practitioners across the globe, focusing on terms that lack standardized definitions (e.g. *microfragment*, *reskinning*). In addition, the CRC community has recognized and acknowledged the need to promote standards for restoration, as per the Society for Ecological Restoration (McDonald et al. 2016), and a comprehensive guide to monitoring coral reef restoration activities has recently been published (Goergen et al. 2020). In the guide, the CRC recommends that "universal" metrics such as reef area and colony size are measured at any and all reef restorations, regardless of the particular goal of the restoration, its size, or geographic location. The reasoning behind developing "universal" metrics was 2-fold, to help provide practitioners with a basic monitoring plan and to enable comparisons among restoration projects which can vary widely in geography, size, and methodology. As practitioners adopt and begin collecting data using these metrics, the CRC is developing an open-access database to upload and share data on reef restorations as they mature. The database will facilitate within- and cross-basin comparison of restoration efforts to restore populations, communities, and ecosystems.

Support Coral Reef Restoration Practitioners Working in Diverse Geographic Locations

Central to the CRC's mission is hastening reef restoration by accelerating the science and ingenuity knowledge cycle. Rapidly accumulating knowledge and experience can be disseminated along several axes—geographic (e.g. Caribbean to Indo-Pacific), protection status (e.g. from Marine Protected Area to shipping harbors), scientists to practitioners. As a way to expand the geographic scope and scale of restoration, the CRC will facilitate access to knowledge and help build capacity to adopt new technologies and methods. Central to this action is sharing established and emerging resources and tools to guide and support practitioners working around the globe (e.g. Shaver et al. 2020). Resources may include: (1) training programs (e.g. virtual courses, recreational and professional SCUBA diving programs, larval-based propagation workshops); (2) planning materials to help expand the community of local stakeholders (e.g. citizen scientists, fishermen, tourism operators, hotels); and (3) new technological tools (e.g. software applications for processing and visualizing monitoring data, web-based portals, and systems developed to upload monitoring data).

The CRC also aims to facilitate the increase in number and the capacity of groups around the world working in coral reef restoration. Ways to build capacity include developing targeted communications about restoration for different audiences (e.g. community groups, various levels of government, and practitioners) and providing resources for effective stakeholder engagement. The key is to identify new practitioner groups to lead or assist with restoration projects, such as tourism operators or experienced divers, and provide the necessary training to support their involvement. Through the combined effect of increasing the capacity and skill of current restoration practitioners, the number of programs conducting coral reef restoration using best available science and knowledge, and the sense of ownership by new and existing stakeholders (Hein et al. 2017; Hesley et al. 2017), restoration efforts may indeed scale up to meaningful levels around the world ensuring a better chance for coral reef persistence (see Bayraktarov et al. 2020 for a regional example).

Closing Remarks: Expanding Representation in the Field to Enhance Efficacy in Restoration

Herein we presented six priorities that can advance the scale, efficiency, and efficacy of coral reef restoration efforts around the world. Although they align with the eight principles for ecological restoration defined by the Society for Ecological Restoration (Table 1, Gann et al. 2019), these priorities do not encompass all that is needed to save coral reefs. There is much research still needed to refine coral interventions that can help coral species adapt and reef communities maintain ecological processes as the oceans continue to change. Systematic trials focused on the restoration of specific ecosystem services, such as coastal protection, are critical in the face of increasingly severe storms. The CRC, in concert with other science and conservation groups including the International Coral Reef Society, International Coral Reef Initiative, Reef Resilience Network, and Australia's Reef Restoration and Adaptation Program, can contribute to the collective stewardship of the world's natural resources. Under the UN Decade of Ecosystem Restoration, the CRC is poised to streamline progress on the priorities outlined above, and we invite our partners to join our community of practice as we strive toward these goals. Only together we can stem the tide of coral reef loss in the time frame necessary for these ecosystems to persist.

Where most reefs are located, there is great disparity among those who work on coral reef research, those who benefit from coral reefs, and the local populace—often people of color who are socioeconomically depressed. Coral reefs are global resources and therefore any constituency committed to their preservation must sufficiently represent the diverse voices of geography, ethnicity, culture, and socioeconomic standing. More research alone will not curtail the loss of coral reef ecosystems, but an integrated approach among practitioners, educators, policymakers, and local community members may. This is the goal of the CRC and we strive for inclusiveness by all vested parties, regardless of location, education, role, or ethnicity. Working in global collaboration as a united coral reef conservation and restoration community could give reefs a chance to feed, protect, delight, and amaze future generations.

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