水 研 機 構 研 報，第50号，83 − 89，令 和 3 年
Bull. Jap. Fish. Res. Edu. Agen. No. 50，83−89，2021

Scaling up coral restoration to meet the demands of a collapsing ecosystem

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Abstract: Coral reefs feed millions of people on earth and are critical to the livelihoods of millions more. They house approximately a quarter of the ocean's biodiversity and are critical to fisheries worldwide. Their importance and fragility to humans cannot be overstated. According to climate models, in about thirty years half of all coral reefs are predicted to disappear due to bleaching caused by unprecedented ocean warming (Bindoff *et al*., 2019). If political and economic forces begin to seriously address emissions, corals will still need help maintaining enough abundance and diversity to rebuild reefs by the end of the century when ocean temperatures may begin to stabilize. With the tacit assumption that emissions will be curbed, an explosion of coral restoration and research into coral "interventions has taken place over the past two years. Coral aquaculture is a pivot point of any advancement in scaling-up restoration or implementing a new intervention – as any and all applications involve the delicate care and propagation of corals in the water or on land. NOAA has taken a lead role in coordinating coral restoration efforts throughout the US and the globe, primarily via the Coral Restoration Consortium and by commissioning the National Academies of Sciences to review coral interventions. This paper highlights recent restoration and intervention successes in the U.S. and globally, and describes NOAA's proposed research and action plan on coral interventions.

Key words: coral, restoration, larval propagation, coral restoration, coral bleaching

Background

Coral reef restoration is a new and rapidly evolving field, made necessary by the calamitous degradation of coral reefs worldwide (Bostrom-Einarsson *et al*., 2020). The primary threat to coral reef ecosystems is ocean warming, and current climate change trajectories which predict a rise in global temperature of 2°C, also predict a loss of 99% of the world's reefs (Bindoff *et al*., 2019). The increasing severity and frequency of climate-change related coral bleaching events and tropical storms are limiting the ability of coral reefs to recover naturally between disturbances (Fabricius *et al*., 2017; Hughes *et al*., 2019). With this rapidly changing, unprecedented scale of decline, there has been an increasing shift in management priorities from a reliance on passive interventions that facilitate natural recovery processes (*e.g.* marine protected areas) to active interventions (*e.g.* coral gardening) which promote adaptation and resilience to changing conditions (Rinkevich 2005, 2008, 2019; Young *et al*., 2012; Possingham *et al*., 2015; Bostrom-Einarsson *et al*., 2020).

The Coral Restoration Consortium

As the field of coral reef restoration and the number of practitioners grows rapidly, so does the need to share the successes and failures, and to ensure the latest science reaches restoration practitioners working underwater. To meet this need, the Coral Restoration Consortium (CRC) was started by NOAA in 2017 to facilitate cooperation and communication among coral reef restoration practitioners, managers, researchers, and educators

2020年12月11日受理（Accepted on December 11, 2020）
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in order to support scientific and practical ingenuity in the field. At its inception the CRC focused on the Caribbean and most of the leadership was from the Caribbean. Within the past year, as reefs have struggled and a growing number of locations engage in restoration, the CRC has expanded globally. In December 2018, the CRC hosted the first ever international conference on coral reef restoration and shortly afterwards voted in new Steering Committee Members from diverse tropical regions. In September 2019, we adopted three Regional Groups (Eastern Tropical Pacific, Latin America, and Australia). Japan is a notable exception and we would welcome a Japanese Regional Group!

Priorities for Coral Restoration

Here we present the six priorities as defined by Coral Restoration Consortium to help guide and promote the scaling-up of coral reef restoration efforts across disciplines and localities. These priorities were not developed to the exclusion of the priorities developed by other organizations. The task of conserving and restoring coral reefs is immense. No one organization nor a consortium of organizations will solve these issues alone. Our goal in articulating these priorities is to encourage others to join, either formally or via parallel efforts, so that we are working towards common goals.

1. Increase restoration efficiency, focusing on scale and cost-effectiveness of deployment.

A large majority of coral reef restoration projects fall under the "coral gardening" umbrella (Bostrom-Einarsson *et al.*, 2020). This technique involves taking coral fragments (often grown in a nursery) and transplanting them onto a degraded reef. The CRC takes pride in tackling restoration issues from multiple angles. While the CRC provides guidance based on the latest science, we also have a firm understanding that most of the restoration occurring in the world today is the relatively simple technique of coral gardening. Although this technique alone will not save the world's coral reefs – it can be done more or less effectively, and more or less efficiently. By improving the efficiency of the most common method, we could vastly increase the potential for corals to weather the next 50–100 years.

2. Scale-up larval propagation for its effective integration in coral reef restoration efforts, with an emphasis on recruit health, growth, and survival.

Larval recruitment from sexually assisted coral reef restoration is essential for improving the genetic diversity of small coral populations. Recently, important advances have been made in coral in vitro fertilization, as well as husbandry of coral larvae (reviewed in Randall *et al.*, 2020). However, larval propagation research has focused on broadcast spawning species and post-settlement mortality continues to be high. To increase the scale and efficiency of larval propagation we need to expand the use of existing larval propagation technologies (more species, more places), develop new technologies, and develop criteria for maximizing genetic diversity.

3. Develop guidance that promotes a holistic approach to coral reef ecosystem restoration.

The CRC is developing a roadmap to help the restoration community evolve from restoring single species of corals to restoring a functioning coral reef ecosystem that will be resilient to current and future biophysical challenges.

4. Develop guidance to ensure restoration of threatened coral species takes place within a comprehensive population genetics management context.

In many places around the world, critical reef-building corals are suffering population declines requiring strategic and thoughtful population management plans that can allow these species to be used effectively in restoration programs. To do this, careful consideration is needed to maximize any remaining genetic diversity of degraded coral populations to allow for successful sexual reproduction, adaptation, and recovery (Baums *et al.*, 2019). Sound guidance is needed to ensure population management plans are developed with appropriate genetic (including epigenetic), propagation, husbandry, and environmental considerations, and an understanding of new reef states (Rinkevich, 2020).

5. Develop and promote the use of standardized terms and metrics for coral reef restoration.

Although terrestrial habitat restoration has been conducted for decades, coral reef restoration is a relatively new field. A lack of common definitions and standardized metrics slows the transmission of ideas and the adoption of new techniques, while limiting comparability across projects (Bostrom-Einsarsson *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 public and private sector stakeholder groups with varying levels of technical expertise. This entails (1) identifying commonly used terms, comparing existing definitions, and establishing standard definitions when possible (while also acknowledging differing or conflicting definitions); and (2) developing and promulgating standard metrics for evaluating the success of coral reef restoration efforts.

6. Develop new and synthesize existing resources to guide and support coral reef restoration practitioners working in diverse geographic locations.

While there is a clear need to increase the efficiency of current methods, develop new techniques and approaches, and formalize the best available science, none of this has utility if the information does not reach the hands of people doing the work. Practitioners need knowledge exchanges, resources to build capacity, and access and training to new technological tools.

Recent Accomplishments of the Coral Restoration Consortium

Most of the work that the Coral Restoration Consortium does is via its Working Groups. Here I will outline a few recent accomplishments. The Monitoring Working Group developed a robust webinar on Photomosaics in coordination with the Reef Resilience Network. The webinar presents the state of the science, the benefits of monitoring reefs with this technology, low-budget as well as high-resolution options for implementation, and resources for adoption. Photo-mosaics are an ideal method for documenting the successes and challenges of reef restoration. The large area images can illustrate the ultimate metric of reef health at an appropriate ecological scale. They document species composition, coral cover, and growth of corals, and allow a re-examination of past data. The webinar relied on expertise from several academics and featured case studies by two reef restoration practitioners. It is archived on the Reef Resilience website. The Monitoring Working Group has also prepared Coral Restoration Monitoring Guidelines (Goergen *et al.*, 2020) as well as a beta version of a Restoration Database.

The Genetics Working Group published two recent papers: Molecular tools for coral reef restoration: beyond biomarker discovery (Parkinson *et al.*, 2020), and Considerations for maximizing the adaptive potential of restored coral populations in the western Atlantic (Baums *et al.*, 2019). The latter is a succinct guide to maximizing genetic diversity using various coral aquaculture techniques for restoration. Despite differences in species and environmental conditions, restoration is happening throughout the globe. Although this paper uses a Caribbean example, the recommendations serve as a helpful starting point for coral aquaculture and restoration elsewhere. The paper explicitly recommends the number of genets per area that should be planted to maintain or maximize diversity. Because bleaching, coral gardening, and assisted evolution have the potential to reduce genetic diversity, having clear guidelines that managers and practitioners can understand is paramount for proper aquaculture and coral reef restoration techniques.

Members of the Land-based and Larval Propagation Working Groups created the first trans-regional crosses of an endangered coral population using cryopreservation (Hagedorn *et al.*, 2018). Rescuing genetically depauperate coral populations by increasing genetic diversity from nearby populations, is one of the most feasible coral interventions proposed. This study demonstrated for the first time that viable juveniles of an endangered coral can be created by artificially inseminating cryo-preserved sperm from one population, with eggs of another regionally-distinct population. This project highlighted the importance and need for additional expertise in coral larval rearing and early life-stage aquaculture. Currently, there are only a handful of such experts worldwide. As corals continue to be threatened with extinction primarily due to climate change, these techniques will become increasingly necessary for the long-term persistence of coral reefs.

US National Academies Review of Coral Interventions

In 2018, NOAA commissioned a two-part study by the U.S. National Academies of Sciences, Engineering, and Medicine to examine ecological and genetic interventions that have the potential to increase the resilience of coral reefs. Most of these techniques rely on coral aquaculture in one form or another. The *Research Review* describes the benefits, potential scale of application, current feasibility, risks, limitations, and infrastructure needs for 23 intervention types (NASEM, 2019a). The *Decision Framework* outlines an adaptive management strategy by which interventions can be evaluated against each other, additional research needs, and recommendations for the Caribbean (NASEM, 2019b). Research on coral interventions is progressing very rapidly and these reports thoroughly capture the current state of the science and make recommendations about how the field should move forward in the near future. Given the accelerating pace of threats to reef ecosystems, it is clear that the coral conservation community will need effective, timely interventions, judiciously applied; and that coordinated bodies of scientists, governmental officials, and other stakeholders, will have to decide which blend of conventional management and interventions will maximize their local reef's ability to persist considering budget, local buy-in and policy.

Based on these reports, NOAA created an action plan to guide how the agency will approach coral interventions in the next one to three years (Vardi *et al.*, 2020). Four primary actions are identified: (1) research and test priority interventions (2) develop local or regional structured decision support. (3) review policy implications of coral interventions. (4) invest in infrastructure, research, and coordinate global efforts to maximize results. Under Action (1), the interventions that NOAA chose to prioritize fit the following six objectives (taken directly from Vardi *et al.*, 2020):

1. **Increase Diversity of Coral Populations.** Coral populations are becoming increasingly small and fragmented, leading to depensatory effects that further limit spawning and recruitment. Increasing the stress tolerance or simply the genetic diversity of small, fragmented populations by importing corals from populations in different parts of the species' range or even from within a population, may be some of the least risky and most effective intervention strategies. The interventions that would help accomplish this objective are: Assisted Gene Flow, Outcross Between Populations, Supportive Breeding, and Cryopreservation.
2. **Improve techniques to support interventions.** Techniques to support interventions include: identifying stress tolerant coral colonies or genes ("Managed Selection"), expanding cryopreservation capabilities to capture current genetic variation for future research and restoration, and harnessing the diversity and abundance of coral spawning. Gamete and larval capture and seeding research is being led by institutions in Japan, Australia, and SECORE international.
3. **Develop a framework for coral epidemiology.** Disease is ravaging Caribbean corals and worsening climate conditions are likely to increase the frequency and severity of coral disease outbreaks worldwide. The research, veterinarian, management, and restoration community needs an epidemiology framework for coral-disease intervention, as well as research and development of therapies and delivery mechanisms.
4. **Stress-harden corals ("Pre-exposure").** Multiple lab experiments and field observation have demonstrated that corals can increase their resilience to temperature and ocean acidification stress under certain conditions.
5. **Manipulate algal symbionts to improve thermal tolerance ("Algal Symbiont Manipulations").**

Coral bleaching is expected to increase in frequency over the next decades. Algal symbionts vary in their thermotolerance. Interventions that take advantage of this variability have experimentally increased the thermotolerance of the coral holobiont.

6. **Assess feasibility of environmental interventions.** Environmental interventions are manipulations to the physical or chemical environment to reduce or prevent bleaching, or reduce acidification. They can be geared to protect high-value sites such as nurseries or frequent tourist destinations. Examples include "Shading" corals from incident light, "Mixing of Cool Water", and changing the alkalinity of reef waters by restoring nearby plant communities ("Seagrass Meadows and Macroalgal Beds").

Conclusion

Due to precipitous ocean warming, restoration (including intervention) is a necessary bridge to stave the demise of tropical coral reef ecosystems. Here I have described how NOAA and the Coral Restoration Consortium are approaching this topic. However, the following cannot be overstated – these interventions are fruitless without addressing basic local and regional reef conditions such as sedimentation, eutrophication, and over-fishing as well as global climate change. Restoration should always be conducted within broader resilience-based management strategies in coral reef ecosystems and ideally within effectively managed marine protected areas that reduce and control background factors of coral reef degradation. Coral reef protection and restoration requires local management efforts as well as climate change mitigation if we want to witness coral reef recovery and the restoration of reef ecosystem services.

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NOAA commissioned the U.S. National Academies to review the science behind next generation coral restoration techniques. Most of these techniques rely on coral aquaculture in one form or another. The Research Review groups 23 interventions types (*e.g.* assisted evolution, marine shading to prevent bleaching, genetic engineering) into four categories and describes the benefits, potential scale of application, current feasibility, risks, limitations, and infrastructure needs for each. The Decision Framework outlines an adaptive management strategy by which interventions can be evaluated against each other, additional research needs, and recommendations for the Caribbean. Research on coral interventions is progressing very rapidly and these reports thoroughly capture the current state of the science and make some solid recommendations about how the field should move forward in the near future.

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Data from more than 2500 reefs across the Indo-Pacific Ocean were analyzed to delineate key drivers and suggest appropriate management at three different levels: protection, recovery, and transformation. Over 50% of surveyed reefs would benefit from recovery which includes some form of restoration in addition to traditional management, and, most importantly, reduction in ocean warming. Using comprehensive studies like this and the Global Coral Reef Monitoring Network's reports, should help nations prioritize coral research, restoration, and management efforts.

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