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Editorial: Coral Reef Restoration in a Changing World: Science-Based Solutions

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Editorial on the Research Topic

Coral Reef Restoration in a Changing World: Science-Based Solutions

Coral reef ecosystems are impacted globally by anthropogenic and climate change, altering ecosystem functioning, and the goods and services reefs provide to societies (Bindoff et al., 2019). Further deterioration of the reef framework and decreases in reef-associated biodiversity are expected, necessitating rehabilitation responses. With the increase of anthropogenic impacts, scientists, conservationists, environmentalists, and decision-making authorities initially employed traditional conservation and rehabilitation approaches (such as additional marine protected areas, no use zones, etc.), and practices that aimed to reduce local stressors such as fisheries and tourism, following the rationale that these activities will lead to rehabilitation of reefs by natural recovery. Yet, this approach of 'passive restoration' has generally failed to achieve its goals (Rinkevich, 2008). As a result, more and more practitioners and scientists are opting for active reef restoration (Baums et al., 2019; Bindoff et al., 2019; Bayraktarov et al., 2020; Kleypas et al., 2021), where human activities directly foster the recovery of damaged reef ecosystems. Advances in fundamental science, further development of an applied tool-box (Vardi et al., 2021), and supplementary ecological engineering approaches (Rinkevich, 2021) are needed to help active restoration succeed.

In one way, the declaration of the Decade on Ecosystem Restoration by the United Nations has raised interest in the methods needed to implement best practices for maximum gain. In another way, the International Coral Reef Society (ICRS) has recently published a science to policy paper (Knowlton et al., 2021) describing a "plan to save coral reefs" where three main pillars are presented as equally important for corals to be retained: 1) mitigation of CO2 emissions; 2) mitigation of local pollution; and 3) active restoration. Our most important scientific society pointed out active restoration as one of the requirements for coral reefs to "survive". Yet a lack of restoration protocols, clear criteria for restoration outcomes and financial support posed significant obstacles to its maturation. Based on the above, this Research Topic entitled: 'Coral Reef Restoration in a Changing World: Science-based Solutions' aimed, to encourage and collect studies searching for innovative techniques and ecological engineering approaches in coral reef restoration programs, with an eye to current and anticipated stressors that affect coral reef ecosystems. The articles were spread across the following themes:

- Propagation and Husbandry
- Improved Outplanting Success
- Size Matters! Advances in Microfragmentation for Reef Restoration
- Building Resilient Reefs: Assisted Evolution and Genetic Influence on Performance and Harnessing Environmental Gradients
- Spawning a Future: Assisting Coral Recruitment Through Larval Husbandry
- Socio-economic Studies of Citizen Participation in Restoration Programs
- Species Ecology - Growth, Feeding, and Reproduction
- Monitoring Assessment Technology and Tools
- Models for Restoration and Management

With 116 researchers from 14 countries, the 19 articles in this Research Topic (https://www.frontiersin.org/research-topics/12642/coral-reef-restoration-in-a-changing-world-science-based-solutions#articles), reveal a broad spectrum of science-based coral reef restoration information from around the world—from Palau, Seychelles, Vietnam, Philippines, Kenia, Mozambique, China, Taiwan, Australia to Bermuda, United States, Mexico, Dominican Republic, France, to the United Kingdom (https://www.frontiersin.org/research-topics/12642/coral-reef-restoration-in-a-changing-world-science-based-solutions#authors). Authors belong to a wide range of organizations from universities, and research centers to Non-Governmental Organizations. The articles published here cover numerous subjects within the themes proposed in this Research Topic and have received worldwide attention— from Ukraine, Lithuania, Poland, Germany, Denmark, Russia, China, India, Australia, United States, France, Mexico, to Pacific islands such as French Polynesia, Mauritius, Reunion, Seychelles, Madagascar, or Maldives to mention a few. The top five countries from which articles have been viewed are the United States, Australia, China, the United Kingdom of Great Britain and Northern Ireland and Germany (https://www.frontiersin.org/research-topics/12642/coral-reef-restoration-in-a-changing-world-science-based-solutions#impact).

MONITORING ASSESSMENT TECHNOLOGY AND TOOLS

The Coral Reef Consortium Monitoring Working Group developed a guide to monitor coral reef restoration and to determine restoration success using two metrics (Goergen et al., 2020): Universal and Goal-Based Performance Metrics (GBPM). Four Universal Metrics were suggested (Landscape/Reef-level, Population-level, Colony-level, and Genetic/Genotypic Diversity) and five GBPM were addressed (Ecological Restoration, Socioeconomic, Event driven Restoration, Climate Change Adaptation, and Research). This Research Topic includes articles with both metrics. Hein et al., synthesized recent state of knowledge, providing information on current concepts changes in coral reef restoration, considering the goals, current methods, and the value of reef restoration in the face of climate change. The study further provided recommendations, including the implementation necessity of effective restoration planning/design; the need for defining of specific goals/objectives; more appropriated methods for specific goals/cost, effectiveness, and scalability in reef restoration methods, and four directions to restore coral reef ecosystems. Dao et al., stressed that in many cases, corals live close to their temperature limit, therefore, higher sea surface temperatures may follow with prolonged bleaching events, leading to coral death. Using climate change projections for the Cu Lao Cham-Hoi biosphere (they raised concerns that corals will face prolonged temperature stresses, calling for immediate actions. Dang et al., focused on the role of sea urchins roles in maintaining coral reef equilibria. Sea urchins are important because they can exert top-down control on algae, following the overfishing of other herbivores such as fishes and gastropods. They also revealed a relationship between coral juveniles' survivorship and sea urchin density. Cortés-Useche et al., stressed the importance of fish assemblages in restoration and presented an innovative method where first life stages of fishes are considered in reef regeneration. Protecting early life stages from predation in aquaria and delaying their release until they are juveniles may speed up habitat recovering processes. The authors demonstrated promising results to consolidate this method in the Caribbean Sea.

PROPAGATION AND HUSBANDRY

Coral reef restoration through larval rearing and sexually propagated juvenile corals is crucial for preserving coral reef ecosystem functions and services under global and local stressors (Baums, 2008; Hancock et al., 2021). Sellares-Blasco et al., studied a bottleneck in reef restoration, improved propagation, and husbandry, focusing on coral assisted fertilization, larval rearing/recruit propagation success in the Dominican Republic. Two years following inception, they developed an annual regional coral spawning prediction calendar, seeding >268,200 recruits in 1,880m^2 reef. Maneval et al., maricultured *Acropora cervicornis* fragments from different genets in two nursery types at shallow and deep-water depths over 6.5 months. While documenting high variation between genets, they recorded higher growth rates in the deep-water nurseries that had less biofouling, thus requiring reduced maintenance.

IMPROVED OUTPLANTING SUCCESS

Nowadays, most restoration efforts focus on outplanting corals from nurseries or freshly-pruned fragments to restore coral reefs, and outcomes depend on survival rates. Calle-Triviño et al., highlighted the importance of the improvement of degraded reefs' ecological functions. where coral restoration has been implemented Using *Acropora cervicornis* outplants into four-sites, they recorded increased fish biomass, coral cover, and structural complexity, providing much-needed evidence for active restoration's ecological benefits. Schill et al., have tested imaging spectroscopy from the Global Airborne Observatory (GAO) and reported transplants' survivorship rates at restored sites (Dominican Republic, 3-7m depths) over 11 months. Results revealed that GAO-derived map products provided a quantitative and replicable method for selecting restoration sites characterized by increasing outplant survivals.

SIZE MATTERS! ADVANCES IN MICROFRAGMENTATION FOR REEF RESTORATION

The microfragmentation technique, allows small-sized ramets at the nubbin sizes to grow more rapidly compared to coral fragments of larger sizes. Papke et al., have employed an outdoor experimental setting with *Acropora palmata* microfragments, revealing differential effects of substrates (cement, ceramic) and genets on coral growth. Genet had a more substantial influence than substrate and coral growth on cement-substrates was better when compared to ceramic substrates, suggesting that both factors, genet and substrate should be considered. Koch et al., used a structured light 3D-scanner to evaluate surface-area (SA) measurements of living tissues over time, and developed a novel protocol for quantifying growth rate of fragmented living corals. Compared with the conventional 2D approach (photography and ImageJ analysis), they found that the 3D approach had some advantages but was slower and more expensive. Yet, it is more accurate for measuring SA for complex colony shapes.

BUILDING RESILIENT REEFS: ASSISTED EVOLUTION AND GENETIC INFLUENCE ON PERFORMANCE AND HARNESSING ENVIRONMENTAL GRADIENTS

Climate change affects reef coverage, function, and distribution of species. The question thus arises which species and genets to use when restoring reefs given that environmental conditions are expected to deteriorate for some time to come. Quigley et al., bred corals with variable heat-tolerance, by crossing surviving colonies from the 2016-2017 mass bleaching events among three regions of the Great Barrier Reef (GBR) and followed survival/growth of offspring over 217 days. Crosses within regions had the highest survival rates, suggesting local adaptation. Yet, some between-region crosses grew faster, demonstrating that breeding corals across latitudes may provide a viable approach to increase heat tolerance of restoration stock. Caruso et al., focused on the importance of stress-tolerant species of corals to ensure long-term ecosystem functioning and viability, highlighting the potential costs as well as the existing gap of knowledge associated with their approach. Humanes et al., considered the question if it makes sense to restore reefs with the same coral stock that is currently failing to thrive. Knowing that increasing water temperatures will continue for decades to come, restoration practitioners may rely on selectively breed corals for higher temperature tolerance. Humanes et al., further laid out a framework for how selective breeding may be carried-out, providing data on survivorship and growth of selectively bred corals.

SPAWNING A FUTURE: ASSISTING CORAL RECRUITMENT THROUGH LARVAL HUSBANDRY

While unmitigated CO_2 emissions and the warming oceans they cause remain the biggest threat to reefs world-wide, the lack of coral recruits has emerged as a prime obstacle to coral recovery and adaptation. Harrison et al., reported that "increased coral larval supply enhances recruitment for coral and fish habitat restoration" and that supplying larvae directly to a degraded reef may reestablish breeding populations, increasing coral cover and enhancing fish abundance. Randall et al., experimented with refugia for *Acropora tenuis* recruits on artificial settlement devices, with the aim of reducing grazing and predation pressure. Results revealed increased recruit survival on tiles with wide slits versus lattice grid or flat control tiles. Such a design prevents predation, grazing, and sediment accumulation, which are some of the significant causes for post-settlement coral mortality. Luo et al., examined the genetic diversity and gene flow patterns in *Porites lutea* populations from 9 to 22 degrees latitude in the South China Sea, a less studied region despite its abundant reefs. As elsewhere in the Pacific, gene flows was high among *P. lutea* populations. Instead, the authors found that that genetic diversity correlated with temperature gradients.

SPECIES ECOLOGY - GROWTH, FEEDING, AND REPRODUCTION

Understanding the ecology of coral species should also be considered in conjunction with local/global stressors. VanWynen et al., studied whether inter-species hybrids have accelerated skeletal growth during coral restoration. They found variation in growth rates among two Caribbean Acropora species and their F1 hybrid at three coral nurseries in the Bahamas. The F1 hybrids grew faster than the two parental species, suggesting that the F1 hybrid represents an alternative to repopulate reefs requiring enhanced coral growth. Authors also show that growth rates vary across locations, suggesting that some sites harbor better conditions to enhance coral growth and develop nurseries.

MODELS FOR RESTORATION AND MANAGEMENT

There has been a rapid development of new tools in modeling restoration and management strategies that opens new avenues to improve restoration outcomes. Modelling is necessary to consider the complex influences of global climate impacts and multiple local stressors and help integrate the recent accumulation of massive data sets. Feng et al., assessed the potential environmental impacts of artificial upwelling (AU) over large areas in the GBR, South China, and Hawaiian regions *via* a 3D Earth System model. They obtained variable results from upwelling layer models (from 130 to 550 m) and showed that AU can effectively reduce sea surface temperature (SST) and degree heating weeks (DHW) and slow future coral bleaching events. However, when water is upwelled from a deeper layer (550m) and at high rates, it may cause severe risk to corals, revealing the importance of regional models together with experimental studies on the effects of UA on coral reef systems. Coral reef restoration research further generates an enormous amount of essential information to be appropriately and systematically organized and stored. Moura et al., presented the Coral Sample Registry (CSR), an online resource that establishes and integrates diverse coral restoration data sets. The CRS concept is based on fostering dialogues among restoration practitioners, federal and state agency managers, and researchers for centralizing information on sample collection events.

In summary, this Research Topic showcases the fast development of tools to support active coral reef restoration and highlighted the importance of a comprehensive tool-box. Some of the approaches are more general and can be applied to all most reefs worldwide, and others are more restricted to specific coral taxa and/or reef areas. Coral reef restoration emerged over the last three decades and is now a fully recognized field that is aiming to preserve functional reef diversity until CO_2 emissions have been reduced and the rate of ocean warming slows.

AUTHOR CONTRIBUTIONS

J-AG and BR wrote the first draft of the manuscript. BR, IB, J-AG, CP, ATB, SR edited final manuscript. All authors contributed to summaries and manuscript revision, read, and approved the submitted version.

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REFERENCES

Baums, I. B. (2008). Restoration Genetics Guide for Coral Reef Conservation. *Mol. Ecol.* 17 (12), 2796–2811. doi: 10.1111/j.1365-294X.2008.03787.x

Baums, I. B., Baker, A. C., Davies, S. W., Grottoli, A. G., Kenkel, C. D., Kitchen, S. A., et al. (2019). Considerations for Maximizing the Adaptive Potential of Restored Coral Populations in the Western Atlantic. *Ecol. Appl.* 29 (8), e01978. doi: 10.1002/eap.1978

Bayraktarov, E., Banaszak, A. T., Montoya-Maya, P., Kleypas, J., Arias-González, J. E., Blanco, M., et al. (2020). Coral Reef Restoration Efforts in Latin American Countries and Territories. *PloS One* 15 (8), e0228477. doi: 10.1371/journal.pone.0228477

Bindoff, N. L., Cheung, W. W., Kairo, J. G., Arstegui, J., Guinder, V. A., Hallberg, R., et al. (2019). "Changing Ocean, Marine Ecosystems, and Dependent Communities. Chapter 5," in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Ed. H. O. Pörtner, et al (Geneva Switzerland: IPCC).

Goergen, E. A., Schopmeyer, S., Moulding, A. L., Moura, A., Kramer, P., and Viehman, T. S. (2020). "Coral Reef Restoration Monitoring Guide: Methods to Evaluate Restoration Success From Local to Ecosystem Scales," in *NOAA Technical Memorandum NOS NCCOS 279* (Silver Spring, MD), 145 pp. doi: 10.25923/xndz-h538

Hancock, J. R., Barrows, A. R., Roome, T. C., and Huffmyer, A. S. (2021). Coral Husbandry for Ocean Futures: Leveraging Abiotic Factors to Increase Survivorship, Growth, and Resilience in Juvenile *Montipora Capitata*. *Mar. Ecol. Prog. Ser.* 657, 123–133. doi: 10.3354/meps13534

Kleypas, J. A., Allemand, D., Anthony, K., Baker, A. C., Beck, M., Hale, L. Z., et al. (2021). Designing a Blueprint for Coral Reef Survival. *Biol. Conserv.* 257, 109107. doi: 10.1016/j.biocon.2021.109107

Knowlton, N., Grottoli, A. G., Kleypas, J., Obura, D., Corcoran, E., de Goeij, J. M., et al. (2021). "Rebuilding Coral Reefs: A Decadal Grand Challenge," in *International Coral Reef Society and Future Earth Coasts*, 56 pp. doi: 10.53642/NRKY9386

Rinkevich, B. (2008). Management of Coral Reefs: We Have Gone Wrong When Neglecting Active Reef Restoration. *Mar. Pollut. Bull.* 56, 1821–1824. doi: 10.1016/j.marpolbul.2008.08.014

Rinkevich, B. (2021). Ecological Engineering Approaches in Coral Reef Restoration. *ICES J. Mar. Sci.* 78 (1), 410–420. doi: 10.1093/icesjms/fsaa022

Vardi, T., Hoot, W. C., Levy, J., Shaver, E., Winters, R. S., Banaszak, A. T., et al. (2021). Six Priorities to Advance the Science and Practice of Coral Reef Restoration Worldwide. *Restor. Ecol.* 29 (8), e13498. doi: 10.1111/rec.13498

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