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Editorial

Towards Coral Reef Resilience

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Coral reef habitats provide valuable ecosystem services which have benefitted human society for millennia, but intense anthropogenic pressure, especially in the latter part of the last century, has resulted in widespread habitat degradation and loss of ecosystem services with severe environmental and societal consequences. Climate change impacts are expected to increase habitat stress further and compromise recovery and functioning of large swathes of reefs globally. Future scenarios range from almost total devastation to continued existence but in modified ecological states. Are coral reefs sufficiently resilient to withstand the changed environmental conditions of the future? This is an interesting aspect to consider. Numerous types of management responses have been attempted, and broadly include protection and restoration. Research is necessary to gain a better understanding of how reefs will respond to improved management as well as a changing climate. This would encompass various approaches to characterize and analyze reef responses from the molecular to community and habitat levels. Analyses may rely on spatially extensive and/or long-term monitoring data to detect and understand specific trends that are relevant to the formulation of novel management policy.

Research activity on reef resilience is increasing and will continue expanding as each piece of research adds some facet of information that helps to build the big picture. The five contributions (two reviews and three long-term monitoring assessments) in this volume provide interesting and critical information in this area.

New approaches to reef restoration built upon the reef gardening concept are proposed by Rinkevich [1]. They include improved coral gardening techniques, ecological engineering, assisted migration/colonization, assisted genetics/evolution, assisted microbiome, coral epigenetics, and coral chimerism. These components combined in an active reef restoration toolbox will reinforce the reef gardening restoration approach by helping to enhance coral resilience and adaptation to changing conditions and perhaps enhance our endeavor to secure a future for coral reefs.

From their review of the relationship between thermal stress and resilience, Carballo-Bolaños et al. [2] contend that natural response mechanisms of corals may not be sufficient to contribute to the habitat's ecological functioning if current greenhouse gas emission levels are not reduced. Corals mitigate thermal stress through various mechanisms including acclimatization, adaptation, and association with thermally tolerant endosymbionts. They resist thermal stress through molecular protective mechanisms such as heat shock proteins and antioxidant enzymes. Furthermore, each species of coral host and endosymbiont responds differently to thermal stress, highlighting the physiological diversity and complexity of the symbiotic partners. They conclude that thermal stress tolerance can be enhanced by approaches mentioned by Rinkevich [1], which include assisted migration/colonization, assisted evolution, ecological engineering, assisted genetics, and coral epigenetics.

The community analysis of Malauka'a fringing reef at Kāne'ohe Bay, Hawai'i, by Barnhill and Bahr [3] showed that corals acclimatized to a climate change-induced 0.96 °C increase over an 18-year period (2000 to 2018)—covering two major bleaching events—by retaining live coral cover and maintaining the two dominant species *Porites compressa* and *Montipora capitata*. However, a coral species compositional shift was attributed to the local loss of two species (*Pocillopora meandrina* and *Porites lobata*), replaced by a previously unrecorded species (*Leptastrea purpurea*). A significant decrease of the alga *Dictyosphaeria*, dominant in 2000, was seen together with the loss of *Gracilaria salicornia* and *Kappaphycus alvarezii*, accompanying an increase in non-coral substrate cover. The authors caution that while the reef system displayed resilience, the response may not be sufficiently swift to tolerate future temperature elevation and increasing bleaching frequency [3].

Keshavmurthy et al [4]. analyzed spatial and temporal (1986 to 2019) dynamics of corals in Kenting National Park (KNP), southern Taiwan, which features a fluctuating thermal environment induced by a branch of the Kuroshio Current and tide-induced upwelling that favored thermally-resistant corals, especially those close to the thermal effluent of a nuclear power plant. Major typhoons and bleaching caused coral cover fluctuations and spatial heterogeneity in coral cover recovery suggesting variable degrees of reef resilience between localities. Corals exposed to progressively warmer and fluctuating thermal environments possessed the ability to modify their endosymbiont community with a dominance shift to the thermally-tolerant *Durusdinium* spp. and reduce bleaching. Their study indicated that within a small geographical range with unique environmental settings and ecological characteristics, corals may be resilient to bleaching. They highlight the relevance of conservation efforts that are resilience-based to address climate change challenges [4].

An assessment of the resilience potential of inshore and offshore reef communities in the western part of the Gulf of Thailand by Sutthacheep et al. [5] over the last two decades showed that some sites in both areas had low resilience to bleaching. These reefs were also exposed to anthropogenic disturbances. However, some sites both inshore and offshore had high resilience potential based on bleaching survival rates although juvenile coral density was low. At most sites, juvenile coral density was not dependent on adult coral cover, particularly for *Acropora*. The authors recommend that resilience-based management should take into consideration natural processes that promote the resistance and recovery of corals, appropriate restoration efforts, and physical interventions such as shading during bleaching events.

Whether a reef is resilient to disturbance is challenging to uncover as it requires understanding of corals' susceptibility to and recovery from various stressors, which are often interacting with immense complexity. As presented in a number of the contributions here, evaluating the resilience of natural reefs requires long-term community data (>2 decades) and high-resolution environmental measurements. Due to the multiple factors involved, it is of no surprise that reef conditions and recovery outcomes post-disturbance are variable over relatively small spatial scales. These studies, and others emerging over the last decade, provide insight into the trajectories of coral reefs amidst more severe and frequent climate-related perturbations, including the possible scenario in which corals continue to survive and even dominate certain reefs, but with dramatic transformations at community to molecular levels. To anticipate these changes, restoration and management approaches must consider building resilience factors into coral reefs to future-proof these diverse and beneficial ecosystems.

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