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The critical role of coral reef restoration in a changing world

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Recent discussions have raised concerns about the long-term effectiveness of coral reef restoration efforts, questioning whether current interventions can effectively address the ongoing loss of reef ecosystems. However, details matter and vary greatly with respect to scale, social context and benefits, and diverse approaches are needed to maintain functional coral reef ecosystems.

Concerns have recently been raised about the utility and potential risks associated with coral reef restoration activities, including ecological, geoengineering and bioengineering approaches[1,2]. Restoration interventionist approaches were critiqued as lacking compelling empirical evidence to improve outcomes for reefs; distracting attention from dealing with the causes of reef decline; undermining critical research on changing reefs; and creating undue optimism in the scientific and technological ability to restore ecosystems. As practitioners and scientists dedicated to advancing the rigour, feasibility, scalability and effectiveness of coral reef restoration, we contend that these concerns overlook the important roles restoration plays in coral reef conservation. Here we highlight the complexities of coral reef restoration, which must consider the nuanced, region-specific strategies developed in response to urgent local ecological, cultural, social and economic challenges, as well as the need for experimentation to rapidly advance the science necessary for effective restoration. Furthermore, the role of restoration is particularly important in responding to smaller-scale and localized disturbances, which require targeted restorative actions. Three factors are particularly overlooked in recent narratives critical of restoration[1,2], as discussed below.

Evidence-based coral reef restoration

Both the science and practice of restoration are well established for many terrestrial ecosystems, but it is still a relatively young field in the marine world. Nevertheless, conceptual and empirical scientific support is emerging for coral reef restoration, a broad field that includes active intervention efforts to support the resilience-oriented restoration of reef structure, function and diversity in response to stress, ensuring the continued provision of ecosystem services[3,4]. The field has experienced major advances in recent years, increasing the scale of spatial activity and ecological complexity[3–7]. Early evidence of coral transplantation as a restoration technique to assist the natural recovery of coral communities dates back to the 1970s[7]. More complex longer-term efforts, such as Hope Reef in Indonesia[5], Laughing Bird Caye National Park in Belize[6] and projects elsewhere[3,4] have demonstrated, at various ecological levels, assisted coral reef recovery. For example, net reef carbonate budgets at degraded sites shifted from negative to positive following coral transplantation, tripled over four years and became comparable to healthy reefs, based on surveys across restored, non-restored and healthy reference areas[5]. Similarly, comparisons between negative control, reference sites and intervention sites show that large-scale, science-based restoration projects with at least a three-year time frame can effectively assist reef recovery[8].

Technological advances have played a critical role in accelerating the effectiveness of conservation and ultimately restoration efforts. For instance, standard genotyping of wild and captive corals[9] alongside improved coral husbandry allowed the restoration community in the Florida Keys to collect enough fragments for all 167 known wild Florida *Acropora palmata* genets for preservation in land-based facilities, preventing the loss of critical genotypic diversity during the 2023 heatwave[10]. In the Philippines, larval enhancement successfully restored breeding coral populations in an area lacking natural recruitment due to past environmental damage. *Acropora tenuis* colonies grew to reproductive size within two to three years from microscopic larvae settled on degraded, algae-dominated reefs, leading to high coral cover and fish populations[11]. By contrast, control plots without larvae showed no recovery[11]. Coral reef restoration projects globally continue to expand their scales, over space and time, often through staged activity[12] that can scale 'up', 'out' or 'deep'[13].

New science needs to learn

Criticisms of restoration confuse the outcomes of restoration ecology experiments, that is, the 'science' of restoration designed for rapid iteration and learning to improve effectiveness, with outcomes of ecological restoration (Fig. 1)[3]. In many instances, applying 'fast fail' methodologies for rapid learning and iteration is required to quickly identify restoration approaches best suited to local environmental and ecological contexts, leading to inferences that restoration has failed (or is ineffective)[2] when, in fact, it is a critical pathway to success.

Despite the successes, many efforts so far have been reactive and hence constrained in their ability to have a positive habitat- or ecosystem-level impact. Reef restoration, like all conservation efforts, is hindered by challenges such as limited funding, socio-economic barriers, political constraints and slow regulatory implementation. Even so, many reef restoration efforts to date, regardless of their success in reef recovery, have catalysed multiple 'carry-over outcomes'. These include cross-discipline and industry connections as well as

Fig. 1 | Examples of restored coral reefs, coral nurseries and community-led stakeholder initiatives. a,**b**, Restored coral reefs in the Lingayen Gulf in Pangasinan, northern Luzon, Philippines (**a**), where sexual larval-based propagation was used to restore an area with almost no natural recruitment[11], and in Salisi Besar, Spermonde Archipelago, Indonesia (**b**), where rubble was replaced by reef star restoration structures that are now difficult to see beneath the established reef. **c**, Restored coral reef in Pickles Reef, Florida Keys Marine Sanctuary, USA. **d**,**e**, Community-led coral nurseries and restoration efforts at the Great Barrier Reef, Australia (**d**) and Indonesia (**e**). Panel **a** reproduced from ref. 11 under a Creative Commons license CC BY 4.0. Credits: **b**,**e**, Indo Pacific Films; **c**, Coral Restoration Foundation; **d**, Emma Camp.

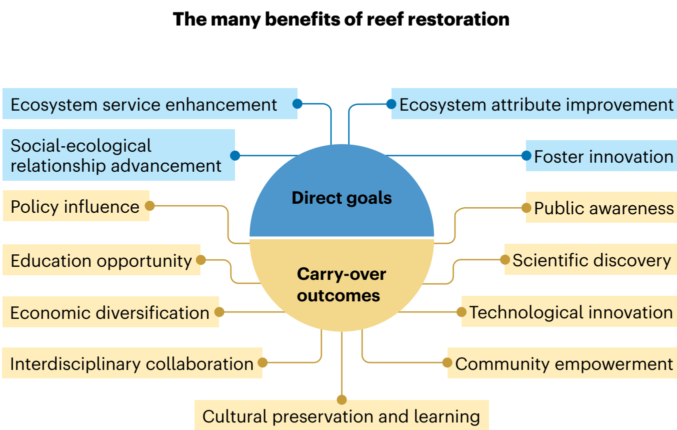

Fig. 2 | Coral reef restoration offers both direct and indirect benefits with short- and long-term impacts. Direct goals include: improving ecosystem health (for example, coral cover, biodiversity); enhancing ecosystem services (fisheries, coastal protection, tourism); fostering innovation through cost-effective solutions; and strengthening sustainable social-ecological relationships. Indirect 'carry-over' outcomes include: driving scientific research; developing new technologies; promoting interdisciplinary collaboration; empowering communities through co-design and stewardship; preserving cultural practices; supporting economic diversification; raising public awareness; creating educational opportunities; and influencing policy from local to international levels.

innovations with broad-reaching benefits (Fig. 2), such as the selection of more resilient source corals (species, population genetics and phenotypes); reef imaging and digital reconstruction to support planning and monitoring; ecological modelling to evaluate ecosystem-level improvements; novel aquaculture practices to support larger-scale larval production and outplanting; artificial intelligence- and machine learning-based analytical approaches; and large-scale experimental standardization and data sharing. Together, these innovations directly and indirectly deepen our knowledge and insight to inform more effective reef management.

Local challenges differ and one size does not fit all

Perceptions that restoration efforts distract from addressing the root causes of coral decline, notably the primary driver (climate change), are not uncommon and have been extensively discussed. Restoration practitioners and scientists have persistently communicated that mitigating climate change is crucial and that we "cannot restore our way out of the climate crisis"[3]; in fact, restoration and addressing climate change – as well as local challenges – are interdependent and complementary, not mutually exclusive.

First, local contexts matter greatly, and restoration cannot be performed without understanding and managing local stressors. Locally customized approaches are critical for restoration to be effective and need to consider the complex specific socio-ecological networks[12], spanning site ecologies and disturbance histories as well as local expertise, needs and resources. Many reefs will not meet the criteria to be restored, nor will a single restoration tool be effective everywhere under all conditions. Tools and protocols must be customized to support site- and condition-specific bottlenecks in reef recovery, informed by a detailed scientific understanding of specific socio-ecological systems and efforts planned accordingly[12], including through the incorporation of resilience-oriented frameworks to ensure interventions are long-lasting.

Second, criticism often focuses on the anticipated need for large-scale (for example, regional) reef restoration as climate change progresses. Such centralized large-scale aspirations are particularly pertinent for extensive reef systems such as the Great Barrier Reef. However, such critique neglects the urgent needs, different economic reality and substantial restoration efforts already underway, particularly in low- to middle-income countries, as well as at priority sites on the Great Barrier Reef. In the latter case, for example, stakeholder-led efforts at some targeted high-value tourism reef sites have shown improved coral cover and/or abundance of small-size classes needed to enhance recovery and overcome natural recruitment bottlenecks[4,12]. In many cases around the world, restoration projects have been initiated simply as local attempts to preserve the resources on which subsistence or industry depends, often based on generations of historical knowledge of reef form and function rather than model-based forecasts. Notably, restoration projects in the Americas[6,13,14] and Indo-Pacific[4,5,12] that are underpinned by research co-designed by scientists and other stakeholders are making notable strides in preserving and restoring reef ecosystems with cost-effective interventions at larger scales than other developed countries[6,13,14].

Third, concerns regarding the pace and severity of current climate change impacts and the uncertainty of climate change projections simply underpin the need to act. We no longer need to balance predictions as current declines are certain enough to justify immediate action. Local communities have no option but to respond where climate (and/or local) impacts are already pronounced and clearly jeopardize livelihoods and homes when reef services (coastal protection, food security) are lost. Community co-design, modelling, in situ and ex situ laboratory production, and small-scale studies have proved crucial to support prudent decisions[11,12,14]. However, to recalibrate the discussion, we believe the risks of action must be balanced against the risk of inaction while we continue to advocate the critical need to reduce emissions.

Restoration is part of a broader conservation strategy

Recent years have witnessed forecasts becoming reality: increased frequencies and intensities of coral bleaching events have led to unprecedented rates of coral mortality. Mitigation and adaptation strategies are necessary to prevent the loss of a majority of coral reefs globally by the time greenhouse gas emissions and other primary stressors are effectively addressed. We need to buy time and/or fast-track the capacity of corals to adapt and reefs to become more resilient to current rates of change. Active coral reef restoration is one of the three equally important pillars (besides mitigating local stressors and reducing global climate threats) essential to a contemporary coral conservation strategy[15]. Consequently, the dismissal of restoration efforts as ineffective or superficial undermines a crucial component of coral reef conservation. While we widely advocate the need to critically evaluate and continuously improve restoration practices and monitoring, it is equally important to recognize the substantial progress and successes achieved in this field. Before we get lost in absolutes (yes, we need evidence-based practices, which require carefully building that evidence; no, we don't need blind heroism or misleading promises of quick fixes to solve a global crisis), it is essential to remember the complexity and urgency of the coral crisis and embrace the need for equally diverse and multifaceted solutions.

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