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Comment

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Restoration as a meaningful aid to ecological recovery of coral reefs

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Restoration supports the recovery of ecological attributes such as cover, complexity, and diversity to slow the areal decline of natural ecosystems. Restoration activity is intensifying worldwide to combat persistent stressors that are driving global declines to the extent and resilience of coral reefs. However, restoration is disputed as a meaningful aid to reef ecological recovery, often as an expensive distraction to addressing the root causes of reef loss. We contend this dispute partly stems from inferences drawn from small-scale experimental restoration outcomes amplified by misconceptions around cost-based reasoning. Alongside aggressive emissions reductions, we advocate urgent investment in coral reef ecosystem restoration as part of the management toolbox to combat the destruction of reefs as we know them within decades.

Coral reefs have an estimated trillion-dollar value, supporting goods and services for almost one billion stakeholders worldwide[1], many of whom are accelerating stewardship-based management of dwindling reef resources[1–3]. While coral reef restoration has been practiced for 50 years, activity has recently surged as reefs catastrophically degrade under climate change and persistent local stressors. Increasingly frequent and severe mass coral bleaching episodes have been eroding reefs across the globe since the 1980s[4]. Another global mass coral bleaching episode began in 2023[5], reinforcing the need for action more than ever[1–3]. Reef restoration efforts have been catalyzed by international commitments to significantly recover the area and health of natural ecosystems (e.g., UN Decade for Ecosystem Restoration, Kunming-Montreal Global Biodiversity Framework, Coral Reef Breakthrough[1,2], and more diverse financing instruments including parametric insurance[6]). Consequently, the coral reef restoration community continues to grow and integrate across practitioners, scientists, managers, policymakers, and the private sector—aiming to protect or enhance ecosystem services, such as tourism and coastal resilience. However, restoration has reached a pivotal point: despite globally intensifying activity, innovation, and financing, the role of restoration in meaningfully aiding the ecological recovery of coral reefs is in dispute. Critical commentaries of reef restoration [e.g., refs. 7,8] argue that a limited scale of activity is an expensive distraction from addressing the root causes of reef decline, often intended to increase attention to other stressors or combat other media messaging that restoration activity "saves reefs". However, the net outcome is an inferred interpretation that restoration plays no tangible role in reef management. Such perceptions are at direct odds with the growing evidence for restoration in aiding ecological recovery [e.g., ref. 9], including for reefs [e.g., refs. 10,11; Fig. 1]. We contend that such disputed perceptions, in part, arise where ecological (or ecosystem) restoration is inferred from the outcomes of restoration ecology experiments and are exacerbated when restoration viability is reasoned around cost.

Restoration for coral reefs is described as an active intervention to assist the recovery of reef structure, function, and key species in the face of stress, promoting resilience and the sustainable delivery of ecosystem services[3,12]. Such interventions exist along a continuum of approaches, from mitigation and rehabilitation[12,13] to building longer-term ecosystem resilience to the impacts of climate change through assisted-evolution[2,3,12]. However, two foundational disciplines underpin any of these approaches: *ecological restoration*, the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed; and restoration ecology, the science underpinning the practice of ecosystem restoration[13]. Employing both is critical to achieving restoration success, i.e., how well projects can meet articulated goals[14,15].

Restoration ecology experiments include discrete "fast fail", activities designed to develop techniques and detect problems as early as is feasible in the development phase, and pilot studies. Both carry specific time- and scale-dependent research-and-development objectives and often serve as essential prerequisites for achieving ecological restoration[6,12–15]. Experiments may also be necessary to forecast risks and benefits to governing authorities. However, judgements of how well reef restoration activity can deliver widespread ecosystem impacts have relied on either extrapolating outcomes from restoration ecology experiments[16] or collective assessments of restoration activity[15–17], which conflate outcomes from ecological experiments with those from restoration. Indeed, the most recent comprehensive feasibility reviews of coral reef restoration drew >66% of evidence from small-scale experiments rather than restoration projects[16,17]. In such studies, viability (or scalability) may be erroneously inferred where expectations, outcomes, and measures of success for ecological restoration are considered equal to those from restoration ecology experiments. Whilst reef restoration has been underway for decades, the relatively few early efforts have often been unable to monitor and report longer term ecological outcomes via resource constraints. Reef scale restoration has now begun in earnest within the last years, but few have yet moved past the early phases. Consequently, reef restoration projects have rarely been well documented at scale—the net result of assessing all reef restoration and experimentation together is thus a skewed perception of collective restoration activity.

Differentiating ecological restoration from restoration ecology is critical, where the perception of meaningful reef restoration is framed around

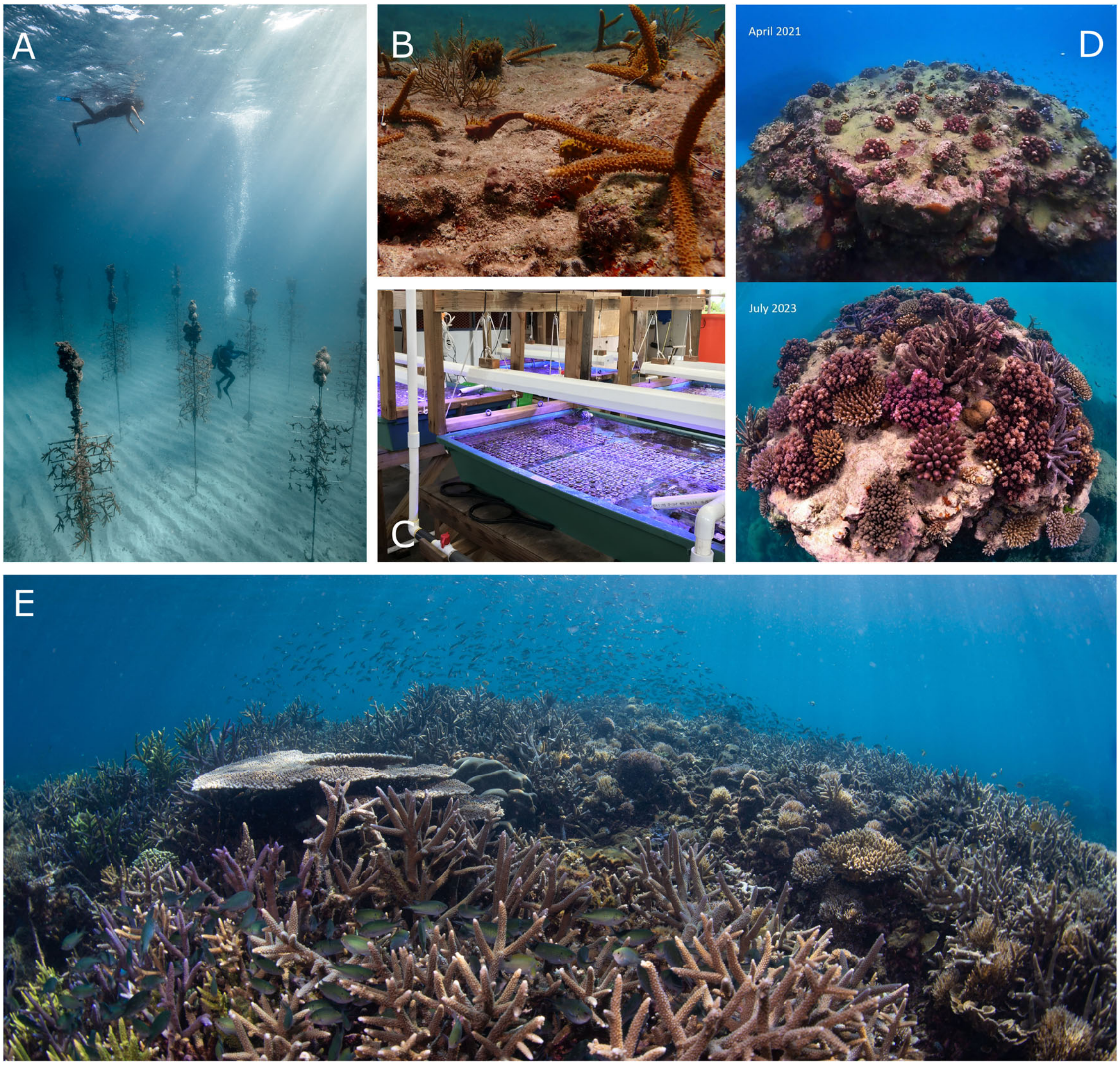

Fig. 1 | Examples of reef restoration practice spanning restoration ecology to ecological restoration. **A** In situ nursery propagation for at-scale reef deployment and **B** subsequent outplanting of *Acropora cervicornis* in Florida, USA (Credit: Coral Restoration Foundation™); **C** Ex situ propagation of diverse coral assemblages for restoration ecology experiments in Palau (Credit: Adrianna Humanes); **D** Site stewardship outcome of diverse coral reef assemblage on the Great Barrier Reef after <1 year (April 2021) and ~3 years (July 2023) since coral planting (Credit: John Edmondson/Coral Nurture Program); **E** Reef ecological outcomes following 4 years of restoration using the Mars Assisted Reef Restoration System (Spermonde Archipelago, Southwest Sulawesi, Indonesia) (Credit: MARS Sustainable Solutions).

service values and cost[3,18,19]. A common criticism of reef restoration viability to date is that it remains too expensive to deliver ecological recovery at any meaningful scale. Financial considerations include cost-effectiveness, i.e., the output of item-based metrics such as the cost per coral planted; or cost-benefit, i.e., costs relative to an outcome, such as the extent of service value compared to restoration cost for any given reef unit[15,18]. Assessing coral restoration in this manner has two challenges. First, assessments inappropriately aggregate disparate activities with different intentions, purposes, and expected outcomes. Second, an implicit normative assumption whereby lower cost, however measured, is always better regardless of context or desired outcomes. Restoration ecology experiments often examine the cost or cost-effectiveness of specific methods or tools[6,15,18], a practical approach useful for decision-making around scaled activity[6,15] but not forecasting ecological outcomes and ecological restoration success. Labeling activity as "expensive" [e.g., refs. 8,17])—the cost relative to the financing available to meet long-term goals—carries little meaning where the benefits, which are difficult to measure, are not quantified. However, benefit valuation often defaults to quantifying the instrumental worth returned or preserved (e.g., tourism economic value[6]), overshadowing the fundamental need to restore intrinsic value[19,20] in parallel to trivializing the conversion of ecological and cultural values to economic values.

It is unlikely that many restoration programs will be inexpensive. Therefore, meaningful restoration must be framed around safeguarding coral reefs' intrinsic and instrumental values[19,20], including service provision at targeted sites[3,12,14]; as such, quantifying ecosystem service extent inherent to the socio-ecological system in question should be a core starting point to ask, does restoration add value? Or, by extension, what is the cost of no restoration activity?[21] Asking such questions is more important than ever. Reef restoration activity has particularly advanced in the Caribbean as a result of decades of loss to critical coral populations[11,22]. However, recent significant coral loss to restoration efforts in the Caribbean from the 2023 mass bleaching [e.g., refs. 22,23], has further fueled commentaries that challenge the value of meaningful restoration [e.g., "failed solution", ref. 24]. In most cases, coral genotypic and phenotypic diversity—factors that underpin population resilience—is now better understood and preserved (but otherwise may have been lost) only because of these Caribbean restoration efforts. Consequently, sites on the brink of collapse now at least contain population remnants. Practitioners now better understand the benefits of restoration under repeated thermal stress[25] and optimized site selection for restoration[22] through difficult lessons learned. What if restoration had not been implemented?

Coral reefs carry immense value[1–3,6,12], so developing mechanisms to weigh costs against benefits is critical for investment decision-making around reef restoration. Even so, intended outcomes matter independently of cost[21]; for example, where emergency response to reef impact events (e.g., ship groundings, storms) aims to restore impacted areas rapidly. Here, the level of compensatory action should not be primarily governed by cost or cost-effectiveness but rather by the extent of ecosystem service that has been lost. Indeed, investments with less-than-ideal restoration success may be better to implement now—even to the point of maintaining the status quo and buying reefs more time until emissions reductions are achieved—rather than waiting for further degradation, loss of ecosystem services, and higher restoration costs. Thus, given variability in quantifying ecosystem services and the wide range of time- and geographic scales of restoration and recovery, any perception (let alone quantification) of economic viability for reef restoration attained through collective evidence across studies becomes flawed. The same principle applies when cross-comparing restoration of reefs with restoration of other habitats. Ultimately, there is no "one size fits all" method for restoring coral reefs or measuring success, nor will we restore our way out of the climate crisis[5,25]. Projects' needs, goals, success, and viability will vary based on unique ecological and social conditions.

Accelerating global needs and opportunities to invest in socio-ecologically meaningful coral reef restoration leads to the fundamental question: how do we ensure against flawed perceptions of success and viability? Evaluations must be based on project-specific facts, including intent, purpose, scale, and outcomes without restoration[14]. Differentiating ecological restoration from restoration ecology experiments remains paramount in evidencing coral reef restoration but will require more transparency in goal setting, evaluation, and communication to avoid misperceptions of intent[12,14]. For example, *a priori* goals should be staged appropriate to specific project context (e.g., maturity, location, and available resources)[12,14,18] and hence in a way that partitions continual improvements in practice from the fundamental desired outcomes for restoration. If anything, the disproportionate evidence of activity from small-scale experiments to date[16,17] exemplifies the nature of short-term funding for restoration[1,6] and not whether ecological restoration outcomes can be achieved. Such historical weighting of evidence from small-scale experiments coupled with the urgency to recover degraded coral reef ecosystems warrants investment in scales necessary to examine ecological restoration outcomes. Investment to do so will not be "cheap", nor should it be, where we value achieving ecological scale outcomes.

Ecosystem restoration—including for coral reefs—is a relatively "long game"[3,12], yet perceptions of meaningful coral reef restoration remain centered around success from short-term, restoration ecology-based projects. Lower than desirable success—or even "failure"—is an inevitable and important learning attribute of restoration efforts under the recent acceleration of experimental activity by global stakeholders fine-tuning practices to local contexts. However, small-scale experiments do not predispose mature-stage ecological restoration activity to the same success, and in turn, whether restoration is worthwhile. Global calls to restore 30% of all ecosystems by 2030[1] rest more than ever on ensuring our community of practitioners, researchers, managers, policymakers, and communicators carefully and robustly identify when, where, and to what extent reefs can be restored. Implementation of restoration efforts and their goals can only be context-specific, especially given continued global discrepancies in access to resources and technology, as well as the extent of coral reef degradation and natural variability, across regions. Given current rates of emissions, ocean warming, and mass bleaching, we advocate maximizing investment to demonstrate the role of ecological restoration (and not just restoration ecology experiments)—within the broader toolbox of resilience-based management for reefs[2,3]—is time-critical to avoid prematurely discounting restoration as a meaningful aid to conserve coral reefs.

Data availability

No datasets were generated or analysed during the current study.

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Competing interests

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