Journal of Environmental Management 397 (2026) 128298

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Review

A staged and layered approach to restoring turbid nearshore coral reefs

C.A. Page[a,*], H.A. Smith[b,c], T.N. Whitman[a,b], C. Giuliano[a], D.G. Bourne[a,b], C.J. Randall[a]

[a] Australian Institute of Marine Science, Townsville, QLD, 4810, Australia
[b] College of Science and Engineering, James Cook University, Townsville, QLD, 4811, Australia
[c] Centre for Marine Science and Innovation, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, NSW, 2052, Australia

ARTICLE INFO

Keywords:
Inshore
Coastal
Fringing
Rehabilitation
Conservation
Recovery

ABSTRACT

The ecosystem services provided by turbid nearshore coral reef ecosystems support the livelihoods of almost a billion people globally. Yet these services are threatened by ocean warming, coupled with population growth, overfishing and changing land-use practices that drive deteriorating water quality. While novel approaches to reef restoration are being developed in an attempt to build reef resilience and safeguard coral persistence through the Anthropocene, many interventions are being tested on offshore and/or clear-water reefs. Here we contend that the suite of challenging conditions faced by turbid nearshore coral reefs hinder the direct translation of restoration methods developed outside of this context. Drawing on learnings from terrestrial and coastal restoration, we advocate for an integrated, phased approach to nearshore reef restoration that addresses site-specific challenges. The approach includes (1) a habitat modification and enhancement stage aimed at facilitating natural recovery and priming the site ahead of coral restoration, (2) a coral delivery stage, and (3) a final stage of protection and maintenance of the rehabilitated site. Concomitantly, protecting and restoring connected and adjacent habitats should be prioritised, alongside improvements in catchment and reef management, including the regulation of extractive activities. Most importantly, strong action on climate change is essential to ensure restoration efforts and investments are not wasted.

1. The value of nearshore coral reefs

A large proportion of the world's coral reefs are located close to island or continental coastlines (Bryant et al., 1998). The human population density within 10 km of a coral reef is four times the global average (Sing Wong et al., 2022). As such, nearshore coral reefs, also commonly referred to as inshore or coastal reefs, disproportionally contribute to human economic, social, and cultural values, while protecting over 150,000 km of shoreline in 100 nations and territories (Burke et al., 2011). Indeed, more than 775 million people are dependent on reef-derived goods and services (i.e. food and livelihoods), particularly in developing countries (Selig et al., 2019). In the Asia-Pacific region alone, coral reef tourism and fisheries contribute $25 billion annually (Bartelet et al., 2024), highlighting the critical importance of maintaining functional nearshore coral reefs.

Nearshore reefs support unique and diverse biological communities (Fabricius et al., 2005; Ellis et al., 2017; Zweifler (Zvifler) et al., 2021) that are naturally tolerant of harsh environmental conditions (Fabricius et al., 2005; Cacciapaglia and van Woesik, 2016; Mies et al., 2020). Importantly, they connect interdependent coastal habitats including salt marshes, mangrove forests, and seagrass meadows (Sheaves, 2009), and link these coastal habitats to offshore reefs and oceanic waters (Blaber, 2009). While many nearshore reefs are 'clear water' reefs, along oceanic islands or deep continental shelfs, here we focus our discussion on nearshore reefs heavily influenced by coastal processes and typified by high turbidity, sedimentation, eutrophication and pollution (Fabricius 2005; Mies et al., 2020; Zweifler (Zvifler) et al., 2021) (Fig. 1). Turbid nearshore reefs account for approximately 12 % of the world's reefs (Sully and van Woesik, 2020) and can be found circumtropically throughout Southeast Asia, in Central and South America and the Eastern Tropical Pacific, Australia's inshore Great Barrier Reef (GBR) and north-west, and around islands with large catchments (Sully and van Woesik 2020; Zweifler (Zvifler) et al., 2021). Many reefs located in the biodiverse Coral Triangle are turbid nearshore reefs (Sully and van Woesik, 2020).

Degradation of nearshore coral reefs is accelerating, with coastal

* Corresponding author.
E-mail address: c.page@aims.gov.au (C.A. Page).

https://doi.org/10.1016/j.jenvman.2025.128298
Received 23 June 2025; Received in revised form 24 November 2025; Accepted 8 December 2025
Available online 12 December 2025

development and land use driving increases in turbidity, sedimentation, nutrients and pollutants to levels exceeding the tolerances of many reef taxa (Golbuu et al., 2003; Fabricius et al., 2005). Over 25 % of reefs globally are threatened by agricultural pollution (Burke et al., 2011). Burgeoning coastal human populations reliant on coral reefs for food have contributed to reef degradation through destructive and unsustainable fishing (He and Silliman, 2019) (Fig. 1). Climate warming is also increasing the frequency and intensity of marine heat waves and mass bleaching events, causing stronger storms and rainfall events, and increasing ocean acidification and hypoxia (Oliver et al., 2018; Cornwall et al., 2021; Wang et al., 2022; Pezner et al., 2023). This increase in climate warming-related disturbances is driving further coral declines on reefs globally and reducing windows for reef recovery (Osborne et al., 2017; Hughes et al., 2017; Corazza et al., 2024) (Fig. 3a and b). Cumulative local and global stressors are degrading and reducing the resilience of turbid nearshore reefs, increasing macroalgal biomass and inducing shifts to lower diversity alternate states in some areas (Gardner et al., 2003; Bruno et al., 2009). While aesthetically less appealing than some clear-water reefs, turbid reefs support diverse reef communities and are most likely to provide corals refuge through fluctuating climate conditions, via turbidity-moderated coral bleaching (Cacciapaglia and van Woesik, 2016; Mies et al., 2020). Given their accessibility and importance for food, livelihoods, and ecosystem services, particularly in developing countries (Burke et al., 2011; Selig et al., 2019), it is critical to conserve nearshore reefs while also accelerating the development of restoration methods tailored to these systems.

2. An integrated and staged approach to nearshore reef restoration

It is increasingly recognised that novel approaches to managing coral reefs are required to ensure their persistence into the future (Duarte et al., 2020; Morrison et al., 2022; Mies et al., 2025). Alongside calls for strong action on climate change in conjunction with conventional management approaches (i.e. catchment and marine resource management), innovative interventions to increase reef resilience are being developed, tested, and risk assessed (Anthony et al., 2017; Bay et al., 2023). Given most nearshore reefs face multiple interlinked challenges

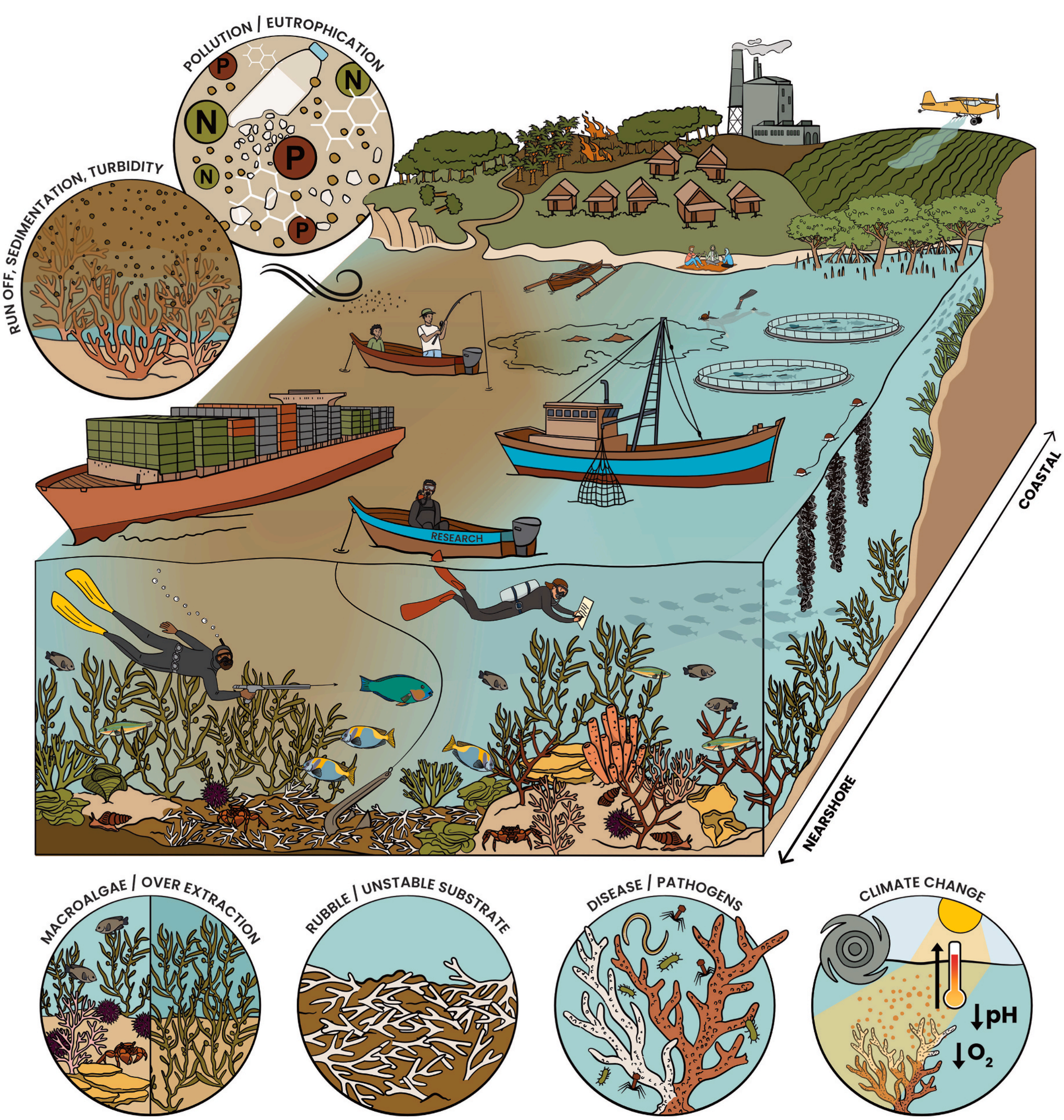

Fig. 1. Attributes of, and pressures impacting, turbid nearshore coral reefs.

(e.g. high turbidity, sedimentation and eutrophication, freshwater inundation, macroalgal competition and substrate instability), we propose a staged and layered approach to the restoration of these ecosystems (Fig. 2). This approach borrows from a long history of restoration in terrestrial and coastal environments and includes stages to address site-specific impacts to support natural recovery ahead of active rehabilitation of target taxa (Knutson et al., 2014; Davies et al., 2021), alongside the protection and maintenance of the restored site, which is essential for long-term success (Gagnon et al., 2021). This approach also incorporates ecological theories including competition, predation, food-web and facilitation theories (Silliman et al., 2024). Here we detail this staged approach, which aims to improve the success for restoration efforts on turbid nearshore reefs, using examples of methods that have, in some cases, already been trialled in these habitats. We detail the challenges faced when applying these and other methods that are untested in nearshore reef environments, and suggest ways to overcome those challenges (Fig. 2, Table 1). Rather than presenting a systematic review of all current restoration methods and their potential utility in these challenging environments, many of which have little or no data to support their use in these contexts (but see Gouezo et al., 2021, Humanes et al., 2024; Meis et al., 2025), we discuss potentially useful or promising restoration methods for such settings based on trials to date. Local reef scientists, managers, restoration practitioners and stakeholders with detailed knowledge of site-specific environmental

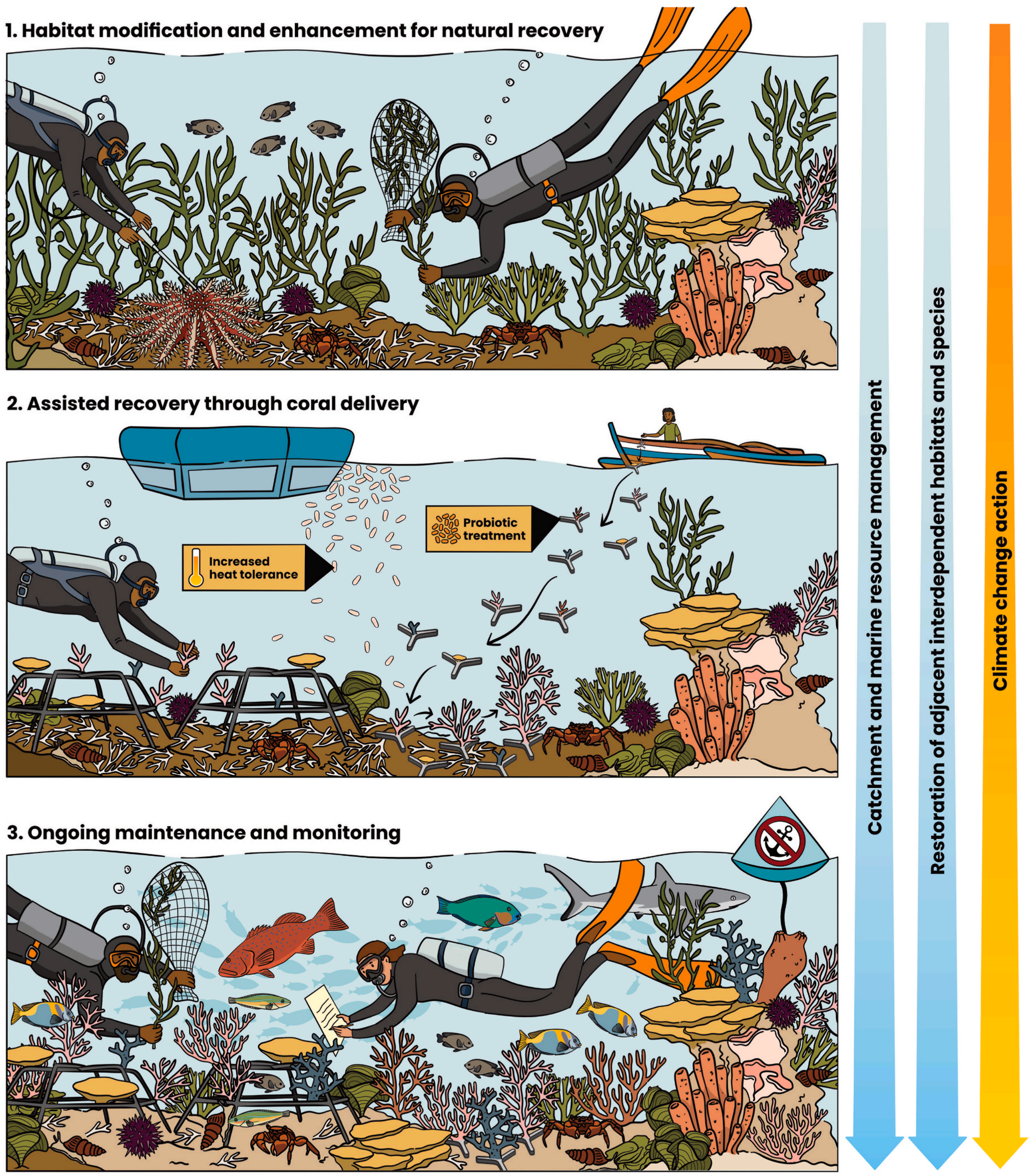

Fig. 2. Proposed staged and layered approach to restoration of turbid nearshore coral reefs, and concomitant actions (right arrows) required to maximise the success of restoration. Stage 1 – Habitat modification and enhancement for natural recovery; Stage 2 – Assisted recovery through coral delivery; Stage 3 – Ongoing maintenance and monitoring. Concurrently, catchment and marine resource management, restoration of adjacent interdependent habitats, and species and climate change action are required to maximise restoration success.

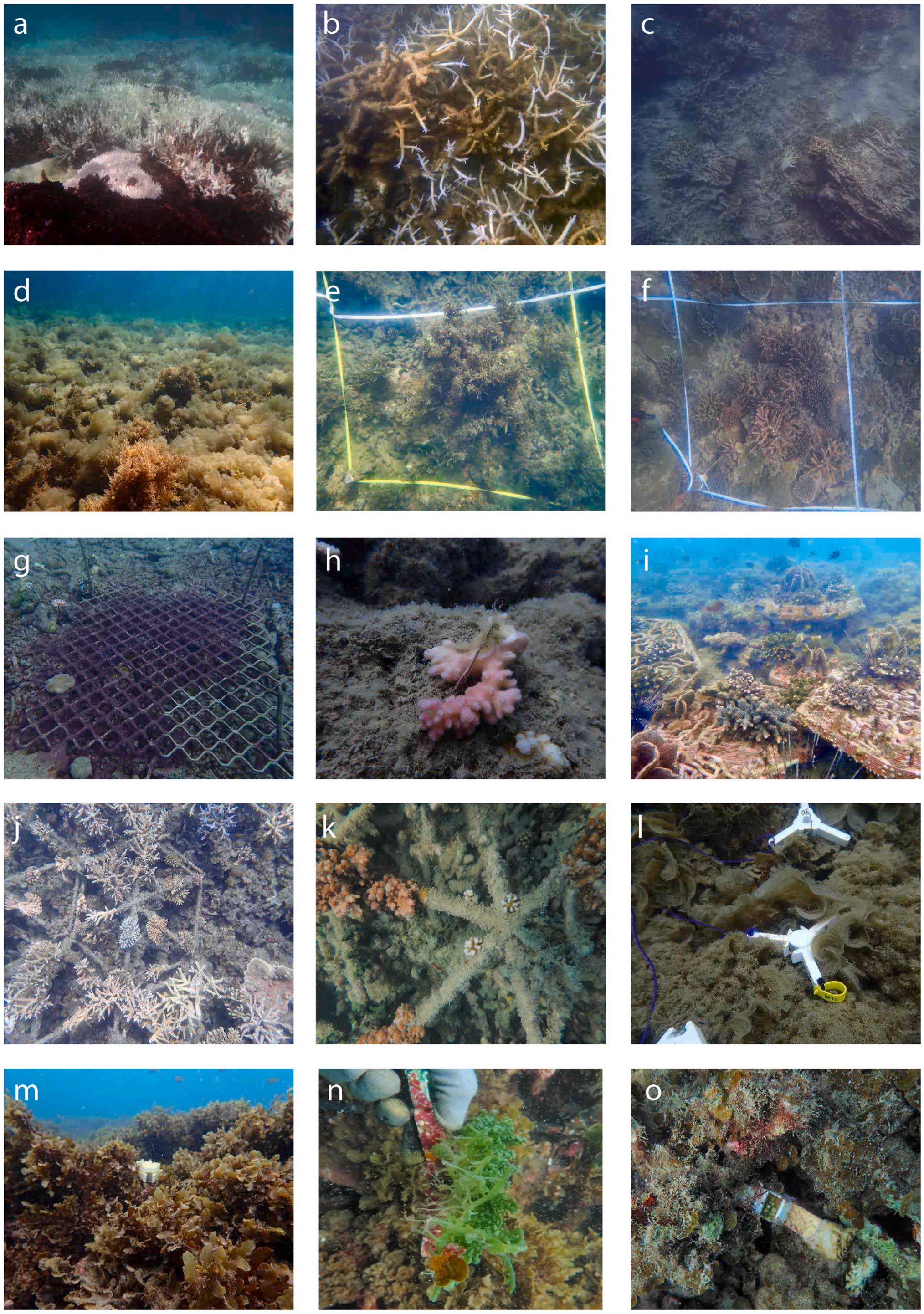

Fig. 3. Examples of nearshore turbid coral reefs and restoration trials in these ecosystems. a) Severe bleaching and coral mortality (foreground) at Sloping Reef April 2024 (Keppel Islands southern Great Barrier Reef (GBR), Carly Randall), and b) Samoa in April 2024 (Hillary Smith). In time branching *Acropora* colonies will break down to form an unstable rubble substrate on which coral recovery is slow, c) rubble dominated substrate reef (Fiji, Hillary Smith), d) *Sargassum* and *Colpomenia* dominated reef at Clam Bay 2023.(Keppel Islands GBR, Cathie Page). Site was previously dominated by branching *Acropora* (Keppel Islands GBR, Cathie Page), e) Arthur Bay plot prior to macroalgal removal in May 2019 (Magnetic Island Central GBR, Stella Fulton), f) the same Arthur Bay plot in May 2023 following nine macroalgal removal events (Belinda Phanphengdy), g) rubble stabilisation trial (Bait Reef, Whitsundays GBR, Tanya Dodgen), h) *Pocillopora damicornis* fragment secured to the sediment laden reef via a CoralClip (Whitsunday Islands GBR, Lorna Howlett), i) Archiereef 3D printed tiles after a 2.5 year deployment with added coral fragments (Bluff Island, Hong Kong, David Baker), j) coral fragments secured to MARRS stars approximately 1-year after installation. Stars were installed in October 2022 (Keppel Islands, southern GBR, Collette Bagnato), k) natural *Pocillopora r*ecruitment to MARRS stars in February 2025 (Keppel Islands, Cathie Page), l) device seeded with sexually produced corals deployed to degraded macroalgae dominated Home Reef (Keppel Islands, Taylor Whitman), m) seeded device deployed to *Sargassum* dominated reef at Clam Bay (Keppel Islands GBR, Cathie Page), n) seeded device overgrown by *Caulerpa* macroalgae after 13 months deployment to Clam Bay (Keppel Islands GBR, Cathie Page), and o) 1-year old surviving seeded coral on device almost buried in rubble at Halfway Reef (Keppel Islands GBR, Cathie Page).

Table 1
Challenges to restoration on turbid nearshore reefs and proposed in-water restoration and rehabilitation solutions that could be applied in the proposed staged and layered approach to restoration, alongside climate change mitigation, best-practice reef and catchment management and the restoration of adjacent habitats. Example references are provided; however, this table is not intended to be an exhaustive review of all relevant methods.

Challenge	Proposed actionable restoration and rehabilitation solutions	Example References
Benthic competitors	• Removal of benthic competitors (e.g. manual removal, chemical treatment)[a] • Incorporation of elevated features (i.e. MARRS stars)[a] • Prevention of benthic competition through use of foul-release coatings on seeding devices or settlement substrates • *Ex-situ* co-culturing of corals with grazers • *In-situ* grazer restocking[a] • Delivery of corals larger than size-escape thresholds[a]	(Toh et al., 2013; Tebben et al., 2014; Work et al., 2018; Neilson et al., 2018a; Montalvo-Proano et al., 2025; Spadaro and Butler, 2021; Neil et al., 2021; Hylkema et al., 2022; Smith et al., 2023; Butler et al., 2024)
Sedimentation	• Incorporation of small structures or elevated features (i.e. MARRS stars)[a] • Use of sediment-tolerant coral taxa and/or broodstock • Delivery of corals larger than size-escape thresholds[a]	(Ceccarelli et al., 2020; Lamont et al., 2022; Nuñez Lendo et al., 2024; Lange et al., 2024; Mies et al. 2018, 2025; Montalvo-Proano et al., 2025; Oliveira et al., 2008)
High turbidity	• Use of low-light tolerant coral taxa and/or broodstock • Use of heterotrophic coral taxa and/or broodstock • Delivery of corals with low-light adapted symbionts (either seeded symbionts or naturally acquired)	(Oliveira et al., 2008; Mies et al., 2018; Mies et al., 2025
Substrate instability and mobile rubble beds	• Substrate stabilisation via introduction/ enhancement of natural binders (CCA, sponges) • Mechanical substrate stabilisation via incorporation of small structures (i.e. MARRS stars, reef bags)[a] • Substrate stabilisation using bio-glues or natural fibres	(Ceccarelli et al., 2020; Nuñez Lendo et al., 2024; Leung et al., 2024; Kenyon et al., 2025)
Pollutants (chemicals, nutrients)	• Use of pollutant-tolerant coral taxa and/or broodstock • Applying probiotics	Peixoto et al. (2021)
Diseases and pathogens	• Treatment or removal of diseased individuals[a] • Consideration of disease-transmission dynamics in spatial planning of restoration[a] • Applying probiotics	(Peixoto et al., 2021; Neely et al., 2021)
Predation	• Removal of corallivores (COTS, *Drupella*, cushion stars etc)[a] • Use of seeding device designs and/or small structures/cages to reduce predation[a] • Delivery of corals larger than size-escape thresholds[a]	(Nozawa, 2008; Baria et al., 2010; Muhando and Lanshammar 2020; Whitman et al., 2024; Matthews et al., 2024)
Hypoxia	• Use of hypoxia-resistant coral taxa and/or broodstock	Alderdice et al. (2021)
Heat	• Use of heat-tolerant coral taxa and/or broodstock[a] • Use of heat-evolved symbionts • Heat-harden corals prior to deployment	(Quigley et al., 2018; Godoy et al., 2021; Humanes et al., 2024; Nitschke et al., 2024; Mies et al., 2025)

[a] = method actively in use on reefs.

conditions and social factors (Gouezo et al., 2021, Humanes et al., 2024; Meis et al., 2025), are best positioned to identify methods most suitable for testing as part of each stage of our approach detailed below.

2.1. Stage 1 – Habitat modification and enhancement for natural recovery

Restoration of many terrestrial or coastal plant communities includes a habitat modification and enhancement stage during which the substrate and environment are primed following identification of the site-specific pressures that are limiting natural recovery (Querejeta et al., 2000; Lewis, 2005). This stage typically includes (i) the removal of competitive or invasive species via weeding, burning or other methods (Knutson et al., 2014; Davies et al., 2021), (ii) the reintroduction of herbivores to reduce the biomass of competitive or invasive species (Dvorský et al., 2022) and (iii) the treatment or stabilisation of the substrate (Hatchell et al., 2022). The equivalent phase on nearshore reefs could include (i) removal of competitive benthic organisms and corallivores, (ii) seeding of herbivores to reduce macroalgal biomass, and (iii) stabilisation of the substrate (Fig. 2). This preparatory phase is likely to be more important on turbid nearshore reefs than clear-water reefs given the pervasive impacts of high macroalgae biomass, sedimentation, eutrophication, pollution and unstable substrates in these environments (Fig. 1). Habitat modification and/or substrate preparation are not as common in marine as in terrestrial restoration, but their utility has already been demonstrated (Gouezo et al., 2021; Smith et al., 2023) (Table 1).

High macroalgal abundance significantly impedes both natural recovery and restoration on inshore reefs, due to its widespread negative impacts on coral recovery processes, including settlement, growth, recruitment and reproduction (McCook et al., 2001; Vieira, 2020; Page et al., 2023) (Fig. 3d and e). Following a shift to macroalgal dominance, a negative feedback loop can perpetuate this state (McCook et al., 2001). As demonstrated in terrestrial ecological studies where removal of weeds via mowing was sufficient to allow regeneration of Swiss fen meadows and sedge wetlands (Billeter et al., 2007; Kołos and Banaszuk, 2013), the removal of macroalgae or other benthic competitors may be sufficient to facilitate natural coral recovery (Conklin and Smith, 2005; Smith et al., 2022, 2023). For example, a significant biomass (10 kg/m^2) of invasive red algae (*Kappaphycus spp.)* was successfully removed from Kane'ohe Bay reefs in Hawaii, although rapid re-growth was noted (Conklin and Smith, 2005), highlighting the likely need for repeat removal events. Also, the manual removal of predominantly *Sargassum spp.* increased coral cover and natural coral recruitment at small spatial scales on nearshore fringing reefs of Magnetic Island in the central GBR (Smith et al., 2022, 2023) (Fig. 3e and f). Nearshore reefs may also benefit from the removal of other benthic competitors (i.e.

corallimorphs, sponges, soft corals), including invasive species (Work et al., 2018; Creed et al., 2021), the risk of which is likely elevated on coastal reefs near ports and shipping lanes. Chlorine was successfully used to control invasive corallimorpharians on Palmyra Atoll (Work et al., 2018) and *Caulerpa* on Californian reefs (Anderson, 2005). Chemical treatments may prove useful in controlling invasive benthic competitors on nearshore reefs, however the risks of unintended consequences must be weighed against the potential impacts of invasive taxa establishment. The manual removal of benthic competitors at useful spatial scales may also be possible, as demonstrated by the large-scale operationalised manual removal of crown-of-thorns starfish (COTS), *Acanthaster* spp. (Matthews et al., 2024). Specifically designed machinery or tools may also increase the efficiency of predator and competitor removal from reefs.

Repeat algal removal events are typically required to maintain low algae biomass (Smith et al., 2023) (Fig. 3e and f). However, seeding herbivores may minimize or negate the need for repeat removal (Lorenzen et al., 2013; Butler et al., 2024). While invasive macroalgae quickly regrew following manual removal in Kaneohe Bay (Hawaii), reduced macroalgae biomass was maintained for 2-years when removal was coupled with urchin seeding (Neilson et al., 2018a). Similarly, manual removal was insufficient to maintain low algae biomass on reefs in the Florida Keys but translocation of herbivorous crabs (*Maguimithrax spinosissimus*) decreased macroalgae by up to 80 % and increased coral recruitment (Spadaro and Butler, 2021). Aquarium-based studies have demonstrated that *ex-situ* co-culturing with urchins, crabs, gastropods and asteroid grazers (Toh et al., 2013; Craggs et al., 2019; Neil et al., 2021, 2024) can reduce algal competition and benefit small corals ahead of delivery, highlighting the potential utility of a range of invertebrate grazers for controlling algae biomass on nearshore reefs.

Fish also play an important role in regulating algae on reefs (Mumby et al., 2006; Butler et al., 2024), removing an estimated >50 % of the total algal biomass on the GBR (Bellwood et al., 2018). Fish biomass is traditionally managed via marine park zoning and catch limits, but mariculture, restocking, and assisted natural recovery (Hylkema et al., 2022) could boost herbivorous fish and invertebrate populations on nearshore reefs with flow-on benefits for corals (Lorenzen et al., 2013; Neilson et al., 2018a). While protecting herbivore abundance could promote coral dominance, trade-offs should be considered. Some herbivorous fish hinder coral recovery by unintentionally removing juvenile corals while feeding (Trapon et al., 2013; Whitman et al., 2024). Therefore, careful selection of the fish taxa used in restocking or assisted natural recovery is required.

The management of corallivorous gastropods and asteroids is a standard technique used to reduce coral mortality, particularly at high-value tourism sites (Fig. 2). The removal of COTS from reefs of the GBR and Tanzania have accelerated natural coral recovery (Muhando and Lanshammar 2020; Matthews et al., 2024), noting that COTS rarely occur on nearshore turbid reefs in some regions. Intense predation of coral transplants by COTS and *Drupella* in the Philippines (Cabaitan et al., 2015), and the fireworm, *Hermodice carunculate,* in the Caribbean (Miller et al., 2014), highlight the potential benefits of corallivore removal or predator protection prior to coral delivery. The removal of cushion sea-stars from experimental plots in the Maldives improved the survival of natural recruits by 9 % and transplanted *Acropora* and *Pocillopora* fragments by 25 % (Walker et al., 2024), further demonstrating the potential benefits of corallivore management. Local knowledge of site-specific corallivores is critical to understanding the potential need for predator management during site preparation.

High turbidity and sedimentation are distinguishing characteristics of many nearshore reefs, particularly during wet seasons and floods when large inputs of terrestrial sediments and freshwater can combine to result in catastrophic coral mortality on nearshore reefs (Golbuu et al., 2003; Jones and Berkelmans, 2014). Elevated nutrient and pollutant concentrations are often associated with these events (Devlin and Brodie, 2005; Moran et al., 2023), the impacts of which are complex and dependent on sediment/nutrient/pollutant specific characteristics (reviewed in Fabricius, 2005; Erftemeijer et al., 2012). Turbidity, sedimentation and the eutrophication of nearshore reefs is best addressed via catchment and land-use management. Already a large focus in many regions is establishing native riparian buffers or constructed wetlands along waterways to filter out sediments, nutrients and pollutants before they reach coastal waters and flow to nearshore reefs (Vozzo et al., 2023). Concrete, rocks or engineered structures and frames (e.g. Reef-Balls, Archiereefs, reef bags, MARRS stars, gabion cages or metal grids) have been used to elevate coral habitats to reduce coral-sediment interactions and enhance coral settlement, survival and growth (Ceccarelli et al., 2020; Kenyon et al., 2025) (Fig. 3i, j and k). The installation of structures has the added benefit of stabilising unconsolidated substrates that may be limiting natural coral recovery (Fox and Caldwell, 2006; Heyward et al., 2024), noting that the approval process for the installation of such structures may be complex. Indeed, the installation of artificial or biodegradable stabilisation structures has enhanced natural recovery of seagrass and mangrove communities (Wood et al., 2019; Tan et al., 2020). While potentially beneficial, it is important to consider the topography and composition of introduced structures, as these can impact sediment dynamics. Including grooves, lattices or microrefugia into structures (Randall et al., 2021) and foul-release coatings (i.e. antifoulants) could limit sediment and competitive interactions on elevated structures (Tebben et al., 2014; Roepke et al., 2022), facilitating coral recruitment and longer-term survival.

Nearshore reefs often have a high relative abundance of rubble and unstable or unconsolidated substrate (Allen Coral Atlas, 2020), which hampers natural coral recovery (Fox and Caldwell, 2006; Johns et al., 2018; Leung et al., 2024) (Fig. 1 and 3c and g). Shallow coastal reefs with lower pH may also be more susceptible to net dissolution under ocean acidification (Uthicke et al., 2014; Silbiger et al., 2014) perpetuating reef instability. Increasing climate-change driven disturbances (i.e. storms), as well as blast-fishing and vessel strikes, are likely to further expand areas of rubble (Kenyon et al., 2022; Kopecky et al., 2024). Without stabilising rubble, coral restoration interventions are unlikely to succeed. Indeed, the combined impacts of substrate instability and high sedimentation may explain lower survival of transplanted coral fragments on turbid nearshore reefs compared to off-shelf reefs of the GBR (Suggett et al., 2020; Scott et al., 2024) (Fig. 3h). Rubble fields may be stabilised via seeding of natural binders (e.g. crustose coralline algae or sponges), securing with bio-glues or natural fibres, or by adding structures (Ceccarelli et al., 2020) (Fig. 3g–j and k). Elevated structures may also attract fish and provide habitat for invertebrates that may help control macroalgae biomass (Ménard et al., 2012). Given the challenges of substrate stabilisation and the value of rubble fields to cryptic species (Wolfe et al., 2021), stabilisation may be best applied at targeted sites at small scales, allowing some rubble to be maintained, particularly where historically present.

When planning and undertaking habitat-modification activities, it is important to consider the characteristics of the site, the timing of potential disturbances (i.e., storms, floods and bleaching events), seasonal processes and life cycles (e.g. seasonal fluctuation in macroalgae biomass and recruitment), and the timing of natural recovery processes including coral spawning, to maximise impact and avoid the need to repeat activities. Region-specific protocols may require development, for example identification of local grazers or competitive/invasive taxa and development of mariculture industries for key nearshore reef herbivores (Lorenzen et al., 2013). In some cases, habitat modification may be sufficient to allow natural recovery of corals given adequate larval supply; in these instances, no further action may be required. However, reef recovery at many sites is likely to benefit from the delivery of corals to the prepared site, through stage 2.

2.2. *Stage 2 – Assisted recovery through coral delivery*

Following habitat modification, restoration of terrestrial and coastal ecosystems typically includes a delivery phase, where seeds or seedlings of target taxa are added to the site (Knutson et al., 2014; van Katwijk et al., 2016; Davies et al., 2021) (Fig. 2). A similar approach can be applied to inshore reef systems with the delivery of coral larvae, newly settled spat, or fragments after they have been modified or enhanced. The delivery of corals to prepared sites will be most important in areas with small, isolated, and low-density populations (Mumby et al., 2024), and in areas limited by larval supply. Identifying the most appropriate coral delivery method will require consideration of site-specific challenges and restoration goals, alongside the funding, human resources, infrastructure, stakeholder engagement and approvals required to undertake the works (Peixoto et al., 2024; Burdett et al.).

Historically, coral restoration has focused on the transplantation of coral colonies, fragments or microfragments that are secured to the reef or artificial structures (Boström-Einarsson et al., 2020; Suggett et al., 2020) (Fig. 3h). High sedimentation, macroalgae biomass and unstable substrates are likely to challenge the success of transplanted corals on nearshore reefs. This hypothesis is supported by high mortality of coral fragments planted on an inshore reef of the GBR (Scott et al., 2024). Coral delivery methods that release corals from sedimentation and competition with macroalgae, whilst also providing a stabilised substrate and protection from predation, are likely to increase transplant success on nearshore reefs (Fig. 3i, j and k). Elevated structures (i.e. Archiereefs, MARRS stars or similar) that stabilise rubble and support coral fragments have increased coral cover and carbonate accretion on clearwater reefs (Nuñez Lendo et al., 2024; Lange et al., 2024) and have also shown promise on turbid reefs in Indonesia (Lamont et al., 2022), the GBR (GBRMPA, 2025) and Hong Kong (Fig. 3i, j and k). Further testing of the utility of elevated structures to support coral delivery is warranted, to understand how coral and structure maintenance requirements and performance might differ on nearshore reefs.

Improvements in coral aquaculture (Ramsby et al., 2024; Fong et al., 2024) have seen an increase in captive rearing of sexually produced corals (Randall et al., 2020). Seeding coral larvae directly to the substrate, much like aerial seeding in terrestrial habitats, increased coral cover on a Philippine reef, demonstrating that this method can succeed in clear water environments (dela Cruz and Harrison, 2017). Yet high sedimentation and macroalgal loads are known to impede coral settlement (Ricardo et al., 2017; Smith et al., 2022) and thus direct seeding on nearshore reefs may be less successful. The deployment of engineered devices housing coral spat is a newer approach being tested on reefs around the world (Chamberland et al., 2015) (Fig. 3l–o). Coupled with the periodic removal of macroalgae, coral seeding on devices was found to increase early coral survival on the inshore GBR (Magnetic Island). However, survival after two-years was low and not enhanced by macroalgae removal (Smith et al., 2025). Overgrowth of seeded devices by macroalgae (Fig. 3n) and lower survival amongst branching *Acropora* colonies (Page et al., 2024), highlight the complex relationship between seeding environment and survival. Further trials are needed to refine methods to increase coral survival on reefs influenced by high sediment and macroalgae, and amongst rubble fields. In many developing countries, the absence of facilities for sexual reproduction of corals may mean that delivering 'corals of opportunity' (Suggett et al., 2020) is most feasible.

Selecting appropriate taxa to deliver to nearshore reefs should be guided by the current and former (if known) community composition, with considerations of stress-tolerant traits and planning for desired functional traits under future climate change trajectories (Madin et al., 2023; Silliman et al., 2024; Mies et al., 2025). Nearshore reefs often harbor locally acclimatised and/or adapted populations and are likely the most appropriate source of corals for restoration of nearshore reefs (Van Oppen et al., 2015; Banha et al., 2020; Mies et al., 2020; Alderdice et al., 2021). To achieve early success, the use of fast-growing taxa that are primary colonizers with strong sediment clearing and heterotrophic feeding capacities are ideal candidates (Anthony et al., 2017; Mies et al., 2020; Mies et al., 2025). Communities can then be diversified with other taxa where and when appropriate, for example as corals become more dominant and macroalgae competition diminishes. Restoration with a mix of taxa and different sized outplants may reduce density-dependent transmission of pathogens amongst restored corals and increase inter-taxa facilitation (Ladd et al., 2018; Silliman et al., 2024), yet it's important to consider allee effects when spacing corals (Mumby et al., 2024). Similarly, initially delivering fragments or colonies that are larger than size-escape thresholds, followed by sexually produced corals, may be a useful approach in instances where it is critical to rapidly restore the competitive dominance of corals. The most suitable suite of coral taxa for restoration will nonetheless be region and site specific and must be assessed and identified at this scale (Madin et al., 2023; Mies et al., 2025).

Breeding for heat tolerance in corals and symbionts is a very active area of research (van Oppen et al., 2015; Humanes et al., 2024) and is expected to lead to new recommendations for coral delivery (Table 1). The inoculation of coral spat with heat-adapted symbionts may provide additional protection against temperature extremes on nearshore reefs (Quigley et al., 2018; Zhang et al., 2021), while treating corals with probiotics (Peixoto et al., 2021), akin to promoting plant growth through rhizobacterial inoculation (Dobbelaere et al., 2003), may improve survival in polluted environments where pathogens are elevated (Bruno et al., 2003). These interventions are currently being trialled at small experimental scales and may be available for upscaling in the future. Nearshore reefs should be a major focus for this research, to capitalize on their existing natural tolerances of environmental extremes (Mies et al., 2020; Sully and van Woesik, 2020). Breeding to increase tolerances of other environmental extremes, including pollution, sedimentation, turbidity, and competition should also be considered, to ensure restocking of nearshore reefs with resilient corals is possible, particularly in locations where standing genetic diversity is depauperate (Table 1). Following the delivery of corals to the prepared site, restoration can then focus on monitoring and ongoing maintenance to sustain the success of work to date.

2.3. *Stage 3 – On-going maintenance and monitoring*

Restoration of nearshore reefs will require on-going maintenance, protection and reiterative interventions informed by tracking of key performance indicators against goals (Fig. 2). Strong but adaptive project planning is essential for the successful maintenance of a restored site. The recovery of reef community ecology metrics (i.e. cover, diversity, rugosity) and ecosystem functions and services will likely require longer timeframes and more varied monitoring approaches to quantify, and more diverse and layered intervention methods to achieve. Maintenance of herbivores via no-take marine reserves or fisheries management and/or direct stocking may be required to maintain low macroalgae biomass, but could reduce the need for repeat macroalgal removal events (Spadaro and Butler, 2021; Smith et al., 2023). Protection of the restored site from at least some damaging and extractive activities (e.g. boat anchoring, fishing and collection, and other damaging activities) is likely required to maximise restoration success, but the need for such protection will be site-specific. Maintenance of, or the installation of additional elevated structures may also be required to further stabilise rubble or provide sediment-free surfaces for coral recruitment or delivery, particularly following acute disturbances such as tropical storms. Repeat coral deliveries to increase species richness or genetic diversity may also be required, especially after selective sweeps by marine heat waves and other disturbances. Long-term funding for monitoring and adaptive maintenance, must be accounted for in restoration project budgets and timelines to ensure long-term success (Boström-Einarsson et al., 2020; Gagnon et al., 2021). The on-going reporting of results, positive or negative, would also assist in accelerating the development of targeted restoration methods for nearshore reefs.

3. Site selection considerations

Successful coral restoration depends on selecting an appropriate site, guided by both environmental and social factors (Boström-Einarsson et al., 2020; Gouezo et al., 2021; Mies et al., 2025). Local reef scientists, managers, restoration practitioners and stakeholders, with detailed knowledge of site-specific environmental challenges and social contexts, are best positioned to identify suitable sites for implementing such a staged and layered approach. Sites experiencing lower levels of chronic stressors, including sedimentation, eutrophication and damaging or extractive activities may generally be preferred to maximise restoration success. However, other ecological factors, including connectivity to surrounding reefs (e.g., to reduce the need for repeated coral additions and enhance the broader downstream ecological benefits of restoration), should also be considered (Frys et al., 2020; King et al., 2023). The visibility, use and value of a reef to stakeholders is also an important consideration when choosing a site.

4. Concomitant actions

The long-term success of nearshore reef restoration is contingent on concomitant actions, including (i) improvements in catchment and marine resource management, (ii) the restoration of adjacent interdependent habitats and species, and (iii) most critically, strong action on climate change (Anthony et al., 2017; Waltham et al., 2020; Vozzo et al., 2023; Mies et al., 2025) (Fig. 2).

Firstly, adjacent terrestrial and coastal ecosystems are intrinsically linked to nearshore coral reefs (Sheaves, 2009; Nagelkerken et al., 2015). Improvements in land-use practices and catchment management are critical to reducing siltation, eutrophication and pollution of these ecosystems. Yet reductions over relevant and large spatial scales requires significant funding and political will supported by government policy (Kroon et al., 2014). Extractive and damaging activities on reefs (for example fishing and some tourism activities) are typically managed via relatively small marine reserves and fisheries restrictions (Russ, 2002; Williamson et al., 2004; Cinner et al., 2020). However, the growing mismatch in scales at which stressors, such as inputs of pollutants and sediments from poorly managed catchments, and the small-spatial scales at which reefs are managed, necessitates the novel and multiscale governance of coral reefs (Bellwood et al., 2019; Duarte et al., 2025). Without proper management, local, chronic stressors will persist and increase the need for ongoing maintenance of restoration activities on nearshore reefs, which may be prohibitively costly and lead to failure.

Secondly, restoration of ecosystems and species adjacent to nearshore reefs should be prioritised to capitalize on physical, chemical and biological connections and cross-habitat facilitation (Vozzo et al., 2023), particularly where degradation of these habitats currently limits coral recovery. For example, restoration of degraded mangrove or seagrass communities and their capacity to filter sediments and reduce pathogen loads (Lewis, 2005; Lamb et al., 2017), will undoubtedly benefit nearshore reefs (Fig. 2). Mangroves and seagrass communities also act as nurseries for many reef fish, which are critical to maintaining coral dominance and thus support coral restoration on adjacent reefs.

Finally, climate change is the overwhelming driver of recent coral declines, threatening the persistence of coral reefs globally (Reimer et al., 2024). Even with strong action on climate change and carbon sequestration, warming will continue to degrade reefs (Bozec et al., 2025), which necessitates resilience-based restoration actions (Anthony et al., 2017; Peixoto et al., 2024). Yet without strong action to limit greenhouse gas emissions and moderate further warming, current and future investments in coral restoration will be wasted (Fig. 2)(Duarte et al., 2025).

5. Gaining stakeholder support for restoration on accessible reefs

Consultation with reef users is essential to reach agreement on the need for, and the goals of restoration, and is likely to lead to more successful outcomes (Bayraktarov et al., 2016; Westoby et al., 2020). Yet the dependence of increasing human populations on nearshore reefs for their livelihoods, food, and cultural values (Selig et al., 2019), as well as their accessibility and visibility, may raise challenges to achieving broad social license for restoration in these habitats (Mora et al., 2011; Abelson et al., 2020; Mies et al., 2025). Alternatively, shared interests in maintaining the values of nearshore reefs may facilitate agreement on the need for restoration and strong consultation can address these challenges (Bayraktarov et al., 2016; Westoby et al., 2020; Mies et al., 2025). Restoration goals must be realistic with respect to original site conditions, remaining stressors, funding, and human resources available, to minimize the risk of real or perceived failures.

An assessment of restoration options against multiple criteria (cost, likelihood of success, potential unintended environmental and social consequences, and stakeholder support), is recommended to ensure identification of the most appropriate interventions and provide transparency in decision making (Corsair et al., 2009). Restoration in marine environments is expensive (Bayraktarov et al., 2016), but cost is only one of many considerations when assessing options (Corsair et al., 2009). Importantly the value of coral reefs to coastal communities, the ecosystem services they provide, and the cost of their loss, must be taken into account (Suggett et al., 2024; Reimer et al., 2024). A costly method with a high likelihood of success and strong support from stakeholders may be preferred over a cheaper method that is less likely to succeed and/or has low stakeholder support. However, the economics of restoration are highly context-dependent, and cost–benefit thresholds are likely to vary across regions and sites. Ideally, activities that threaten to undo the benefits of restoration (i.e. pollution, fishing, anchoring, extraction) should be restricted at the restoration site, or restoration should occur where conflicting activities are absent (Abelson et al., 2020).

6. Conclusions

Restoration alone is not the solution to the increasing degradation of coral reefs (Peixoto et al., 2024). Yet conserving and restoring nearshore corals reefs is critical to support their immense value and enable them to continue providing ecosystem services as oceans warm and acidify, as sea levels rise, and as the coastal zone increasingly hosts more human mouths to feed (Harris et al., 2018; Selig et al., 2019). The recommendations put forth here are intended to address the challenges facing turbid nearshore reefs, and provide a practical, staged approach for restoration practitioners working in these valuable habitats. Realistic restoration goals supported by adequate investment in a phased program of activities that seek to overcome site-specific stressors, while also addressing the larger-scale issues of climate warming, adjacent catchment management and the sustenance needs of the many people in developing countries, can maximise the chances of successful restoration on turbid nearshore reefs.

CRediT authorship contribution statement

C.A. Page: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **H.A. Smith:** Writing – review & editing, Writing – original draft, Investigation. **T.N. Whitman:** Writing – review & editing, Writing – original draft, Investigation. **C. Giuliano:** Writing – review & editing, Writing – original draft, Investigation. **D.G. Bourne:** Writing – review & editing, Writing – original draft, Investigation. **C.J. Randall:** Writing – review & editing, Writing – original draft, Investigation.

Data statement

This manuscript constitutes a review and as such does not include data.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Page reports financial support was provided by BHP. Randall reports financial support was provided by BHP. Giuliano reports financial support was provided by BHP. Whitman reports financial support was provided by BHP. Smith reports financial support was provided by Earthwatch Institute. Bourne reports financial support was provided by Earthwatch Institute. Bourne reports financial support was provided by Mitsubishi Corporation. Smith reports financial support was provided by Mitsubishi Corporation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We acknowledge all the Traditional Custodians of the sea Countries that host coral reefs around the world as the first caretakers of reefs and the first scientists. We pay our respects to their elders past, present, and emerging and acknowledge their continuing spiritual connection to their sea Countries. HS and DB were supported by a partnership with Earthwatch Australia and funded by Mitsubishi Corporation. CAP, CG, TNW and CJW were supported by the BHP#8212; AIMS Australian Coral Reef Resilience Initiative's Woppaburra Coral Project.

Data availability

No data was used for the research described in the article.

References

Abelson, A., Reed, D.C., Edgar, G.J., et al., 2020. Challenges for restoration of coastal marine ecosystems in the Anthropocene. Front. Mar. Sci. 7, 544105. https://doi.org/10.3389/fmars.2020.544105.

Alderdice, R., Suggett, D.J., Cárdenas, A., et al., 2021. Divergent expression of hypoxia response systems under deoxygenation in reef-forming corals aligns with bleaching susceptibility. Glob. Change Biol. 27, 312–326. https://doi.org/10.1111/gcb.15436.

Allen Coral Atlas, 2020. Imagery, maps and monitoring of the world's tropical coral reefs. Zenodo, 105281/zenodo3833242.

Anderson, L.W.J., 2005. California's reaction to *Caulerpa taxifolia*: a model for invasive species rapid response. Biol. Invasions 7, 1003–1016. https://doi.org/10.1007/s10530-004-3123-z.

Anthony, K., Bay, L.K., Costanza, R., et al., 2017. New interventions are needed to save coral reefs. Nat. Ecol. Evol. 1, 1420–1422. https://doi.org/10.1038/s41559-017-0313-5.

Banha, T.N.S., Capel, K.C.C., Kitahara, M.V., et al., 2020. Low coral mortality during the most intense bleaching event ever recorded in subtropical Southwestern Atlantic reefs. Coral Reefs 39, 515–521. https://doi.org/10.1007/s00338-019-01856-y.

Baria, M.V.B., Guest, J.R., Edwards, A.J., et al., 2010. Caging enhances post-settlement survival of juveniles of the scleractinian coral *Acropora tenuis*. J. Exp. Mar. Biol. Ecol. 394, 149–153. https://doi.org/10.1016/j.jembe.2010.08.003.

Bartelet, H.A., Barnes, M.L., Cumming, G.S., 2024. Estimating and comparing the direct economic contributions of reef fisheries and tourism in the Asia-Pacific. Mar. Pol. 159, 105939. https://doi.org/10.1016/j.marpol.2023.105939.

Bay, L.K., Gilmour, J., Muir, B., Hardisty, P.E., 2023. Management approaches to conserve Australia's marine ecosystem under climate change. Science 381, 631–636. https://doi.org/10.1126/science.adi3023.

Bayraktarov, E., Saunders, M.I., Abdullah, S., et al., 2016. The cost and feasibility of marine coastal restoration. Ecol. Appl. 26, 1055–1074. https://doi.org/10.1890/15-1077.

Bellwood, D.R., Pratchett, M.S., Morrison, T.H., et al., 2019. Coral reef conservation in the Anthropocene: confronting spatial mismatches and prioritizing functions. Biol. Conserv. 236, 604–615. https://doi.org/10.1016/j.biocon.2019.05.056.

Bellwood, D.R., Tebbett, S.B., Bellwood, O., et al., 2018. The role of the reef flat in coral reef trophodynamics: past, present, and future. Ecol. Evol. 8, 4108–4119. https://doi.org/10.1002/ece3.3967.

Billeter, R., Peintinger, M., Diemer, M., 2007. Restoration of montane fen meadows by mowing remains possible after 4–35 years of abandonment. Bot. Helv. 117, 1–13. https://doi.org/10.1007/s00035-007-0743-9.

Blaber, S.J.M., 2009. Relationships between tropical coastal habitats and (offshore) fisheries. In: Nagelkerken, I. (Ed.), Ecological Connectivity Among Tropical Coastal Ecosystems. Springer, Netherlands, Dordrecht, pp. 533–564.

Boström-Einarsson, L., Babcock, R.C., Bayraktarov, E., et al., 2020. Coral restoration – a systematic review of current methods, successes, failures and future directions. PLoS One 15, e0226631. https://doi.org/10.1371/journal.pone.0226631.

Bozec, Y.-M., Adam, A.A.S., Nava, B.A., et al., 2025. A Rapidly Closing Window for Coral Persistence Under Global Warming.

Bruno, J.F., Petes, L.E., Harvell, C.D., Hettinger, A., 2003. Nutrient enrichment can increase the severity of coral disease. Ecol. Lett. 6, 1056–1061.

Bruno, J.F., Sweatman, H., Precht, W.F., et al., 2009. Assessing evidence of phase shifts from coral to macroalgal dominance on coral reefs. Ecology 90, 1478–1484. https://doi.org/10.1890/08-1781.1.

Bryant, D., Burke, L., McManus, J., Spalding, M.D., 1998. Reefs at Risk: a Map-based Indicator or Threats to the World's Coral Reefs. Washington D.C.

Burdett HL, Albright R, Foster GL, et al. Including environmental and climatic considerations for sustainable coral reef restoration. PLoS Biol.

Burke, L., Reytar, K., Spalding, M.D., Perry, A., 2011. Reefs at Risk Revisited. World Resources Institute (WRI), The Nature Conservancy, WorldFish Center, International Coral Reef Action Network, UNEP World Conservation Monitoring Centre and Global Coral Reef Monitoring Network, Washington, D.C., p. 114p

Butler, M.J., Duran, A., Feehan, C.J., et al., 2024. Restoration of herbivory on Caribbean coral reefs: are fishes, urchins, or crabs the solution? Front. Mar. Sci. 11, 1329028. https://doi.org/10.3389/fmars.2024.1329028.

Cabaitan, P.C., Yap, H.T., Gomez, E.D., 2015. Performance of single versus mixed coral species for transplantation to restore degraded reefs. Restor. Ecol. 23, 349–356. https://doi.org/10.1111/rec.12205.

Cacciapaglia, C., van Woesik, R., 2016. Climate-change refugia: shading reef corals by turbidity. Glob. Change Biol. 22, 1145–1154. https://doi.org/10.1111/gcb.13166.

Ceccarelli, D.M., McLeod, I.M., Boström-Einarsson, L., et al., 2020. Substrate stabilisation and small structures in coral restoration: state of knowledge, and considerations for management and implementation. PLoS One 15, e0240846. https://doi.org/10.1371/journal.pone.0240846.

Cinner, J.E., Zamborain-Mason, J., Gurney, G.G., et al., 2020. Meeting fisheries, ecosystem function, and biodiversity goals in a human-dominated world. Science 368, 307–311. https://doi.org/10.1126/science.aax9412.

Corazza, B.M., Lacerda, C.H.F., Güth, A.Z., et al., 2024. No coral recovery three years after a major bleaching event in reefs in the Southwestern Atlantic refugium. Mar Biol 171, 114. https://doi.org/10.1007/s00227-024-04432-3.

Cornwall, C.E., Comeau, S., Kornder, N.A., et al., 2021. Global declines in coral reef calcium carbonate production under ocean acidification and warming. Proc. Natl. Acad. Sci. USA 118, e2015265118. https://doi.org/10.1073/pnas.2015265118.

Corsair, H.J., Ruch, J.B., Zheng, P.Q., et al., 2009. Multicriteria decision analysis of stream restoration: potential and examples. Group Decis. Negot. 18, 387–417. https://doi.org/10.1007/s10726-008-9148-4.

Creed, J.C., Casares, F.A., Oigman-Pszczol, S.S., Masi, B.P., 2021. Multi-site experiments demonstrate that control of invasive corals (*Tubastraea* spp.) by manual removal is effective. Ocean Coast Manag. 207, 105616. https://doi.org/10.1016/j.ocecoaman.2021.105616.

Davies, K.W., Bates, J.D., O'Connor, R., 2021. Long-term evaluation of restoring understories in Wyoming big sagebrush communities with mowing and seeding native bunchgrasses. Rangel. Ecol. Manag. 75, 81–90. https://doi.org/10.1016/j.rama.2020.12.008.

dela Cruz, D.W., Harrison, P.L., 2017. Enhanced larval supply and recruitment can replenish reef corals on degraded reefs. Sci. Rep. 7, 13985. https://doi.org/10.1038/s41598-017-14546-y.

Devlin, M.J., Brodie, J., 2005. Terrestrial discharge into the great barrier reef lagoon: nutrient behavior in coastal waters. Mar. Pollut. Bull. 51, 9–22.

Dobbelaere, S., Vanderleyden, J., Okon, Y., 2003. Plant growth-promoting effects of diazotrophs in the rhizosphere. Crit. Rev. Plant Sci. 22, 107–149. https://doi.org/10.1080/713610853.

Duarte, C.M., Agusti, S., Barbier, E., et al., 2020. Rebuilding marine life. Nature 580, 39–51. https://doi.org/10.1038/s41586-020-2146-7.

Duarte, C.M., Blythe, J., Devlin, M.J., et al., 2025. Layering solutions to conserve tropical coral reefs in crisis. Nat Rev Biodivers. https://doi.org/10.1038/s44358-025-00106-0.

Dvorský, M., Mudrák, O., Doležal, J., Jirků, M., 2022. Reintroduction of large herbivores restored plant species richness in abandoned dry temperate grassland. Plant Ecol. 223, 525–535. https://doi.org/10.1007/s11258-022-01225-w.

Ellis, J., Anlauf, H., Kürten, S., et al., 2017. Cross shelf benthic biodiversity patterns in the Southern Red Sea. Sci. Rep. 7, 437. https://doi.org/10.1038/s41598-017-00507-y.

Erftemeijer, P.L.A., Riegl, B., Hoeksema, B.W., Todd, P.A., 2012. Environmental impacts of dredging and other sediment disturbances on corals: a review. Mar. Pollut. Bull. 64, 1737–1765. https://doi.org/10.1016/j.marpolbul.2012.05.008.

Fabricius, K., De'ath, G., McCook, L., et al., 2005. Changes in algal, coral and fish assemblages along water quality gradients on the inshore great barrier reef. Mar. Pollut. Bull. 51, 384–398.

Fabricius, K.E., 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Mar. Pollut. Bull. 50, 125–146.

Fong, J., Ramsby, B.D., Flores, F., et al., 2024. Effects of material type and surface roughness of settlement tiles on macroalgal colonisation and early coral recruitment success. Coral Reefs. https://doi.org/10.1007/s00338-024-02526-4.

Fox, H.E., Caldwell, R.L., 2006. Recovery from blast fishing on coral reefs: a tale of two scales. Ecol. Appl. 16, 1631–1635. https://doi.org/10.1890/1051-0761(2006)016[1631:RFBFOC]2.0.CO;2.

Frys, C., Saint-Amand, A., Le Hénaff, M., et al., 2020. Fine-scale coral connectivity pathways in the Florida reef tract: implications for conservation and restoration. Front. Mar. Sci. 7, 312. https://doi.org/10.3389/fmars.2020.00312.

Gagnon, K., Christie, H., Didderen, K., et al., 2021. Incorporating facilitative interactions into small-scale eelgrass restoration—challenges and opportunities. Restor. Ecol. 29, e13398. https://doi.org/10.1111/rec.13398.

Gardner, T.A., Cote, I.M., Gill, J.A., et al., 2003. Long-term regions-wide declines in Caribbean corals. Science 301, 958–960.

GBRMPA, 2025. Yarul Dhingiga: Keppel Bay reef rehabilitation project. https://www2.gbrmpa.gov.au/our-work-field-management-conservation-and-monitoring/yarul-dhingiga-keppel-bay-reef-rehabilitation-project. Accessed June 2025.

Godoy, L., Mies, M., Zilberberg, C., et al., 2021. Southwestern Atlantic reef-building corals *Mussismilia* spp. are able to spawn while fully bleached. Mar Biol 168, 15. https://doi.org/10.1007/s00227-021-03824-z.

Golbuu, Y., Victor, S., Wolanski, E., Richmond, R.H., 2003. Trapping of fine sediment in a semi-enclosed bay, Palau, Micronesia. Estuar. Coast Shelf Sci. 57, 941–949.

Gouezo, M., Fabricius, K., Harrison, P., et al., 2021. Optimizing coral reef recovery with context-specific management actions at prioritized reefs. J. Environ. Manag. 295, 113209. https://doi.org/10.1016/j.jenvman.2021.113209.

Harris, D.L., Rovere, A., Casella, E., et al., 2018. Coral reef structural complexity provides important coastal protection from waves under rising sea levels. Sci. Adv. 4. https://doi.org/10.1126/sciadv.aao4350 eaao4350.

Hatchell, B., Konchar, K., Merrill, M., et al., 2022. Use of biodegradable coir for subtidal oyster habitat restoration: testing two reef designs in Northwest Florida. Estuaries Coasts 45, 2675–2689. https://doi.org/10.1007/s12237-022-01094-6.

He, Q., Silliman, B.R., 2019. Climate change, human impacts, and coastal ecosystems in the Anthropocene. Curr. Biol. 29, R1021–R1035. https://doi.org/10.1016/j.cub.2019.08.042.

Heyward, A.J., Giuliano, C., Page, C.A., Randall, C.J., 2024. Rock and roll: experiments on substrate movement and coral settlement. Coral Reefs. https://doi.org/10.1007/s00338-024-02547-z.

Hughes, T.P., Kerry, J.T., Álvarez-Noriega, M., et al., 2017. Global warming and recurrent mass bleaching of corals. Nature 543, 373–377. https://doi.org/10.1038/nature21707.

Humanes, A., Lachs, L., Beauchamp, E., et al., 2024. Selective breeding enhances coral heat tolerance to marine heatwaves. Nat. Commun. 15, 8703. https://doi.org/10.1038/s41467-024-52895-1.

Hylkema, A., Debrot, A.O., Van De Pas, E.E., et al., 2022. Assisted natural recovery: a novel approach to enhance *Diadema antillarum* recruitment. Front. Mar. Sci. 9, 929355. https://doi.org/10.3389/fmars.2022.929355.

Johns, K.A., Emslie, M.J., Hoey, A.S., et al., 2018. Macroalgal feedbacks and substrate properties maintain a coral reef regime shift. Ecosphere 9, e02349. https://doi.org/10.1002/ecs2.2349.

Jones, A.M., Berkelmans, R., 2014. Flood impacts in Keppel Bay, Southern great barrier reef in the aftermath of cyclonic rainfall. PLoS One 9, e84739. https://doi.org/10.1371/journal.pone.0084739.

Kenyon, T.M., Doropoulos, C., Wolfe, K., et al., 2022. Coral rubble dynamics in the Anthropocene and implications for reef recovery. Limnol. Oceanogr. Lett. 12254. https://doi.org/10.1002/lno.12254.

Kenyon, T.M., Jones, C., Rissik, D., et al., 2025. Bio-degradable 'reef bags' used for rubble stabilisation and their impact on rubble stability, binding, coral recruitment and fish occupancy. Ecol. Eng. 210, 107433. https://doi.org/10.1016/j.ecoleng.2024.107433.

King, S., Saint-Amand, A., Walker, B.K., et al., 2023. Larval dispersal patterns and connectivity of *Acropora* on Florida's Coral Reef and its implications for restoration. Front. Mar. Sci. 9, 1038463. https://doi.org/10.3389/fmars.2022.1038463.

Knutson, K.C., Pyke, D.A., Wirth, T.A., et al., 2014. Long-term effects of seeding after wildfire on vegetation in Great Basin shrubland ecosystems. J. Appl. Ecol. 51, 1414–1424. https://doi.org/10.1111/1365-2664.12309.

Kołos, A., Banaszuk, P., 2013. Mowing as a tool for wet meadows restoration: effect of long-term management on species richness and composition of sedge-dominated wetland. Ecol. Eng. 55, 23–28. https://doi.org/10.1016/j.ecoleng.2013.02.008.

Kopecky, K.L., Holbrook, S.J., Partlow, E., et al., 2024. Changing disturbance regimes, material legacies, and stabilizing feedbacks: dead coral skeletons impair key recovery processes following coral bleaching. Glob. Change Biol. 30, e17504. https://doi.org/10.1111/gcb.17504.

Kroon, F.J., Schaffelke, B., Bartley, R., 2014. Informing policy to protect coastal coral reefs: insight from a global review of reducing agricultural pollution to coastal ecosystems. Mar. Pollut. Bull. 85, 33–41. https://doi.org/10.1016/j.marpolbul.2014.06.003.

Ladd, M.C., Miller, M.W., Hunt, J.H., et al., 2018. Harnessing ecological processes to facilitate coral restoration. Front. Ecol. Environ. 16, 239–247. https://doi.org/10.1002/fee.1792.

Lamb, J.B., Van De Water, J.A.J.M., Bourne, D.G., et al., 2017. Seagrass ecosystems reduce exposure to bacterial pathogens of humans, fishes, and invertebrates. Science 355, 731–733. https://doi.org/10.1126/science.aal1956.

Lamont, T.A.C., Razak, T.B., Djohani, R., et al., 2022. Multi-dimensional approaches to scaling up coral reef restoration. Mar. Pol. 143, 105199. https://doi.org/10.1016/j.marpol.2022.105199.

Lange, I.D., Razak, T.B., Perry, C.T., et al., 2024. Coral restoration can drive rapid reef carbonate budget recovery. Curr. Biol. 34, 1341–1348.e3. https://doi.org/10.1016/j.cub.2024.02.009.

Leung, S.K., Kenyon, T.M., Brival, A.J.T., et al., 2024. A Practical Guide to Restoration and Rehabilitation of Rubble on Coral Reefs.

Lewis, R.R., 2005. Ecological engineering for successful management and restoration of mangrove forests. Ecol. Eng. 24, 403–418. https://doi.org/10.1016/j.ecoleng.2004.10.003.

Lorenzen, K., Agnalt, A.-L., Blankenship, H.L., et al., 2013. Evolving context and maturing science: Aquaculture-based enhancement and restoration enter the marine fisheries management toolbox. Rev. Fish. Sci. 21, 213–221. https://doi.org/10.1080/10641262.2013.837358.

Madin, J.S., McWilliam, M., Quigley, K., et al., 2023. Selecting coral species for reef restoration. J. Appl. Ecol. 60, 1537–1544. https://doi.org/10.1111/1365-2664.14447.

Matthews, S.A., Williamson, D.H., Beeden, R., et al., 2024. Protecting Great Barrier Reef resilience through effective management of crown-of-thorns starfish outbreaks. PLoS One 19, e0298073. https://doi.org/10.1371/journal.pone.0298073.

McCook, L.J., Jompa, J., Diaz-Pulido, G., 2001. Competition between corals and algae on coral reefs: a review of evidence and mechanisms. Coral Reefs 19, 400–417.

Ménard, A., Turgeon, K., Roche, D.G., et al., 2012. Shelters and their use by fishes on fringing coral reefs. PLoS One 7, e38450. https://doi.org/10.1371/journal.pone.0038450.

Mies, M., Güth, A.Z., Tenório, A.A., et al., 2018. In situ shifts of predominance between autotrophic and heterotrophic feeding in the reef-building coral *Mussismilia hispida*: an approach using fatty acid trophic markers. Coral Reefs 37, 677–689. https://doi.org/10.1007/s00338-018-1692-z.

Mies, M., Francini-Filho, R.B., Zilberberg, C., Garrido, A.G., Longo, G.O., Laurentino, E., Güth, A.Z., Sumida, P.Y.G., Banha, T.N.S., 2020. South Atlantic coral reefs are major global warming refugia and less susceptible to bleaching. Front. Mar. Sci. 7, 514.

Mies, M., Longo, G.O., Bianchini, A., et al., 2025. Challenges for coral restoration in Southwestern Atlantic reefs: guidelines for ethical and sustainable practices. Biodivers. Conserv. 34, 2287–2313. https://doi.org/10.1007/s10531-025-03071-4.

Montalvo-Proano, J., Flores, F., Severati, A., Negri, A.P., 2025. Fouling release coatings reduce colonisation of coral seeding devices. Sci. Rep. 15. https://doi.org/10.1038/s41598-025-08268-9.

Miller, M., Marmet, C., Cameron, C., Williams, D., 2014. Prevalence, consequences, and mitigation of fireworm predation on endangered staghorn coral. Mar. Ecol. Prog. Ser. 516, 187–194. https://doi.org/10.3354/meps10996.

Mora, C., Aburto-Oropeza, O., Ayala Bocos, A., et al., 2011. Global human footprint on the linkage between biodiversity and ecosystem functioning in reef fishes. PLoS Biol. 9, e1000606. https://doi.org/10.1371/journal.pbio.1000606.

Moran, D., Robson, B., Gruber, R., et al., 2023. Marine Monitoring Program Annual Report 2021-22 Water Quality. Townsville.

Morrison, T.H., Adger, W.N., Agrawal, A., et al., 2022. Radical interventions for climate-impacted systems. Nat. Clim. Change 12, 1100–1106. https://doi.org/10.1038/s41558-022-01542-y.

Muhando, C.A., Lanshammar, F., 2020. Ecological Effects of the crown-of-thorns Starfish Removal Programme on Chumbe Island Coral Park. Zanzibar, Tanzania.

Mumby, P.J., Dahlgren, C.P., Harbourne, A.R., et al., 2006. Fishing, trophic cascades, and the process of grazing on coral reefs. Science 311, 98–101.

Mumby, P.J., Sartori, G., Buccheri, E., et al., 2024. Allee effects limit coral fertilization success. Proc. Natl. Acad. Sci. USA 121, e2418314121. https://doi.org/10.1073/pnas.2418314121.

Nagelkerken, I., Sheaves, M., Baker, R., Connolly, R.M., 2015. The seascape nursery: a novel spatial approach to identify and manage nurseries for coastal marine fauna. Fish Fish. 16, 362–371. https://doi.org/10.1111/faf.12057.

Neely, K.L., Lewis, C.L., O'Neil, K., et al., 2021. Saving the last unicorns: the genetic rescue of Florida's pillar corals. Front. Mar. Sci. 8, 657429. https://doi.org/10.3389/fmars.2021.657429.

Neil, R.C., Humphrey, C., Bourne, D.G., Heyward, A., 2021. Co-culture with grazers can improve survival and growth of multiple coral species. Aquaculture 544, 737095. https://doi.org/10.1016/j.aquaculture.2021.737095.

Neilson, B.J., Wall, C.B., Mancini, F.T., Gewecke, C.A., 2018. Herbivore biocontrol and manual removal successfully reduce invasive macroalgae on coral reefs. PeerJ 6, e5332. https://doi.org/10.7717/peerj.5332.

Nitschke, M.R., Abrego, D., Allen, C.E., et al., 2024. The use of experimentally evolved coral photosymbionts for reef restoration. Trends Microbiol. 32, 1241–1252. https://doi.org/10.1016/j.tim.2024.05.008.

Nozawa, Y., 2008. Micro-crevice structure enhances coral spat survivorship. J. Exp. Mar. Biol. Ecol. 367, 127–130. https://doi.org/10.1016/j.jembe.2008.09.004.

Nuñez Lendo, C.I., Suggett, D.J., Boote, C., et al., 2024. Carbonate budgets induced by coral restoration of a Great Barrier Reef site following cyclone damage. Front. Mar. Sci. 10, 1298411. https://doi.org/10.3389/fmars.2023.1298411.

Oliver, E.C.J., Donat, M.G., Burrows, M.T., et al., 2018. Longer and more frequent marine heatwaves over the past century. Nat. Commun. 9, 1324. https://doi.org/10.1038/s41467-018-03732-9.

Oliveira, M.D.M., Leão, Z.M.A.N., Kikuchi, R.K.P., 2008. Cultivo de Millepora alcicornis como uma ferramenta para Restauração e Manejo dos Ecossistemas Recifais do Nordeste do Brasil. RGCI 8, 183–201. https://doi.org/10.5894/rgci148.

Osborne, K., Thompson, A., Cheal, A.J., et al., 2017. Delayed coral recovery in a warming ocean. Glob. Change Biol. 23, 3869–3881. https://doi.org/10.1111/gcb.13707.

Page, C.A., Giuliano, C., Meehan, K., et al., 2023. Varied effects of *Lobophora* chemistry on settlement of larvae from five coral genera. Mar. Ecol. Prog. Ser. 717, 17–35. https://doi.org/10.3354/meps14380.

Page, C.A., Giuliano, C., Randall, C.J., 2024. Benthic communities influence coral seeding success at fine spatial scales. Restor. Ecol. https://doi.org/10.1111/rec.14212.

Peixoto, R.S., Sweet, M., Villela, H.D.M., et al., 2021. Coral probiotics: premise, promise, prospects. Annu Rev Anim Biosci 9, 265–288. https://doi.org/10.1146/annurev-animal-090120-115444.

Peixoto, R.S., Voolstra, C.R., Baums, I.B., et al., 2024. The critical role of coral reef restoration in a changing world. Nat. Clim. Change. https://doi.org/10.1038/s41558-024-02202-z.

Pezner, A.K., Courtney, T.A., Barkley, H.C., et al., 2023. Increasing hypoxia on global coral reefs under ocean warming. Nat. Clim. Change 13, 403–409. https://doi.org/10.1038/s41558-023-01619-2.

Querejeta, J.I., Rolda′n A, Albaladejo, J., Castillo, V., 2000. Soil physical properties and moisture content affected by site preparation in the afforestation of a semiarid rangeland. SSSA (Soil Sci. Soc. Am.) J. 64, 2087–2096. https://doi.org/10.2136/sssaj2000.6462087x.

Quigley, K., Bay, L., Willis, B., 2018. Leveraging new knowledge of symbiodinium community regulation in corals for conservation and reef restoration. Mar. Ecol. Prog. Ser. 600, 245–253. https://doi.org/10.3354/meps12652.

Ramsby, B.D., Emonnot, F., Flores, F., et al., 2024. Low light intensity increased survival of coral spat in aquaculture. Coral Reefs 43, 627–640. https://doi.org/10.1007/s00338-024-02489–6.

Randall, C., Negri, A., Quigley, K., et al., 2020. Sexual production of corals for reef restoration in the Anthropocene. Mar. Ecol. Prog. Ser. v635, 203–232. https://doi.org/10.3354/meps13206.

Randall, C.J., Giuliano, C., Heyward, A.J., Negri, A.P., 2021. Enhancing coral survival on deployment devices with microrefugia. Front. Mar. Sci. 8, 662263. https://doi.org/10.3389/fmars.2021.662263.

Reimer, J.D., Peixoto, R.S., Davies, S.W., et al., 2024. The fourth global coral bleaching event: where do we go from here? Coral Reefs. https://doi.org/10.1007/s00338-024-02504-w s00338-024-02504-w.

Ricardo, G.F., Jones, R.J., Nordborg, M., Negri, A.P., 2017. Settlement patterns of the coral *Acropora millepora* on sediment-laden surfaces. Sci. Total Environ. 609, 277–288. https://doi.org/10.1016/j.scitotenv.2017.07.153.

Roepke, L.K., Brefeld, D., Soltmann, U., et al., 2022. Antifouling coatings can reduce algal growth while preserving coral settlement. Sci. Rep. 12, 15935. https://doi.org/10.1038/s41598-022-19997-6.

Russ, G.R., 2002. Yet another review of marine reserves as reef fisheries management tools. In: Sale, P. (Ed.), Coral Reef Fishes: Dynamics and Diversity in a Complex Ecosystem. Academic Press, San Diego, pp. 421–443.

Scott, R., Suggett, D., Hayward, C., et al., 2024. Early-stage outcomes and cost-effectiveness of implementing tourism-led coral propagation and outplanting in the Whitsundays (Great Barrier Reef). Front. Mar. Sci. 11, 1418784. https://doi.org/10.3389/fmars.2024.1418784.

Selig, E.R., Hole, D.G., Allison, E.H., et al., 2019. Mapping global human dependence on marine ecosystems. Conserv. Lett. 12, e12617. https://doi.org/10.1111/conl.12617.

Sheaves, M., 2009. Consequences of ecological connectivity: the coastal ecosystem mosaic. Mar. Ecol. Prog. Ser. 391, 107–115. https://doi.org/10.3354/meps08121.

Silbiger, N., Guadayol, Ò., Thomas, F., Donahue, M., 2014. Reefs shift from net accretion to net erosion along a natural environmental gradient. Mar. Ecol. Prog. Ser. 515, 33–44. https://doi.org/10.3354/meps10999.

Silliman, B.R., Hensel, M.J.S., Gibert, J.P., et al., 2024. Harnessing ecological theory to enhance ecosystem restoration. Curr. Biol. 34, R418–R434. https://doi.org/10.1016/j.cub.2024.03.043.

Sing Wong, A., Vrontos, S., Taylor, M.L., 2022. An assessment of people living by coral reefs over space and time. Glob. Change Biol. 28, 7139–7153. https://doi.org/10.1111/gcb.16391.

Smith, H.A., Brown, D.A., Arjunwadkar, C.V., et al., 2022. Removal of macroalgae from degraded reefs enhances coral recruitment. Restor. Ecol. https://doi.org/10.1111/rec.13624.

Smith, H.A., Dallmeyer-Drennen, G., Bourne, D.G., et al., 2025. Sea-weeding enhances early coral survival on seeding devices, but benefits of seeding diminish after one year. J. Environ. Manag. 383, 125322. https://doi.org/10.1016/j.jenvman.2025.125322.

Smith, H.A., Fulton, S.E., McLeod, I.M., et al., 2023. Sea-weeding: manual removal of macroalgae facilitates rapid coral recovery. J. Appl. Ecol. 60, 2459–2471. https://doi.org/10.1111/1365-2664.14502.

Spadaro, A.J., Butler, M.J., 2021. Herbivorous crabs reverse the seaweed dilemma on coral reefs. Curr. Biol. 31, 853–859.e3. https://doi.org/10.1016/j.cub.2020.10.097.

Suggett, D.J., Edmondson, J., Howlett, L., Camp, E.F., 2020. Coralclip®: a low-cost solution for rapid and targeted out-planting of coral at scale. Restor. Ecol. 28, 289–296. https://doi.org/10.1111/rec.13070.

Suggett, D.J., Guest, J., Camp, E.F., et al., 2024. Restoration as a meaningful aid to ecological recovery of coral reefs. npj Ocean Sustain 3, 20. https://doi.org/10.1038/s44183-024-00056-8.

Sully, S., van Woesik, R., 2020. Turbid reefs moderate coral bleaching under climate-related temperature stress. Glob. Change Biol. 26, 1367–1373. https://doi.org/10.1111/gcb.14948.

Tan, Y.M., Dalby, O., Kendrick, G.A., et al., 2020. Seagrass restoration is possible: insights and lessons from Australia and New Zealand. Front. Mar. Sci. 7, 617. https://doi.org/10.3389/fmars.2020.00617.

Tebben, J., Guest, J.R., Sin, T.M., et al., 2014. Corals like it waxed: paraffin-based antifouling technology enhances coral spat survival. PLoS One 9, e87545. https://doi.org/10.1371/journal.pone.0087545.

Toh, T.C., Ng, C.S.L., Guest, J., Chou, L.M., 2013. Grazers improve health of coral juveniles in ex situ mariculture. Aquaculture 414–415, 288–293. https://doi.org/10.1016/j.aquaculture.2013.08.025.

Trapon, M.L., Pratchett, M.S., Hoey, A.S., Baird, A.H., 2013. Influence of fish grazing and sedimentation on the early post-settlement survival of the tabular coral *Acropora cytherea*. Coral Reefs 32, 1051–1059. https://doi.org/10.1007/s00338-013-1059-4.

Uthicke, S., Furnas, M., Lønborg, C., 2014. Coral reefs on the edge? Carbon chemistry on inshore reefs of the Great Barrier Reef. PLoS One 9, e109092. https://doi.org/10.1371/journal.pone.0109092.

van Katwijk, M.M., Thorhaug, A., Marbà, N., et al., 2016. Global analysis of seagrass restoration: the importance of large-scale planting. J. Appl. Ecol. 53, 567–578. https://doi.org/10.1111/1365-2664.12562.

van Oppen, M.J.H., Oliver, J.K., Putnam, H.M., Gates, R.D., 2015. Building coral reef resilience through assisted evolution. Proc. Natl. Acad. Sci. USA 112, 2307–2313. https://doi.org/10.1073/pnas.1422301112.

Vieira, C., 2020. Lobophora–coral interactions and phase shifts: summary of current knowledge and future directions. Aquat. Ecol. 54, 1–20. https://doi.org/10.1007/s10452-019-09723-2.

Vozzo, M.L., Doropoulos, C., Silliman, B.R., et al., 2023. To restore coastal marine areas, we need to work across multiple habitats simultaneously. Proc. Natl. Acad. Sci. USA 120, e2300546120. https://doi.org/10.1073/pnas.2300546120.

Walker, M., Mezger, S.D., Clarke, A., et al., 2024. Cushion sea-star removal enhances coral restoration practices and limits background mortality on recovering reefs. Coral Reefs. https://doi.org/10.1007/s00338-024-02550-4.

Waltham, N.J., Elliott, M., Lee, S.Y., et al., 2020. UN decade on ecosystem restoration 2021–2030—what chance for success in restoring coastal ecosystems? Front. Mar. Sci. 7, 71. https://doi.org/10.3389/fmars.2020.00071.

Wang, G., Wu, L., Mei, W., Xie, S.-P., 2022. Ocean currents show global intensification of weak tropical cyclones. Nature 611, 496–500. https://doi.org/10.1038/s41586-022-05326-4.

Westoby, R., Becken, S., Prieto, Laria A., 2020. Perspectives on the human dimensions of coral restoration. Reg. Environ. Change 20, 109. https://doi.org/10.1007/s10113-020-01694-7.

Whitman, T.N., Hoogenboom, M., Negri, A., Randall, C., 2024. Coral-seeding devices with fish-exclusion features reduce mortality on the Great Barrier Reef. Sci. Rep. 14, 13332. https://doi.org/10.1038/s41598-024-64294-z.

Williamson, D.H., Russ, G.R., Ayling, A.M., 2004. No-take marine reserves increase abundance and biomass of reef fish on inshore fringing reefs of the Great Barrier Reef. Environ. Conserv. 31, 149–159.

Wolfe, K., Kenyon, T.M., Mumby, P.J., 2021. The biology and ecology of coral rubble and implications for the future of coral reefs. Coral Reefs 40, 1769–1806. https://doi.org/10.1007/s00338-021-02185-9.

Wood, G., Marzinelli, E.M., Coleman, M.A., et al., 2019. Restoring subtidal marine macrophytes in the Anthropocene: trajectories and future-proofing. Mar. Freshw. Res. 70, 936. https://doi.org/10.1071/MF18226.

Work, T.M., Aeby, G.S., Neal, B.P., et al., 2018. Managing an invasive corallimorph at Palmyra Atoll National Wildlife Refuge, Line Islands, Central Pacific. Biol. Invasions 20, 2197–2208. https://doi.org/10.1007/s10530-018-1696-1.

Zhang, Y., Yang, Q., Ling, J., et al., 2021. Shifting the microbiome of a coral holobiont and improving host physiology by inoculation with a potentially beneficial bacterial consortium. BMC Microbiol. 21, 130. https://doi.org/10.1186/s12866-021-02167-5.

Zweifler (Zvifler), A., O'Leary, M., Morgan, K., Browne, N.K., 2021. Turbid coral reefs: past, present and Future—A review. Diversity 13, 251. https://doi.org/10.3390/d13060251.