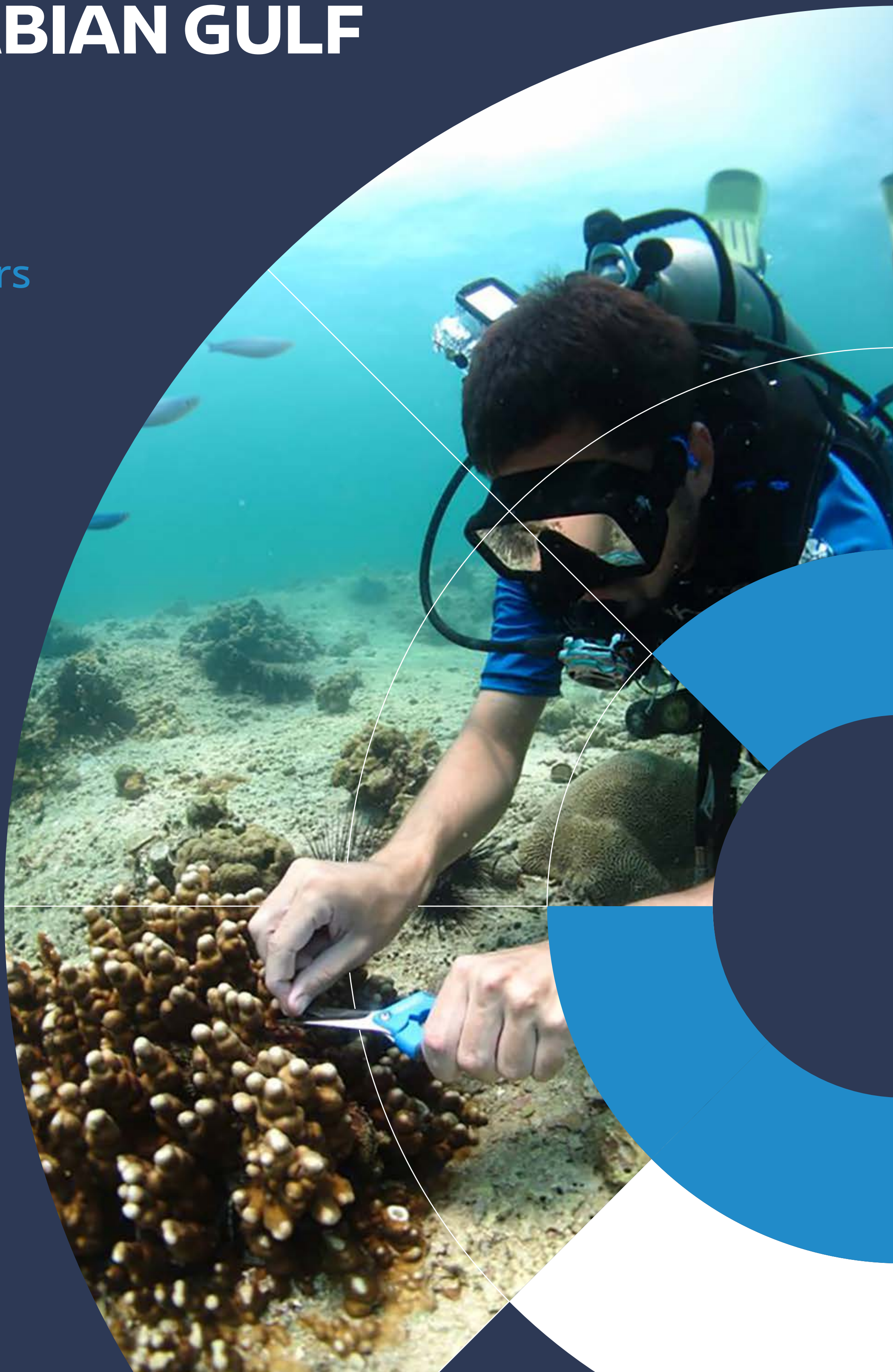
AD PORTS GROUP

CORAL RELOCATION IN THE ARABIAN GULF

Benefits, risks and recommendations for practitioners and decision-makers

جامعـة نيويورك أبوظبي
NYU ABU DHABI



Executive summary

Coral reefs occur in all eight nations bordering the Arabian Gulf, and they represent the most biodiverse and economically important ecosystem in the region. Economic development has spurred rapid population growth across the Gulf in recent decades, necessitating the development of critical infrastructure to support burgeoning populations in coastal cities. While regional environmental regulators should always promote avoidance as central to their impact mitigation strategy in order to maintain the integrity of these important ecosystems, there may be occasional cases where development of critical infrastructure near coral reefs must occur. In these cases, coral relocation may represent a means of offsetting development impacts. While coral relocation appears conceptually simple, it is a highly complex and delicate process that requires careful planning, implementation and post-intervention monitoring to be successful. This report provides a framework for maximising such success.

This manual opens with a discussion of the importance of coral reefs at global and regional levels and explores pressures facing Arabian Gulf reefs. We then examine the impact mitigation hierarchy, to show that coral relocation should be considered only as a last resort measure where coastal development is to occur and provide data and case studies as examples of unanticipated risks and vulnerabilities that are inherent in coral relocation. The remainder of the document then outlines the current best practices for coral relocation that includes elements from the planning phase to the operational phase, incorporating considerations around the unique environmental context of the Gulf, and then describes the critically important post-relocation monitoring phase that is necessary to measure success and inform future programmes on lessons learned.

The intended use of these recommendations is to provide scientifically justified advice, to plan, design, implement and assess relocation programmes for the unique environmental context of the region. Adoption of the principles and practices outlined in this manual will serve to enhance the success of coral relocation programmes in the Arabian Gulf.

David Gatward

Chief Engineering & Technical Services Officer - AD Ports Group

“As we stride towards more sustainable development in the Gulf region, preserving our coral reefs is paramount. This manual is a testament to our dedication to integrating sustainable practices into coastal development. It underscores the significant role of environmental impact assessments and diverse management strategies in safeguarding these vital ecosystems. By focusing on avoiding development activities in vulnerable areas and reinforcing the need for careful planning, execution, and post-relocation monitoring in coral relocation projects, we are setting a new standard in sustainable engineering. This approach protects our natural heritage and ensures that our engineering solutions contribute positively to the environment and its myriad inhabitants.”

Eiman Al Khalaqi

Senior Vice President, Innovation - AD Ports Group

“Innovation stands at the forefront of our efforts in preserving the Gulf's rich and diverse marine ecosystems. As detailed in this manual, the coral reefs around the Gulf represent a stronghold of biodiversity and a crucial economic asset. The challenge of developing infrastructure while preserving these natural wonders has necessitated innovative approaches. Coral relocation, while complex, emerges as a vital tool in our endeavour to balance development with ecological preservation. This manual encapsulates our commitment to pioneering methods that ensure the success of such delicate operations, marking a significant step in our journey towards sustainable innovation.”

Marie Seraphim 1, Erin Collins 2 John A. Burt 3*,

[1] Marine Biology Laboratory, New York University Abu Dhabi, PO Box 129188, Abu Dhabi, UAE; Current address: Scottish Seabird Centre, The Harbour, North Berwick, EH39 4SS, UK

[2] Arts & Humanities Visual Design Lab, New York University Abu Dhabi, PO Box 129188, Abu Dhabi, UAE

[3] Arabian Center for Climate and Environmental Sciences (ACCESS) and Center for Interacting Urban Networks (CITIES), New York University Abu Dhabi, PO Box 129188, Abu Dhabi, UAE

[*] Corresponding author: John.Burt@nyu.edu

Citation information:

Seraphim, M., Collins, E., Burt, J.A. (2024) Coral relocation in the Arabian Gulf: Benefits, risks and best-practices recommendations for practitioners and decision-makers. Published by Abu Dhabi Ports Group, UAE. P. 1-60. DOI: 10.13140/RG.2.2.11660.12162

Table of Contents

Image credit: Oliver Farrell

1

Coral reefs: a valuable, but vulnerable, ecosystem

Coral reefs are one of the planet's most productive and valuable ecosystems. Millions of people are dependent on the ecosystem goods and services they provide, such as food items for tropical fisheries, cultural services and buffering of wave action, thus preventing shoreline erosion [1]. In total, it has been estimated that coral reefs provide over US$6 million per km^2, annually, in economic benefits to coastal populations across the tropics [2] - the highest economic value of all major biomes on Earth [3]. They are also an incredibly important asset for biodiversity. Coral reefs contain over a quarter of all marine species despite occupying less than 0.1% of the ocean area [4], providing shelter, food, and spawning habitats to an estimated 830,000 reef-associated species [5]. They also represent one of the most productive ecosystems in the world, where energy is tightly recycled through their diverse and extensive food webs [6].

Fig. 1. Coral reefs are one of the most biodiverse and economically important ecosystems on Earth. (Image credit: Toby Hudson (CC-BY-SA-3.0)

While corals may superficially resemble rocks or plants, they are actually animals that come in a variety of sizes and shapes that can vary markedly among species and environments [7,8]. Corals have a two-phase life cycle, where the adult colonies typically produce eggs that can drift in the water column for days to weeks as they develop into larvae (planula) that are ultimately capable of swimming down to attach to the reefs [9,10]. As the planula attaches, it begins secreting a calcium carbonate skeleton that permanently cements it to the reef framework and undergoes a metamorphosis from its slug-like larval appearance into a small (ca. 1 mm) anemone-like polyp, a life-stage that it will retain for the remainder of its life [7,10]. Over time, this polyp will grow clonally, making many copies of itself and slowly develop into the large, complex coral colonies that we are familiar with – each of which is comprised of many thousands to millions of clonal coral polyps (Fig. 2). This carpet of clonal polyps forms a thin (1-2 mm) veneer of delicate, jelly-like tissue across the surface of the colony, with the millions of polyps each genetically identical to one another. Although typically not visible to the naked eye, each of these numerous, near-microscopic, polyps is nourished by extending tentacles out to feed on plankton in the water column (typically at night) using stinging cells (nematocysts) similar to their jellyfish cousins to capture food [11]. In addition, each polyp contains hundreds of thousands of microscopic photosynthetic single-celled algae (zooxanthellae) that live symbiotically inside of the polyp tissue [12] (Fig. 2, right). This is an incredibly important symbiosis, as these algae provide over 90% of a coral›s energy supply through photosynthetic product. In exchange, the corals provide the algae with a sustained supply of nutrients gained from polyp feeding, an important nutrient source, given the nutrient-poor waters that corals (and their zooxanthellae) typically inhabit [13,14]. The millions of zooxanthellae per square centimetre are what gives corals their bright, vibrant colours; the coral tissue itself is actually translucent, like their jellyfish cousins, with only their white skeleton visible underneath the thin veneer of jelly-like tissue [7,15].

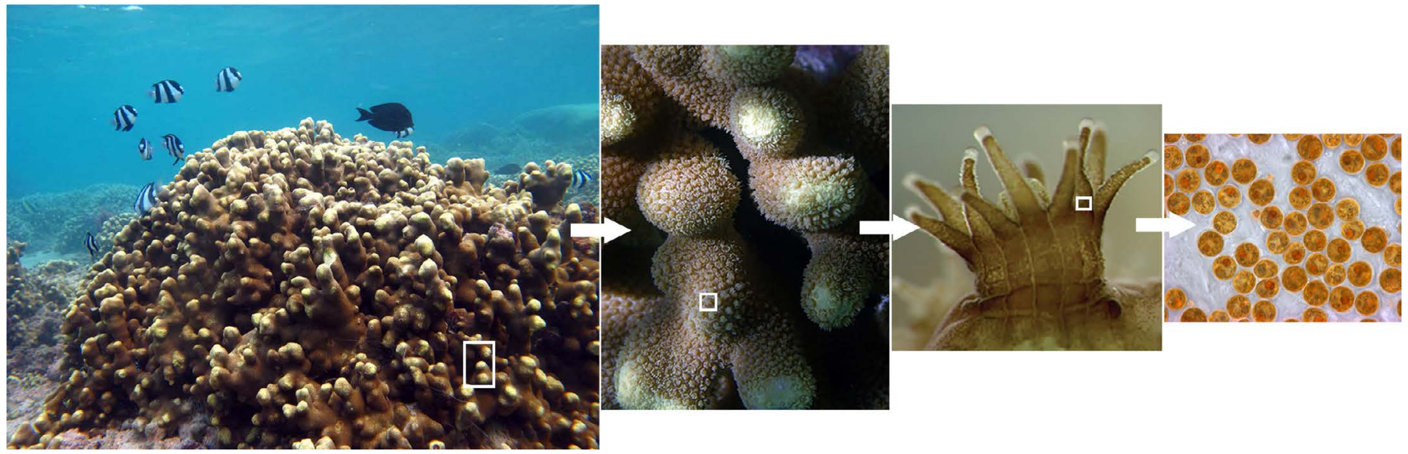


Fig. 2. Corals are colonies typically comprised of millions of clonal polyps, each of which contain hundreds of thousands of microscopic photosynthetic algae that live symbiotically within their tissue. This image "ColonyToSymbiont" (CC-BY-SA-4.0) was created from *Porites cylindrica* by Philippe Bourjon (CC-BY-SA-3.0), *Porites cylindrica* en Samoa by Larry Basch (CC-PD), Zooxantelas en pólipo de *Porites astreoides* by NOAA (CC-PD), and Zooxanthellae by Todd LaJeunesse (CC-BY-2.0).

Corals thrive in clear, shallow, tropical or sub-tropical waters with optimum temperatures of 23° to 29° Celsius (Fig. 3). Coral growth rates differ depending on the species. Thin branch-like species (such as Acropora table corals) can grow at a rate of 100–150 mm/year, while large boulder-like species (such as Porites mound corals) grow much slower (5-10 mm/year), but are typically more sturdy and resilient to external stressors [8,16]. When coral colonies grow, they secrete a calcium carbonate layer that forms the skeleton that underlies the jelly-like polyp surface tissues (Fig. 4). Typically, it is only the top few millimetres of a colony that is living coral tissue, with the underlying non-living skeleton having been laid down like rings of a tree as the colony grows [7]. These hard skeletal structures of individual coral colonies build above one another over time, forming the complex reef framework that provides a three-dimensional habitat for reef associated fauna on local scales, with reef framework so extensive in some areas that it is visible from space (e.g. the Great Barrier Reef) [7].

Fig. 3. Map of the global distribution of tropical coral reefs. Six percent of the world's coral reef area occurs within the Arabian region [17]. Data source: UNEP-WCMC (2021)[2].

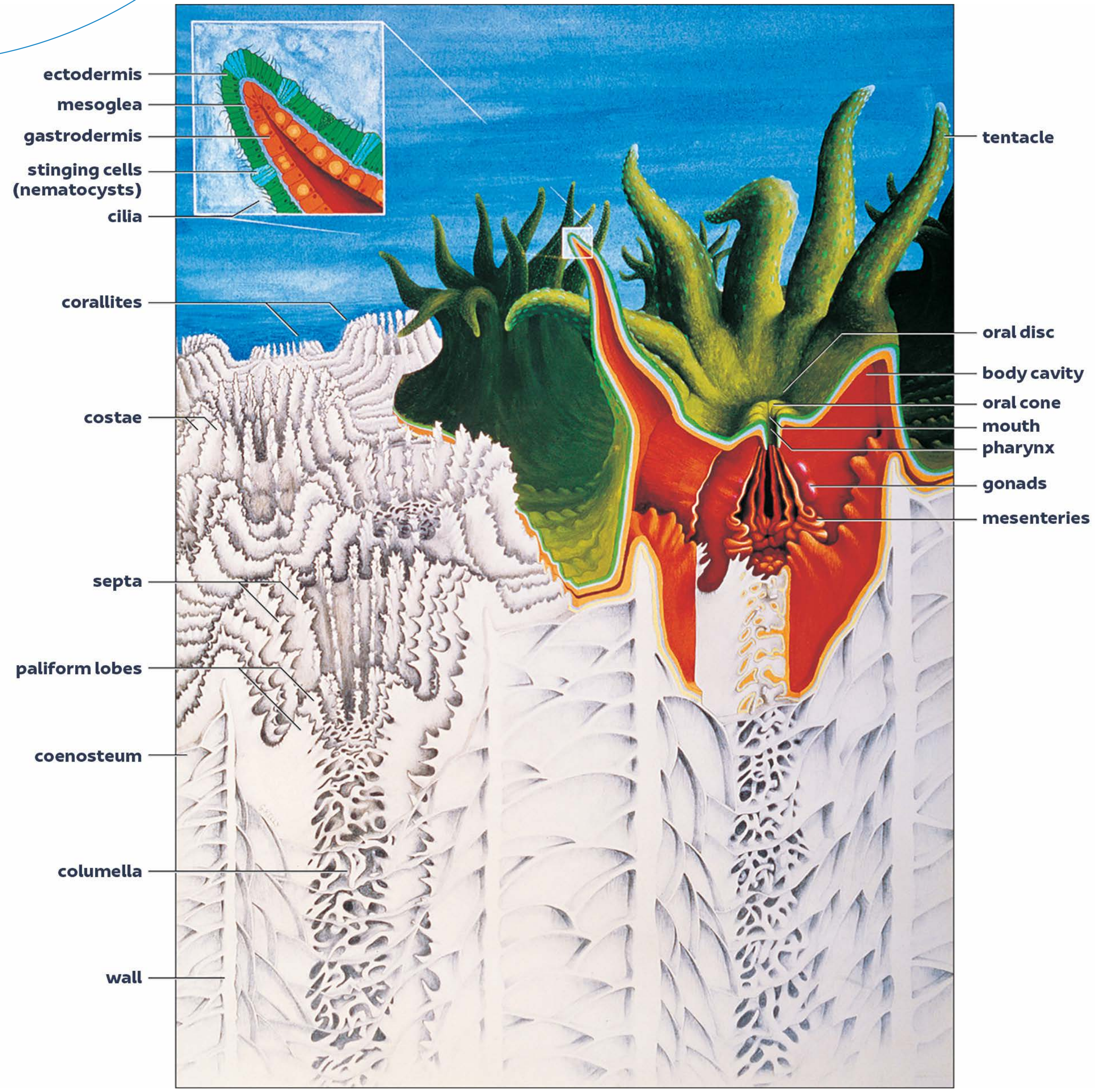


Fig. 4. The anatomy of a coral polyp. Millions of clonal polyps can make up a single coral colony, with the delicate jelly-like surface tissues growing above the many layers of coral skeleton that make up the reef framework. Source: Veron et al. 2022 [19].

While corals and the reefs they create are extremely important ecosystems, these are under threat due to a range of interacting factors at both local and global scales [20]. Rapidly warming sea temperatures associated with global climate change is a major threat to corals, as high temperatures can lead to a chemical cascade within the corals' tissue that causes them to expel their symbiotic algae, often leading to mass coral decline [21-23]. This stress response is characterised by colonies losing their colourful algal pigments, leaving only the bright-white skeletons visible under the 1-2 mm translucent coral tissue on its surface, this process is known as "coral bleaching" [22]. Additionally, ocean acidification, characterised by higher levels of carbon dioxide absorbed within oceans leads to lower pH through the formation of carbonic acid, which can inhibit the development and maintenance of coral skeletons [21].

Local environmental threats also include physical destruction due to coastal development and destructive fishing practices, as well as sedimentation and pollution that can inhibit photosynthesis and promote coral disease. Overfishing of key associated organisms, such as herbivorous fishes, is also problematic as these free coral colonies from macroalgae competition [24].
A combination of these threats has cumulatively led to the loss of 14% of coral reefs globally since 2009 [25], and a third of coral species are now considered to be at risk of extinction due to climate change and local pressures [26]. The overall scientific consensus is that coral loss is now outpacing reef growth [27], and consequently prompting an acceleration of research into coral reef restoration and impact mitigation measures.

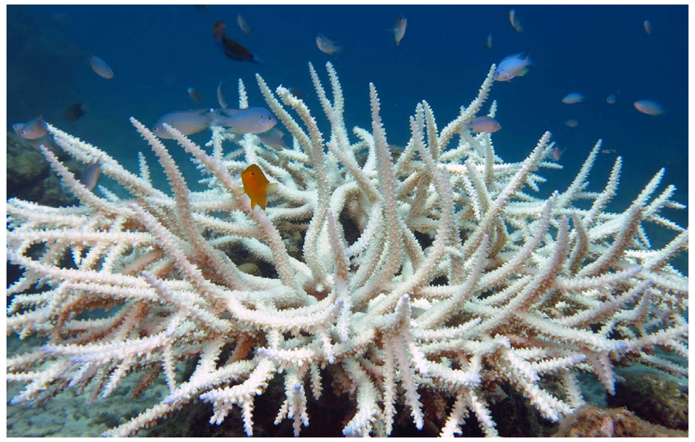


Fig. 5. Coral colonies can 'bleach' during extreme stress (e.g., high temperatures, elevated nutrients, etc), during which they expel their colourful symbiotic algae and turn white. Because those algae provide >90% of a coral's energy budget, such loss of algae during bleaching events can lead to mass coral decline if conditions do not return to normal within a few days. Source: Vardhan Patankar (CC-BY-SA 4.0).

Fig. 6. Sedimentation from coastal development led to widespread mortality of corals in UAE - 2007 [28]. Sedimentation from coastal development should be carefully monitored and managed in areas even hundreds of metres from vulnerable reef ecosystems. Source: John Burt.

2

The importance of coral reefs in the Arabian Gulf

Coral reefs occur in all eight nations bordering the Arabian Gulf, representing an important natural asset for Gulf nations. Reefs are the most species rich ecosystem in Arabia, which is of particular importance given the arid nature of the region and the constraints this puts on terrestrial diversity [29]. The complex and productive framework of Gulf reefs provides food, shelter and spawning habitat to over 300 species of reef-associated fishes, sharks and rays [30,31], with many of these species being fully reef-dependent for part or all of their life cycle [32]. Biomass of fish is substantially higher on coral reefs than in surrounding habitats and many reef-associated fish species are also commercially valuable [33], with reefs supporting a fishing industry that is second only to oil as an economic resource sector as well as a burgeoning recreational diving and ecotourism industry [34]. Thus, coral reefs represent a critically important ecosystem in terms of both biological diversity and economic value for Gulf nations [35].

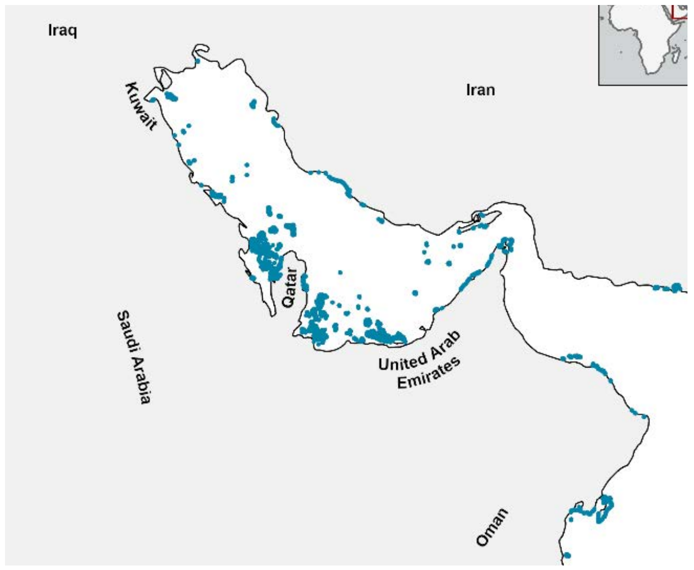


Fig. 7. Map of coral reef distribution in the Arabian Gulf and Sea of Oman. Data source: UNEP-WCMC (2021)[18].

Gulf reefs also represent an incredibly important asset for global science. The Gulf is one of the most extreme seas on earth due to its location in the arid subtropical high-pressure belt, its shallow depth (average 30 m), and its semi-enclosed geography that restricts mixing with the Indian Ocean [29].
These conditions result in a marine system that is characterised by extreme and highly variable water temperatures (<12 to >36 °C annually), hyper salinity (up to 44 PSU in open water, and higher in embayments), occasional hypoxia, and often turbid conditions [29,36,37]. As a result of these environmental extremes, the Gulf is home to a relatively hardy subset of reef-associated species that occur in the Indian Ocean (e.g. corals, reef fishes and reef invertebrates [36,38,39], with diversity that is typically ca. 10% of that occurring in the Indian Ocean, but with assemblages that are typically heavily dominated by stress-tolerant fauna [36].
Recent research has demonstrated that as a result of their exposure to high temperatures, since the Gulf was colonised by corals following the most recent glacial retreat >12,000 years ago, corals in the Gulf have genetically adapted to cope with extreme temperature and today represent the most temperature-tolerant corals in the world [40-42]. Thus, given the rapid pace of climate change, Gulf reefs have become a source of research on how corals cope with and respond to extreme temperatures, providing insights into how corals in other parts of the world may respond to warming temperatures in the coming decades [43,44].
Additionally, there is growing research on whether active intervention using Gulf corals (e.g. assisted migration, crossbreeding) could be utilised to support reefs in other regions [45-47].
The scientific value of Gulf reefs to the international science community cannot be overstated [35,43].

Fig. 8. Arabian Gulf corals are among the most thermally tolerant in the world, making this region a source for climate change related research. Here, a researcher samples a coral in Qatar for a genetics study. Source: John A. Burt.

While Gulf corals are among the most thermally tolerant in the world, regional variation in coral diversity and tolerance does occur as a result of environmental gradients across the Gulf. Most species with rich and complex coral reefs can be found along the coast of Iran and towards the northern Gulf waters of Kuwait and eastern Saudi Arabia, where incoming water from the Sea of Oman as well as greater depths buffer coral reefs from extreme temperatures [38]. Towards the south - where shallow depths result in more extreme temperatures and where salinity is highest - coral diversity is low [48-50], but the total amount of coral (i.e., percent cover of reefs by live coral) is typically comparable to, and sometimes greater than, on reefs in more benign parts of the Gulf [51], with coral assemblages largely dominated by stress-tolerant species. Thus, while diversity and community composition vary regionally, coral reefs represent an important ecosystem regardless of their location in the Gulf.

Fig. 9. Coral reef communities vary throughout the Gulf in response to environmental differences. More sensitive table corals (*Acropora*) tend to dominate in areas with more benign conditions (e.g., Sir Bu Nair island in the central Gulf, left), while more robust brain and mound corals (*Platygyra, Porites*) tend to dominate where conditions are more extreme (e.g. Ras Ghanada, Abu Dhabi, right), although the amount of live coral is often comparable across reef types [51]. Source: John A. Burt (photographed in 2014).

Pressures on Arabian Gulf reefs

Although coral reefs in the Arabian Gulf are highly important in terms of biodiversity, economic value, and as assets for global science, increasing pressures on these ecosystems is resulting in their degradation and decline across the region [52].

Marine heat waves have been occurring in the Arabian Gulf with increasing frequency and severity as a consequence of global climate change [51].

While Gulf corals are among the most thermally tolerant in the world, during summer they live very close to their upper thermal limits that even modest increases in temperature (≥ 1 °C above normal maximum temperatures) can push them beyond their physiological limits, resulting in bleaching and, in extreme cases, mass mortality. Historic records of marine heat waves and bleaching in the Arabian Gulf indicate that the first bleaching event occurred in 1982, followed by a long period without thermal stress [53]. However, since the late 1990s, bleaching events associated with marine heat waves have been recorded with increasing frequency in the Gulf, occurring in 1996, 1998, 2003, 2010, 2011, 2012, 2017 and in 2021 [51,54,55].

The most recent bleaching events have been among the most severe on record, and the amount of live coral on reefs has declined by over three-quarters in particularly badly affected areas as a result of mass coral mortality [54].

Overall, coral cover across the Arabian Gulf has declined by 40% between 1996 and 2019, largely as a consequence of bleaching events associated with marine heat waves [52].

While global climate change and marine heat waves represent the most widespread threat to coral reefs in the Arabian Gulf, more localised pressure from coastal development and urbanisation has led to loss and degradation of reefs around coastal cities and the industrial sites that support them [56,57].

Dredging and reclamation to support growth of coastal real estate and navigation channels to support seaborne industry and commerce has transformed much of the nearshore environment of the Gulf, with some estimates suggesting that as much of 40% of the Arabian Gulf coastline is now comprised of heavily modified or artificial coastline [29,57]. Infrastructure development operations such as harbour construction, channel dredging or land reclamation can directly threaten fragile coral reef ecosystems through their direct removal during dredging or burial during reclamation activities [58,59]. Furthermore, even reefs outside of the footprint of development may be indirectly threatened by elevated sedimentation during construction phases and longer-term changes in hydrodynamics afterwards [60]. Therefore, while more localised in extent compared with climate change impacts, coastal development to support urban expansion represents a ubiquitous environmental pressure in the Gulf given the extensive nature these activities [56,57].

As a result, there has been a growing interest from regulators and developers to work together to establish and implement more robust environmental management measures to better enhance the sustainability of coastal construction.

Fig. 10. Recurrent marine heat waves have caused coral bleaching to occur with increasing frequency and severity in the Arabian Gulf in recent decades, such as during this bleaching event on Kubbar Reef in Kuwait in 2015. Source: John A. Burt.

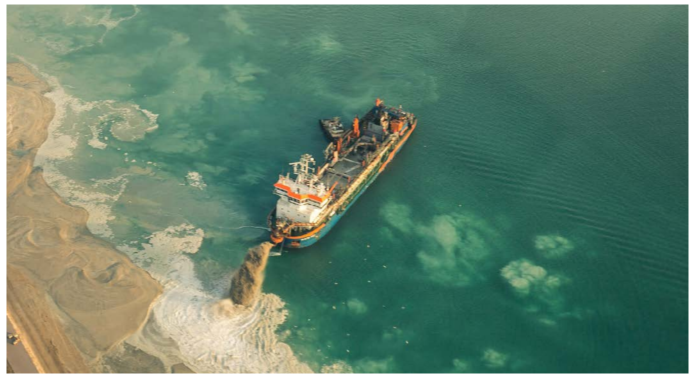


Fig. 11. Coastal reclamation has been widely used to create iconic, globally recognised waterfront real estate across the Arabian Gulf. Sediments from this process can be environmentally impactful if conducted in close proximity to delicate ecosystems such as coral reefs. Source: Richard Schneider (CC-BY-NC 2.0).

3

Towards a more sustainable development in the Arabian Gulf

Recognising the importance of coral reefs, there has been growing interest in developing more sustainable approaches to coastal development in the Gulf region [58,61-64]. Government agencies across the region are continuously strengthening environmental impact assessment (EIA) processes and engaging other policy and management controls to conserve coral reefs (e.g., establishing marine protected zones around areas of particular biodiversity value) [65-67]. These activities have included the development of marine spatial planning and ecosystem-based management approaches that encourage avoidance of development activities in vulnerable areas [64,68-72].

These rapidly evolving regulatory frameworks are likely to lead to substantial improvements in ensuring the integrity of coastal ecosystems while allowing for a more sustainable economic growth through coastal development [73]. With a primacy placed on avoidance, such approaches will curtail development activities that threaten coral reefs, instead favoring permits where alternative development plans are created to fully avoid ecosystem impacts [74,75]. Such avoidance approaches should be considered the first response in development planning, as it maintains the integrity of functioning natural ecosystems without the risks and limitations inherent in minimisation or compensatory approaches [76,77].

While full avoidance of ecosystem impacts should be the goal of environmental management, there are occasionally situations where development must go forward. In such situations, the focus for project managers then needs to shift to minimisation of impacts, supported by activities that repair, rehabilitate or restore the impacted areas, potentially including offsets or compensation where necessary to remedy any negative impacts [78,79]. Coral relocation serves as one potential tool in the mitigation hierarchy where full impact avoidance is not feasible [80-83]; it is, however, not without risk. This report will focus on the benefits, challenges and design features that must be appreciated when considering coral relocation as an impact mitigation approach.

The elements of mitigation

Fig. 12. The mitigation hierarchy should be adopted to best preserve intact and functioning coastal ecosystems in areas where development is to occur.

Offsetting development impacts through coral relocation

Due to the rapid pace of coastal urbanisation in the Gulf region to meet the requirements of growing populations [34,61], and the consequent decline of fragile coral reef ecosystems that often occur in close proximity to coastal cities [57,62], biodiversity offsetting is becoming an increasingly popular tool to mitigate impacts from development in recent years across the Gulf region.

Biodiversity offsetting is a type of management action involving the active increase of biodiversity at an alternative site (using methods such as coral relocation) to compensate for unavoidable damage at a proposed development site [84-86]. In theory, ecological offsetting may help meet environmental and conservation objectives while simultaneously allowing for continued economic growth through development [81], although it does entail some risk due to the uncertainty of success [86-88]. Key concerns include lack of guidelines, partial implementation (or even none) due to non-compliance issues, long timelines and lag effects, limited transparency about outcomes of previous offset projects, a lack of clarity regarding who is responsible for monitoring and dissemination of results post-implementation [87-90]. As stated above, priority should always be given to avoidance and minimisation before contemplating compensation and offsetting [90].

Development decision sequence

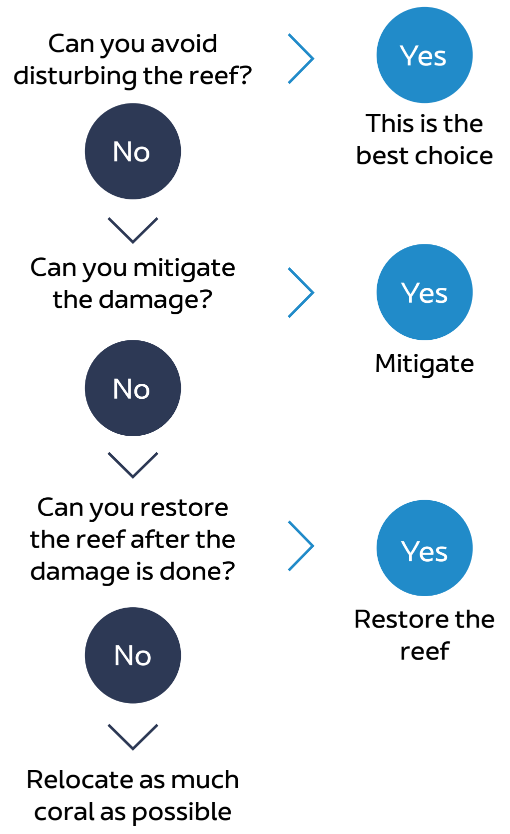


Fig. 13. Flowchart illustrating the sequence of decisions that must be considered before contemplating whether coral relocation is necessary. If relocation is to occur as an offset strategy for development impacts, the goal should then be for no net loss of biodiversity.

4

Coral relocation: Still a developing science

This section of the manual highlights some of the challenges and limitations of the process of coral relocation so that readers are aware of the often-underappreciated complexities of this field. The following sections then highlight approaches that can be taken at the various stages of the relocation workflow (planning, implementation, monitoring and dissemination) to limit such challenges and enhance success of relocation efforts.

Coral reefs are complex ecosystems and relocation science is still developing

Coral reef relocation is the process of offsetting potential impacts of marine construction at one location by moving the targeted biodiversity to an alternative site outside of the development area [83]. While coral relocation may appear to be a relatively simple solution to resolve coastal development and environmental conservation, reefs are complex ecosystems that cannot be easily replaced or transferred. The science of coral restoration and relocation is relatively new and experimental in nature and remains an area actively under development today. As such, a large amount of prior planning using evidence-based best-practice is needed to maximise success and mitigate potential downsides of any relocation programme [27,80,82,91,92], and as the field is still developing and because relocation success is often highly context-specific, no single approach should be considered as a solution.

Coral reefs are the results of various complex ecological interactions between the corals, that act as 'ecosystems engineers', and the various organisms that inhabit, benefit from, and promote reef function [93]. These include interactions between the corals and the various coral-associated or coral-dependent mutualists (e.g., cleaner shrimps, corallivorous fishes), as well as second-order beneficiaries (e.g., predatory fishes that hunt on reefs) that also provide benefits to corals (e.g., nutrient excretion) [94-99]. Overall, key processes and functional interactions need to be maintained in restoration and relocation projects to ensure thriving assemblages [103]. While individual coral colonies can be physically relocated with relative ease from one location to another, the complex and often underappreciated functional relations with other reef members can result in quite negative unintended consequences that can inhibit relocation success without considerable prior planning. For example, grazing by herbivorous fishes and invertebrates has been shown to be essential to prevent coral transplant overgrowth by algae [100-102], indicating that these key reef-associated fauna need to be considered as part of any relocation effort. Accordingly, the priority for any development project should always be to maintain the integrity of existing natural ecosystems through avoidance or stringent mitigation measures, rather than relying on unpredictable and often unsuccessful efforts involving relocation.

Challenges to coral relocation

Preservation should always be prioritized over relocation!

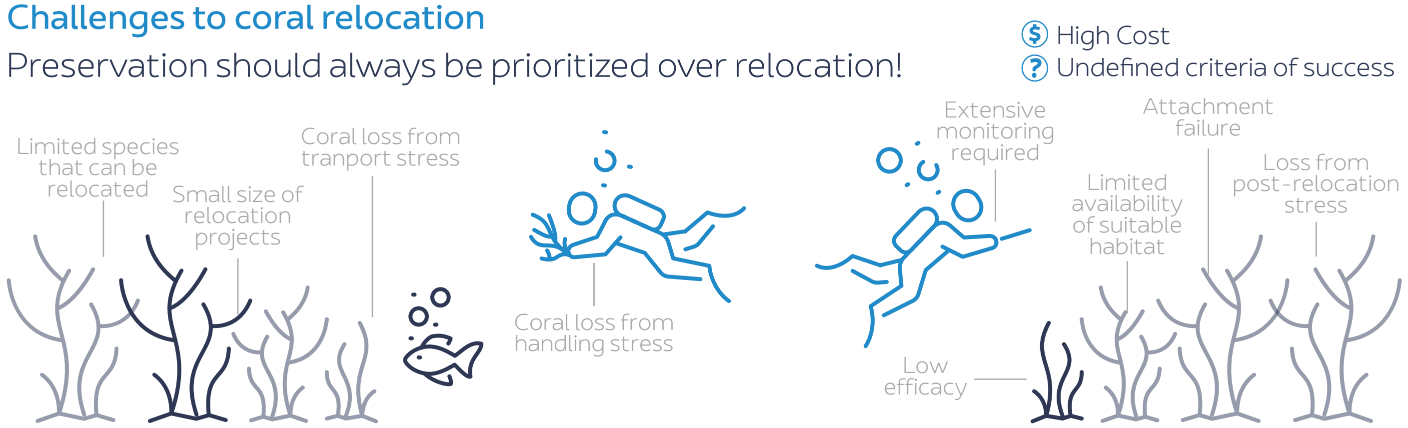


Fig. 14. A graphical summary of the challenges facing coral relocation projects, a number of which often work in concert to limit successful implementation. In all contexts, impact avoidance should be the primary goal in the mitigation hierarchy.

Practical challenges of coral relocation

Coral reef relocation is not without its challenges. Firstly, most published restoration activities have been of relatively small size ($100\ m^2$ on average [104]). While the scale of relocation should be no less than the scale of degradation based on impact mitigation theory and best-practices (i.e., no-net-loss of ecosystem value), large-scale projects are generally unachievable due to the high cost of coastal relocation and restoration work [90]. For instance, mitigation activities such as coral transplanting costs US$ 400,000 per hectare of reef, on average [105]. Budget setting itself is also complicated, as planners need to estimate costs for pre- and post-relocation monitoring surveys, operational costs for collection, transport, and transplantation, as well as probes and loggers for environmental monitoring. Despite the great costs and time that have been expended in recent decades and the rapid growth of research in the field, success rates remain low in many programmes due to the complex reality of trying to establish a new ecosystem [106].

Furthermore, it is often difficult to find suitable recipient habitats for coral relocation. In fact, one of the major causes of marine restoration failure is inappropriate site selection [90,106]. Corals and their associated organisms thrive in very specific environmental conditions and therefore recipient sites need to match the thysical and biological SETTING of their natural sites. This includes similar hydrodynamic conditions (such as water temperature, dissolved oxygen, pH, wave action and currents), turbidity and sedimentation, and having availability of hard substrate suitable for attachment. Sandy or silty habitats are generally unsuitable as fine particles may cover coral polyps, inhibit natural recruitment, or promote disease [60,107]. Other considerations include existing benthos at recipient sites. Loose rubble may need to be physically removed by divers or stabilised in place with wire mesh, limestone boulders, or concrete [108] and such activities must be done while ensuring that resident organisms are not damaged or displaced by the site preparation or relocation processes.

If a suitable site is available, other challenges remain. Of primary concern is the damage or physiological stress than can be induced by the removal and transport process at the donor site prior to relocation. Corals can suffer significant stress handling during their removal from the substrates, which generally involves mechanical cutting for branching species and use of hammers and chisels for massive (boulder-like) species; subsequent jostling in transport containers can exacerbate these issues. As discussed earlier, the jelly-like top 1-2 mm of coral tissue is extremely delicate, so any physical handling by divers, contact with tools, or rubbing against crates and/or other corals can result in tissue damage. This can lead to localised partial-colony mortality or result in impaired whole-colony health as energy is redirected towards repairing damaged tissues, making damaged colonies vulnerable to coral disease [109]. This, combined with transport stress due to contact with air and sun, or exposure to high water temperature (in crates on transport boats), can cause a large proportion of collected corals to be significantly stressed and potentially cause reduced growth, reproduction, or survival after translocation unless careful prior planning is used to ameliorate these risks [110,111].

Fig. 15. Even brief direct air and sunlight exposure, such as shown here, represents a major stressor for most corals. Care should be taken to avoid air exposure, or minimise the time and intensity by using shading and/or immersion (e.g., pools). Source: Doug Helton (CC0-PD).

If relocation is successful, survival is yet not assured as a high proportion of transplanted corals can suffer later dislodgement unless appropriately planned (50% loss by detachment [112]). Dislodgement rates vary with attachment method (cable ties, epoxy, cement, etc.), however a formal comparison of the different techniques is lacking, and an ideal attachment method is yet to be determined beyond small-scale experimental investigations [113], although it is known that survival is low if no manual attachment methods are employed [114]. Other considerations must also be taken into account; for instance, while cable ties are a fairly successful and cost-efficient way of attaching corals to existing structures, they do degrade over time and plastic is a growing environmental concern [115].

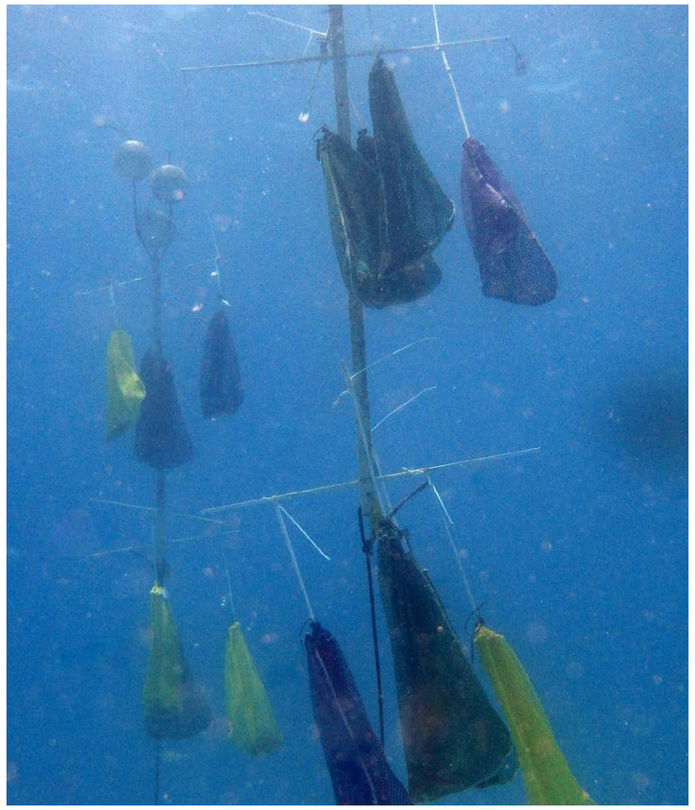


Fig. 16. Mesh bags are being used to store recently removed coral fragments prior to relocation. A water-immersion approach can benefit corals by reducing the time they are exposed to extreme temperatures, air or sunlight while awaiting transport to the receiving site, and by keeping them elevated above the mobile sands on the sea bottom. However, the contact of the mesh bag against the delicate colony surface can cause non-visible damage to the coral tissues. Extreme care must be taken to consider and reduce any possible sources of handling stress in coral relocation programmes. Source: FWC Fish and Wildlife Research Institute (CC-BY-NC-ND 2.0).

Even if transportation and relocation initially appear successful, post-relocation, stress may take weeks to months to manifest due to lag effects from handling stress, emerging disease, and responses to conditions in the new environment. Therefore, while a relocation programme may look successful in the first days or weeks, post-relocation loss may grow over time and may not always be obvious if the crucial step of follow-up monitoring is lacking. In cases where long-term monitoring has been implemented, conclusions have often been drawn from small subsamples of total relocated corals due to financial and logistical constraints, which reduce the reliability of the results [81,116]. As relocation projects have often involved the use of small-sized coral fragments for ease of transportation, reduced fecundity may arise due to the lack of reproductively mature colonies and coral oocyte resorption due to handling stress [111,117] Furthermore, while broken fragments of larger colonies may appear sexually mature, these fragments may not reproduce until they have re-grown sufficiently to a pubescent size, thus further hindering natural reproductive processes on relocated reefs [118]. In addition to reduce reproductive capacity, a selection bias towards more easily removed coral species may also disrupt ecosystem function and promote the spread of disease while simultaneously defeating the purpose of no net loss of biodiversity that is implicit in relocation efforts being used for impact offsetting [119]. Finally, even in the best-case scenario, where relocation is successful with minimal loss over time, such activities can be hampered by local population-related pressures (e.g., pollution) [80], so marine managers should be focused, not only to the relocation effort itself, but the long-term viability of the site.

Coral relocation should not be considered a remedy for construction-related impacts given the young and largely experimental nature of the field [111,120,121]. Better establishment of long-term monitoring and dissemination of the results would provide better evidence on approaches where coral relocation can be an appropriate tool to compensate for coastal development [104]. Given the constraints discussed above, relocating corals should never be the first point of action, and should only be considered as the measure of last resort after appropriate prevention and mitigation measures have first been adopted (see Fig. 12, 13).

For sustainable development to occur, where the integrity of natural ecosystems is given due consideration, modification of development masterplans to avoid or minimise impacts to vulnerable ecosystems must be given priority. Multiple alternative options may be explored, and the impacts of the various alternatives may be calculated and weighed accordingly. Robust risk mitigation measures can be put in place (e.g., use of silt screens, automated turbidity monitoring stations, establishment of stop-work thresholds) that can drastically lower potential damage to critical reef habitats during coastal construction. By using such approaches, coastal regulators and developers can preserve reef ecosystems largely intact. As such, coral relocation should only be adopted after all other options in the impact mitigation hierarchy (e.g., avoidance, mitigation) have been exhausted, and only with very careful planning to ensure that there will be no net loss of biodiversity and that approaches are used to ameliorate known risks inherent with coral relocation efforts.

Fig. 17. A biologist carries a basket of branching corals to a boat for transport to a relocation site. While it appears that the basket is being used to reduce handling stress to the corals, exposure to air, elevated temperatures and direct sunlight while being transported by boat also represents a major stressor to corals that must be avoided or minimised. Source: FWC Fish and Wildlife Research Institute (CC-BY-NC-ND 2.0).

Relocation rationale

Despite the limitations, there will occasionally be instances where impacts cannot be avoided, and in this case, despite the known limitations of coral relocation, it may be the only feasible approach to avoid high or complete loss of corals from a development footprint. In these cases, corporations must follow environmental and social responsibility guidelines that aim to support ecological justice [124]. As such, best practices to minimise loss and enhance long-term survival must be employed and clearly defined as part of ecological offset policies, and coral relocation must remain a complementary tool to other preservation efforts. When used correctly, coral relocation may enhance local environmental awareness, support fish populations that serve as economic resources for surrounding communities and provide coastal protection [125]. But such successes can only be attained with careful planning and consideration of the local context, and the best available knowledge on the factors that may enhance or limit the successful implementation of a relocation effort. The following sections provides advice to enhance such success.

5

Best practices for coral relocation: Planning phase

Planning & goal setting

The first step in planning a relocation intervention is to estimate the primary and compensatory offsets required from developers [126]. Any corporation that causes damage to key natural resources such as coral reefs must be responsible for the restoration and/or replacement of these resources to their original baseline condition, defined as 'primary restoration' [118]. This means that any relocation project should aim to recreate a habitat as close as possible to the natural baseline prior to the planned disturbance, which includes the original ecosystems services. This involves covering the cost of the damage assessment, restoration efforts and pre- and post-restoration monitoring activities [108].

Box 1.
The extent of the proposed impact to reefs must be documented and quantified with a natural resource damage assessment. Per Symons et al., 2006 [108], this assessment must:

- Accurately document the size and shape of the potential impact with georeferencing tools
- Describe the planned nature of the impact (e.g., dislodging and overturning of coral colonies as opposed to damage by extreme sedimentation and land-based discharges)
- Identify and quantify the corals and other benthos affected (which includes description of the reef habitat type)
- Qualitatively document the impact area before and after damages (photographically and with videography) to permit a post-impact assessment of losses

However, there will also be interim losses in ecological services between the time where the original habitat is lost until the relocated habitat has fully recovered, which may take years to decades even in best-case scenarios [121]. Corporations are liable to cover for these losses with additional compensatory restoration, which may come under the form of enhancement or restoration initiatives that go beyond simply relocating corals out of impact zones [118]. For instance, the responsible party may endeavour to enhance natural coral colonisation of the relocation site by seeding the target area (or deployable substrates) with lab-reared larvae as a means of compensatory restoration. Natural larvae can be collected from spawning species, fertilised in a controlled laboratory environment (thus avoiding the usual high mortality in the planktonic phase) and then settled onto chosen substrate by inserting them into 'tent enclosures' deployed underwater [127,128]. Overall, the quicker the primary restoration is in achieving a self-sustaining ecosystem, the lower will be the compensatory restoration needed.

Relocation options must be valued and compared to the value of damaged resources. Predicted total time until complete recovery of reconstituted reefs must be approximated, and various spatial and temporal scales of relocation must be assessed [89]. For the case of compensatory restoration, various planning tools may be used such as a habitat equivalency analysis to calculate the total owed by the responsible party [118]. It is critical that a comprehensive range of stakeholders must be involved in this step of the decision-making process [123], where local communities, organisations and NGOs are engaged in both the planning and implementation stages. This may indeed reduce conflicts over resource use and may even provide collaboration and funding opportunities [129]. When selecting a candidate site for offsetting activities, the level of human dependency of that site (i.e., strong reliance on coral ecosystem services) must be assessed alongside the analysis of restorability [123].

Local environmental knowledge from traditional communities may also be drawn upon to augment relocation success. For instance, local fishers may recommend suitable sites to receive coral transplants based on historical and passed-down knowledge, or they may advise against others where environmental issues have been sighted but not formally recorded. Communicating with locals may also enhance community support [123], which is strongly associated with restoration effectiveness [123]. Such local environmental knowledge approaches are being actively implemented in marine conservation and management in the Arabian Gulf [71], but remain relatively underutilised in the coral relocation sphere. It is also essential for highly trained professionals and scientists to be at the heart of any relocation project so that they may apply their expertise to supporting the implementation and monitoring plans to ensure robust and measurable outcomes. Through this engagement, consensus-driven agreement on approaches should be developed among the various scientists, managers, and other stakeholders. An independent 'quality assurance' team should also be put in place to ensure unbiased oversight [130].

Once planned reef damages and losses of ecosystem services have been approximated, and the expenses earmarked for relocation activities have been agreed upon by all participants, project objectives can be defined. Project goals should be set to permit later assessment of the efficacy of the initiative, in that they must be Specific, Measurable, Achievable, Realistic and Timely (SMART goals) [131,132]. Use of SMART goals is critical, as project failure is often attributed to limited scientific goal setting in marine restoration and biodiversity offset projects [90]. Although commonly used as metrics, item-based goals (e.g., % survival of coral transplants, % coral cover, etc.) should not solely be employed to measure success as these metrics are not synonymous with full ecosystem functions and services [90,106]. Defining clear, quantifiable, and ecologically-sound targets is a crucial step in planning a relocation intervention [90,131]. Goals must also be prioritised in order of importance to aid in later management decisions that may require trade-offs [133].

SMART Goals for Reef Restoration

S Specific
M Measurable
A Achievable
R Realistic
T Timely

Specific — Measurable

Good example: "Relocate 250 coral colonies of three common genera (*Platygyra, Dipsastrea and Porites*) from the donor site to bare substrates on the coral reef located 1 km to the east over two weeks during cool autumn conditions."

Realistic — Timely — Achievable

Poor example: "Move as many coral colonies as possible to a suitable relocation site this year."

Fig. 18. Coral relocation projects should have objectives that are shaped by SMART attributes, which will allow for later assessment of program success through use of unambiguous, specific metrics.

Baseline assessment of donor site

Following consensus on project goals by the various stakeholders, a detailed investigation of the proposed donor site may begin. This baseline of environmental characteristics will be used to ensure minimal loss during conservation interventions. Basic review elements typically include coral, invertebrate and fish surveys along with physico-chemical characteristics of the site, as well as at relevant control (non-impact) sites in the surrounding area for comparison [125]. Common all-encompassing metrics, such as coral percentage cover, are not sufficient and should expand to include, for example, coral species richness, density, composition and reef rugosity, among other ecologically relevant parameters. In addition to spatial replication across impact and reference sites, conducting a single one-time survey is unlikely to be adequate, as biodiversity is not fixed and reefs are dynamic ecosystems, particularly for mobile species such as reef-associated fishes which are known to be a highly seasonally dynamic in the Arabian Gulf [134,135]. Baseline research must account for seasonal aspects and other environmental drivers and therefore be spread over relevant time periods [88]. The use of georeferenced permanent transects or plots is therefore typically preferred over haphazard or random sampling strategies, so that the donor site may be monitored over time, prior and following the proposed impacts, to include tracking of individual colonies and assessment of demographic changes in the community [108]. Photographic and video documentation of the donor site is also essential to provide permanent baseline records for future reference. The use of permanent plots allows for reliable mapping of the donor site as well as documenting key features over repeatable surveys [108].

Baseline assessment of multiple recipient sites

Once baseline assessments of the donor site are completed, the search for recipient sites may begin. Typically, assessment should occur for several potential recipient sites to allow ranking of sites based on environmental suitability, but also to potentially employ multiple recipient sites to hedge risks during relocation.

Assessment of wave exposure and flushing

One of the primary factors in considering a potential recipient site is the degree of wave exposure. In many regions, sheltered environments tend to be preferred due to the potential for detachment loss of relocated colonies due to wave action or from mobile rubble scouring the area during storms [27,121,123]. However, sheltered environments tend to have more extreme temperature fluctuations [121], and in the Arabian Gulf sheltered environments tend to have very high levels of suspended sediment deposition, which has been shown to smother corals, reducing their growth and survival [136]. As such, careful monitoring of several potential recipient sites is essential to determine which locations have the greatest probability of success. In addition, risk mitigation approaches may need to be adopted regardless of the location. For example, using methods to stabilise rubble in shallow areas (e.g., Fig. 15) or relocating corals to slightly deeper depths to avoid the most extreme waves or temperatures, if supported by data.

Assessment of substrate suitability

Substrate condition of potential recipient sites must also be favourable for transplant attachment and growth, as unstable substrates (e.g., unconsolidated rubble or sand) limit the capacity for coral fragments to attach and for coral larvae to settle and grow [137,138], while high amounts of macro-algae can damage coral tissue, reducing coral growth and fecundity [139-141]. As such, bare reef framework or rock are ideal substrates for coral attachment [83]. In areas where only unconsolidated substrates are available, enhancing the physical integrity of the benthos may be possible prior to transplantation [129]. Loose rubble may be secured with concrete mats, cement, limestone boulders, plastic mesh or other overlay structures before corals can be reattached to reduce secondary injury to fragments [27], although such processes are labour and cost intensive. If structural complexity is lacking, three-dimensional structures may need to be introduced to provide shelter and habitat to reef-associated organisms and restore ecosystem function [130].

Surplus waste materials such as tires, small, discarded vessels and related items should be avoided as they are likely to become mobile during storms and/or leak harmful chemicals [142-144], but limestone and concrete may be appropriate materials when attempting to restore structural relief particularly if designed with ecological goals in mind (e.g. 3D complexity for fishes) [145]. Limestone is similar in composition to natural reef framework while common gabbro stone has been shown to be attractive for coral colonisation, and therefore are good materials to use for habitat enhancement if locally available [27,146].

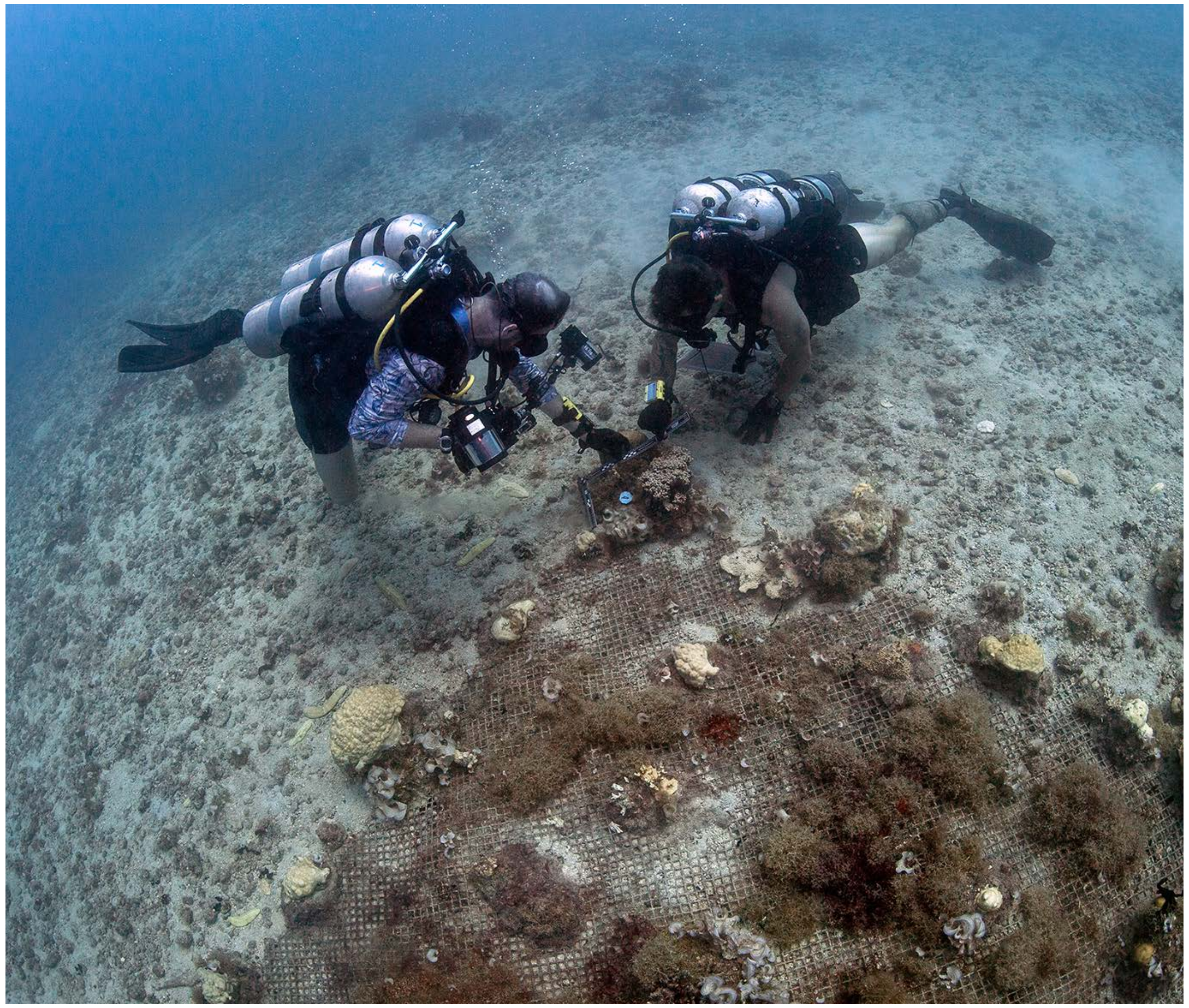


Fig. 19. Substrate suitability and stability is a primary consideration in selecting a candidate receiving site. In some cases, such as here, engineering approaches may have to be used to stabilise rubble and other substrates to ensure that relocated corals are not at risk of dislodgement or damage during storms. Source: Alfred A. Coffield (CC BY-NC-ND 2.0).

Substrate stabilisation or enhancement

In areas where suitable hard-bottom habitat is limited or unavailable, it may be necessary to introduce artificial structures to serve as a substrate for attachment for relocated corals. Such structures may include artificial reef modules [147], quarried boulders [116], 3D-printed clay designs [148] among others. Artificial substrates may not only provide a substrate for relocated fragment attachment, but they may also help control currents, limit rubble movement, and provide habitat for fishes. However, it should be recognised that such structures can never serve as surrogates for natural habitats impacted by development as artificial reef community structure and function differs markedly from that of natural reefs [28,58,149]. Instead, artificial reefs seeded with relocated corals should be recognised as novel habitats, unique in their own right, but that cannot replace natural ecosystems regardless of size and complexity [150]. If built within MPAs, as suggested above, such structures may have the potential to support spillover (of fish) and larval subsidy (or corals and fish) into adjacent areas once the community has matured [102,151,152].

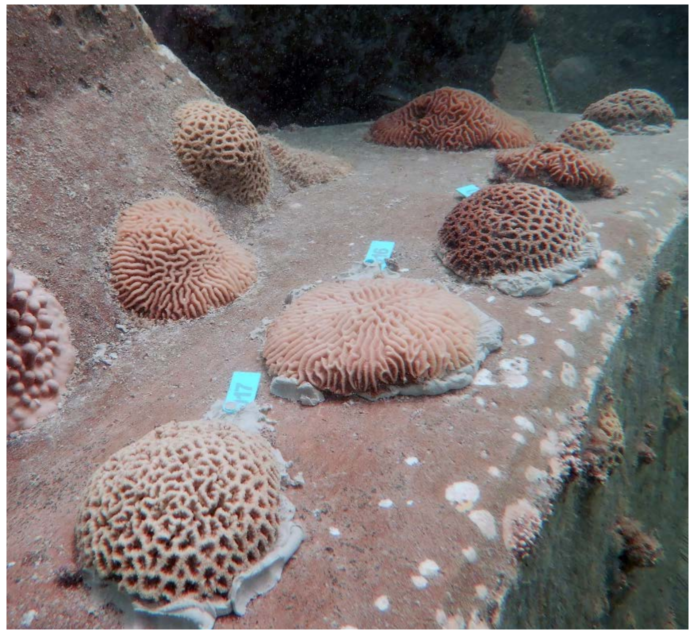


Fig.20. Corals relocated to the environmental breakwater of Khalifa Port in Abu Dhabi, UAE, where the concrete stabits provided a suitable habitat for coral attachment in an area largely dominated by mobile sands and muds (natural corals to left, relocated corals to right). Source: Rob Smith.

Local pressures or protections

Detailed surveys must also identify whether any anthropogenic stressors impact the proposed recipient site. All stressors must be accounted for and quantified in terms of seriousness [130] and sites highly impacted by pollution, algal overgrowth, overfishing or destructive fishing, or other threats must be immediately disqualified if the removal of these stressors is not possible (or affordable) prior to relocation [153]. Sites with chronically high turbidity and sedimentation loads must be avoided as fine sediments reduce coral photosynthetic efficiency and survival [60,107,154]. Related to the general stress context in selecting sites, the 'protected status' of potential recipient sites is also of importance, as established marine protected areas (MPAs) will limit risks from future development [123]. Therefore, sites within a network of national parks, MPAs or reserves are to be favoured where possible.

Assessment of site-specific physico-chemical conditions

Once several candidate recipient sites have been identified based on their hydrodynamics, substrate and pressure status, more detailed assessment of their site-specific environmental conditions can begin. Any intended recipient site must display similar environmental parameters as the original donor site and existing conditions must be established through monitoring if recent environmental data is unavailable [90]. If reefs did not previously exist in a particular area there is usually a reason (e.g., lack of suitable substrate, poor water quality, etc), which would make such candidate sites likely inappropriate for coral transplantation efforts [27]. Pre-relocation monitoring of several candidate relocation sites is essential to determine the variability and extremes of thermal range, depth, wave exposure, current regime, salinity, light levels, and tidal range among other related parameters as abiotic conditions must be sufficient to support coral communities [124,128]. Funding should be sufficient to ensure sufficient in situ data loggers are available for assessment of spatial and temporal variability in conditions [116].

Assessment of site-specific biotic characteristic

The site's biotic suitability must also be thoroughly assessed for biological stressors, for example coral predators such as Crown-of-Thorns starfish (COTs) and competitors such as macroalgae and sponges [153]. Corals' predators can quickly decimate relocated colonies [155], while competitors such as algae may rapidly overgrow and smother transplants [116] or produce chemical cues that inhibit later larval coral settlement into the assemblage [156]. Similarly, algal-farming damselfishes frequently promote algal growth within their territories and aggressively exclude other herbivores that keep algal abundance in check [103], and they have been shown to rapidly colonise coral transplantation areas and reduce coral survival by nipping at and damaging coral colonies near their territories [119]. While such predatory, competitive, or grazing interactions are part of natural processes in functioning reef ecosystems, in recipient sites, any recently transplanted corals will typically have experienced significant relocation stress from which corals need weeks or months to recover and, therefore, negative biotic interactions can have an outsized impact in the early stages of coral community establishment.

The most biologically suitable site for establishment and growth of relocated corals is likely to be a location in which corals are already the dominant biota, as opposed to algae, sponges or others [123]. Recipient sites with existing high coral cover and diversity are prone to provide conditions that support coral survival, provided care is taken not to impact the existing coral community during relocation [121]. In addition to relocation of corals, practitioners should consider whether relocation of other reef-associated fauna is warranted, particularly those that provide functionally important roles that might enhance transplant survival. For example, herbivorous fishes and sea urchins serve an important role in controlling the abundance of algae that often directly compete with corals [157,158], while guard crabs and cleaner shrimp that use corals for shelter provide important roles in removing sediments and epifauna and interfering with coral-predators [97,159,160]. Such a 'whole assemblage' perspective incorporates the functional diversity necessary to support robust ecosystem function, allowing a jump-start to the ecological integrity of the newly established relocation site [102,130].

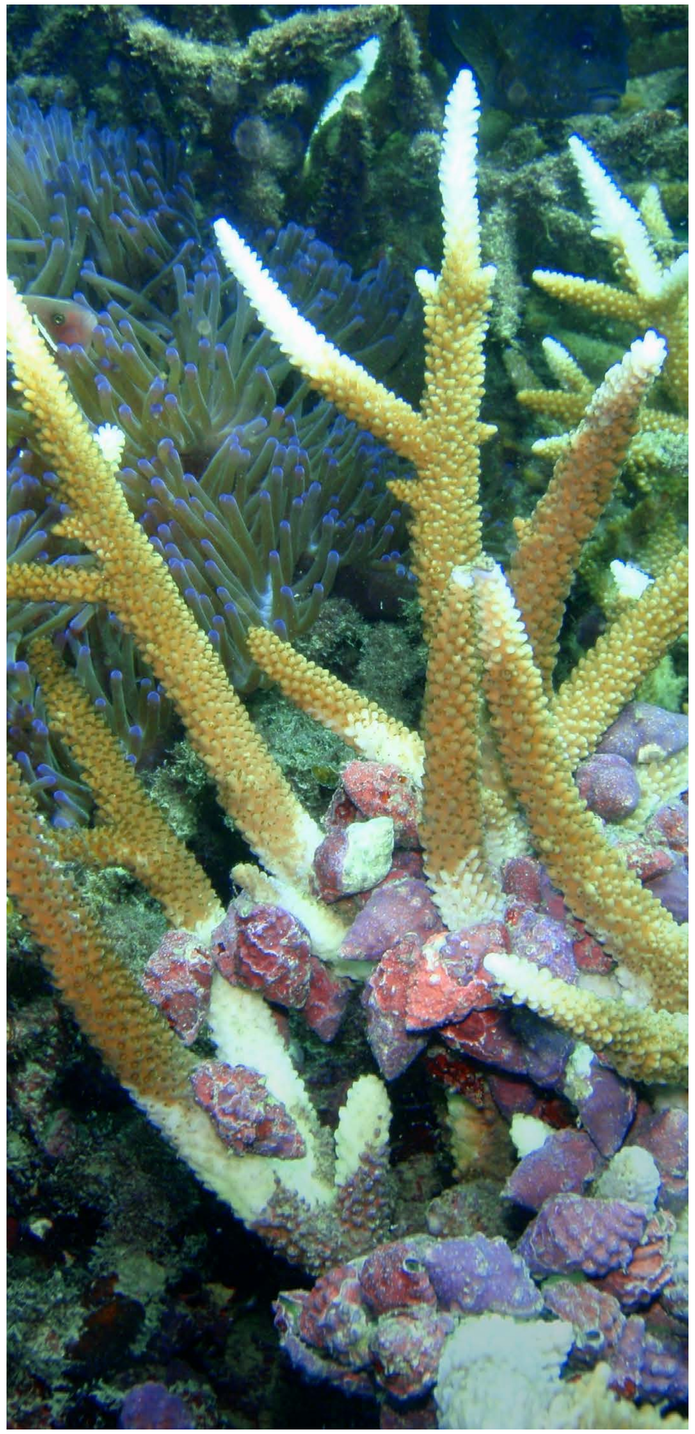


Fig. 21. Assessment of potential coral competitors or predators (such as the coral-eating *Drupella* snail shown here) should be performed for each recipient site in transplantation programmes, as such biotic interactions can have outsized negative impacts on colonies still under stress from relocation. (Image credit: ConserveMarine (CC-BY-SA-4.0)

Logistical considerations

Finally, assessment of logistical and social conditions should be included when selecting potential recipient sites for coral relocation. The proposed sites must be easily accessible, but under minimal influence from human visits (e.g., diving) or pressures (e.g., fishing, pollution, etc.) [161]. It should be in close proximity of the donor site and the staging area in order to reduce transport stress and, particularly, exposure to air, light or extreme temperatures [153], unless resources can be used for immersion-based transportation (e.g., in boat-based holding tanks with flow through water) [82]. Managers should also consider whether it is straightforward to reach the potential receiving sites by boat, and whether snorkelling or a SCUBA-based approach is necessary for coral transplantation, as the latter will undoubtedly add to the cost and risk of operations.

As discussed earlier, priority should be given to recipient sites located within MPAs to limit risks from future pressures. Alongside biotic and abiotic assessments, social surveys (e.g., structured interviews) should be performed to assess project acceptability and its compatibility with existing human uses of each candidate site [123].

It is important to remember that a guiding principle of offset through practices such as coral restoration is a "no net loss" policy, ideally resulting in net gain of biodiversity [90]. Here, biodiversity is in the form of structural attributes such as species richness, coral cover, community composition and others, along with service attributes, be they ecological or human-related; these should be maintained at pre-development levels - if not augmented - through the mitigation hierarchy (avoidance, mitigation, etc.) as well as offset approaches like coral translocation. As such, assessment of potential recipient sites must also consider their size/area, and whether there is sufficient availability of suitable non-occupied space to accommodate the number and diversity of corals that are planned for relocation.

Final planning and piloting

Once a suitable recipient site or series of sites has been identified, consideration of the various coral relocation methods may begin. A wide array of methods is available for each stage of the relocation process (see next section), and one or a combination of several approaches may be more appropriate given the environmental, biological and impact mitigation context of each specific project.

Methods must be specifically tailored to the needs of the project, to the desired scalability, and to the context of the location in which this project will occur [129], and it should be recognised that each possible methodological approach at each stage of the relocation process will come with its own strengths and limitations. Costs must also be considered. Approximate expenses must be budgeted for each alternative method, including staff expenses, specialist diver fees, training for volunteer helpers, boat rentals or fuel, SCUBA equipment, and consumables used in the relocation process, among others. For a summary of the costs for various techniques see Bayraktarov et al., 2019 [105], but recognise that costs will be extremely contingent on the location in which the project occurs and should be estimated using local market rates.

Upon selection of the most optimal combination of methods based on the local context, a pilot study of the proposed methods is highly recommended to ensure project success and minimal biodiversity and economical loss [90,129]. Such a pilot programme will not only allow an assessment of the suitability of the methods generally, but also provide the essential hands-on experience necessary to assess logistic feasibility and related real-world factors that are often unanticipated at the planning stage. Pilot studies should follow the "BACI" approach (Before-After, Control-Impact [162]) to assess the effectiveness of the methods selected. In this approach, monitoring stations must be established at recipient (impact) and non-recipient (control) sites, with monitoring programmes conducted over several time points prior (before) to and following (after) a pilot relocation event. In order to differentiate relocation-related effects from stochastic processes (e.g., a disease outbreak, bleaching, etc), it is necessary to perform pre- and post-relocation monitoring at several distinct relocation pilot sites and several control [163,164], ideally spatially interspersed amongst one another. Such an approach allows for a robust, statistically justified empirical assessment of the efficacy of the proposed coral relocation methods and sites at limited cost, prior to the large financial investment needed for full implementation.

6

Best practices for coral relocation: Operational phase

Species selection for relocation

Following a thorough investigation of the donor site and potential recipient sites and conducting a pilot assessment of the proposed methodology, the operational phase of coral relocation to the selected recipient sites may begin.

As offset programmes are designed to maintain, if not increase, local biodiversity [88,90], all attempts should be made to include each species present at the donor site at the relative proportions at which they occur naturally. Selecting a wide array of coral species not only supports the mitigation goals of the relocation exercise, but will maximising genetic diversity, helping to prevent population collapse in case of disease events and supporting later reproductive success during spawning events [165]. In addition, relocation of a diverse community of corals will also ensure that a variety of coral growth forms is included (e.g., branching, foliose, massive or other shapes), providing enhanced resilience of the relocated coral community as well as more diverse habitat opportunities for fauna that associate with specific morphotypes. For example, while mound-like massive corals are typically much more resilient to environmental stress and are consequently more resilient to relocation processes, they tend to be very slow growing that their re-growth following relocation may take an extensive time [8,110,166]. In contrast, branching corals tend to be more sensitive to relocation, but can grow very rapidly - even after breakage during storms - and provide complex habitats that supports numerous fish species and shade for undergrowth coral assemblages [8,95,166,167].

If relocating the entirety of the donor coral assemblage is not logistically or financially feasible, a wide range of coral species and growth forms should be targeted, particularly for rare species most at risk from the construction works (and justification must be provided for why the whole community was not included in the programme). Within a particular species, priority should be given to heathy, sexually mature specimens, although a range size of colonies >10 cm diameter may be utilised as larger corals have higher fecundity and survival while smaller corals tend to grow more rapidly, and size appears to have no correlation with post-relocation mortality [83,116,168,169]. In all cases, care should be taken to ensure that no colonies being relocated have noticeable evidence of association with disease or invasive species [80,119].

Removal techniques and handling stress

When the proportions of different species and morphologies has been agreed on, removal of colonies or fragments may begin, with corals stored sub-surface while awaiting transfer to the recipient location. These steps must be meticulously planned so that minimum handling stress is exerted on the corals.

As discussed earlier, the upper 1-2 mm of a coral colony is a highly vulnerable jelly-like tissue that is highly sensitive to contact abrasion, be it with hands, tools, the sides of transport crates or bags, other corals, or other surfaces. The corals must be removed from the donor site as gently as possible, with considerable care taken to minimise or eliminate contact with the jelly-like surface tissues of the colonies during all stages of the relocation process, from the colony removal to storage and transfer stages, as well as during later placement in the recipient site [80].

The growth form and size of colonies will typically dictate the most appropriate approach for removal. For mounding or massive species, a hammer and chisel (or crowbars for larger specimens) may be used to sever attachment to the substrate at the

Fig. 22. A marine habitat resource specialist uses a hammer and chisel to remove a coral colony for relocation out of an area of planned impact from a vessel salvage operation. Source: NOAA (CC-BY-NC-ND 2.0).

colony base, with care taken to minimise hand or tool contact with the sides or tops of colonies and constrain contact only to the base of the colony while placing in transport trays [83]. These may then be fixed in the trays with the use of 'lips' cable-tied or screwed across the base of the tray to limit lateral movement of corals, to prevent colonies from sliding into one another or the side of the tray. For large colonies (e.g., large *Porites* bommies) that cannot be transported in trays, large bolts or screws can be drilled into the colony base at various locations once it has been separated from the reef framework by crowbars, and the colony raised and moved underwater using inflated lift-bags [107].

Relocation of whole colonies should be the preferred approach, as this limits damaged tissue that requires energy to repair and provides openings for disease introduction. However, some species' morphologies are naturally more fragile and/or have small substrate attachment points, making whole-colony removal more complicated (e.g., branching or foliose coral species). While priority should be given to whole-colony removal where feasible, where not possible corals may be fragmented into smaller sub-units (e.g., using shears/cutters), with each fragment then provided the same care to reduce contact as is provided for other coral morphologies [83]. The wound area must be a small as possible to facilitate recovery and limit bacterial infections and contact with live coral tissue must be strictly limited, including contact between adjacent colonies and/or the container walls during transportation [81,153].

While micro-fragmentation is increasingly being explored as a reef rehabilitation option (where users are intentionally reducing the size of fragments to later grow out at more rapid rates, typically in nurseries), it is not an approach that supports the offset goals of impact mitigation programmes. Additionally, micro-fragmentation has had highly variable results in real-world applications due to high rates of predation, disease and dislodgement of the fragments, particularly during the early stages [170-173]. Therefore, micro-fragmentation is not recommended as a priority approach in relocation programmes (i.e., it should only be done in incidental cases where colonies are accidentally fragmented).

In all cases, regardless of the species utilised or the removal technique employed, technicians should take care to reduce handling stress immediately after the removal stage, typically when colonies are being temporarily stored underwater and prepared for transport. Corals should be placed in stable storage/transport containers (e.g., plastic trays) rather than on the seabed where they may roll in waves, come into contact with adjacent benthos, and/or be exposed to mobile sediments. Typically transport containers will have weights attached to maintain position at a fixed, flat location on a consolidated area of substrate, and these will only later be fixed with lift-bags to allow movement through the water column for the transport phase.

Relocation of beneficial reef- and/or colony-associated fauna

Particularly where relocation is going towards non-reef areas (e.g., a new artificial reef) because an existing reef habitat is unavailable [116], the relocation process should endeavour to include reef-associated fauna in addition to coral colonies. Such efforts will help to build functional diversity within the new recipient site and support the rebuilding of key ecological processes [130,161,174]. This may include more general reef-associated species such as sea urchins, which play important keystone roles in algal suppression [175] and, as such, can reduce coral tissue loss due to algal competition [158]. Also important are coral-dependent species that have strong mutualistic relationships with individual coral heads used as protective habitats. For example, guard crabs (*Trapezia* spp.) are small crustaceans that live within the complex three-dimensional habitats of branching coral colonies, where they clean out sediments covering coral tissues [159], increasing colony growth rates [98]. They also defend their host against coral predators such as Crown-of-Thorns starfish, reducing tissue loss [176] and enhancing survival [160], and against predatory snails [177], increasing growth rates compared with undefended colonies [97]. Omnivorous coral-associated crabs such as the clinging crab (*Mithrax* spp.) can also defend against algal competition and epifaunal overgrowth, and crab-bearing corals can have enhanced growth and survival [99]. Despite a growing interest in incorporating such ecological processes into coral relocation or restoration programmes, less than a fifth of published studies include trophic interactions in their design [100]. As such, strong consideration of processes such as herbivory, mutualism, corallivory, and nutrient cycling from reef-associated consumers should be incorporated into the planning phases of coral relocation efforts.

Fig. 23. Individual coral colonies are often home to mutualistic partners, such as this guard crab, which actively defend and clean their host colony, supporting coral growth and survival. Coral relocation plans should therefore include relocation of such beneficial mutualists, the coral colonies themselves. (Image credit: Hectoninchus (CC-BY-SA-3.0)

Transportation methods and transport stress

Aside from damage induced by handling during removal, the transport phase of coral translocation projects represents one of the most potentially damaging phases of the project and prior planning should incorporate avoidance and mitigation of such risks. The main issues to consider are contact abrasion (e.g., corals bumping together) during transportation, as well as exposure to environmental extremes (e.g., air, high temperatures, UV).

In an ideal setting, corals should be relocated while remaining fully immersed underwater [80,81,83]. This has the benefit of reducing the likelihood to contact abrasion between colonies and/or with the sides of the transport crate, as corals will not have to be lifted into boats, transported roughly over waves, and then lowered back into the water at the recipient site, where each phase presents its own risks. In addition, by remaining immersed underwater throughout the transport process, corals will remain in a far more thermally stable environment and avoid exposure to air and the unfiltered UV light and solar insolation, stressors that they would experience if carried on the surface.

On small scales, immersion transport can utilise crates affixed to lift bags allowing individual divers to transport colonies between nearby donor and recipient sites (e.g., Fig. 24) [110,121]. For larger distances, transport can be performed by fixing transport crates to hang under the side of the vessel, with relocation occurring at low speed (i.e., <1 knot) to avoid causing corals to slide or tumble within the crates [128]. In a large-scale example of such a process, in 2009 over 22,000 corals growing on 1,100 coral-covered stones were relocated 18 km in Dubai, UAE, to avoid impacts of a pending development [178]. All coral-covered rocks (often >1 ton in weight) were hung beneath transport barges by slings, and the barge then slowly (ca. 1 knot) hauled them to their recipient site, on a breakwater far from the potential impacts of development. By maintaining the corals beneath the water, initial coral survival rates were high and within four years coral cover was estimated to have increased by 20% [179].

While sea-based immersion may be functional for short-distance transport, it is not feasible for all projects, particularly where donor and recipient sites are far from one another. In such cases, care must be taken to ensure that corals are transported on the surface as efficiently as possible to minimise exposure to the elements. Project planners should prioritise using tank-like containers on the transport vessels to allow corals to remain fully immersed in water during the transport process to limit the known stressors of surface-based transport. Large pools or tanks fitted with battery-operated pumps allows a constant flow-through of seawater into the container to maintain water quality, dissolved oxygen and temperature [180], while overhanging shading can be used to limit light stress and UV exposure during the transportation process [110]. Where one cannot use immersion containers for transport, attempts should be made to minimise the travel time as much as possible, and processes used to ensure that the corals stay moist (e.g., continuous/frequent saltwater spray; covering with seawater-soaked towels) and shaded from direct sunlight [110,181,182].

Fig. 24. Technicians use lift bags and crates to relocate large coral colonies. Such an approach reduces handling stress and limits air exposure time. Source: Alfred A. Coffield (CC-BY-NC-ND 2.0).

Seasonal climate considerations

Aside from the mechanics of the transportation process, relocation plans should factor in local climatic conditions, particularly around seasonal temperatures and the potential for storm activity. The Arabian Gulf is characterised by some of the most extreme and variable environmental conditions known to be experienced by corals globally [29,43,183], with winter in the northern Gulf (e.g., Kuwait) leading to remarkably cold sea temperatures (12 °C), while the southern Gulf (e.g., the UAE and Qatar) becomes the world's hottest sea each summer (>36 °C) [36,183]. As such, relocation during peak summer or low winter temperatures should be avoided, as such seasons represent major natural physiological stressors for corals that would only be exacerbated by relocation. Both cold- and warm-water bleaching events have occurred in the Gulf in the past [51,54,184,185], and research has shown that coral growth rates and/or partial-colony mortality can be elevated during either summer or winter [136,184], indicating that either of these extremes represent a pressure on coral health. Thus, coral relocation efforts in the Gulf should only occur during the 'shoulder' seasons of spring and autumn, and ideally early in each season to allow corals to recover from any relocation stress or damage before they are exposed to the stress of the coming season. The specific months of these seasons will vary across the Gulf due to differences in local climatic conditions, so decisions on specific timings must be based on local data of sea and air temperatures for a particular site. But generally, relocation efforts in the Gulf should be prioritised for three to four months before the onset of summer maximum or winter minimum sea temperatures.

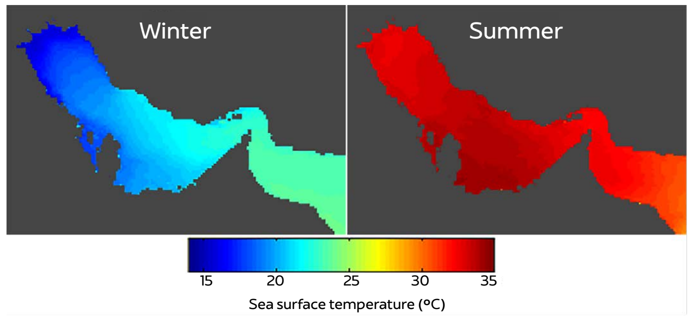


Fig. 25. Sea surface temperatures in the Gulf are extreme and highly variable, and relocation projects should avoid translocating corals in the thermally stressful winter and summer seasons. Here the coldest (left) and warmest (right) monthly sea temperatures, averaged for the decade between 2004-14 (Data from MODIS level 3, 9 km, 11 µm, daytime SST).

In the Arabian Gulf, the local wind environment can also play a role in selecting the timing for coral relocation. Seasonal 'shamal' wind events are typically strongest in the period between late January and March, during which winds can commonly exceed 20 knots for several days and lead to extremely rough sea conditions and elevated turbidity due to bottom sediment suspension [186]. Such conditions not only will result in costly 'lost time' as divers and boats wait at shore for conditions to abate [175], but also make relocation planning and implementation far more logistically challenging. Even if winds do slacken for several days, the residual swell from storm events represents a continues risk, as bottom swell makes careful colony removal or attachment more difficult, and surface swell will increase the likelihood of damage or abrasion during the transportation process [116]. Such storm and swell conditions also increase the likelihood of detachment of any recently attached colonies [82,175], defeating the purpose of the relocation effort. As such, relocation programmes should plan for activities to occur in the period after the local 'shamal' season (which varies somewhat around the Gulf), while also factoring in the temperature conditions discussed earlier. Planning around the 'windy season' will help limit detachment, abrasion and breakage due to wave action [107].

Receiving site preparation

Prior to the actual relocation effort, potential recipient sites should be assessed as outlined in the section above titled 'baseline assessment of multiple recipient sites' to allow identification of the optimal site or sites where corals will be relocated. Factors to consider include the wave climate and flushing, substrate suitability and whether substrate stabilisation or enhancement are required, whether local pressures or protections are likely to affect the project outcomes, and the local physicochemical and biotic conditions of the potential recipient sites (see details in above sub-sections). A detailed assessment of these factors will allow practitioners to maximise successful outcomes from this critical stage of relocation.

Depending on the composition of the substrate at the receiving site, preparation may be required. This may include the addition of artificial substrates (e.g., artificial reefs) for colony attachment [116,147], stabilisation of the substrate through use of cementing or mesh [129,27] (e.g., Fig. 19), or related measures, with consideration towards aesthetics, longevity, and potential unintended consequences on the local biota or surrounding environment. This is particularly true for addition of artificial reefs which have become common in the Arabian

Gulf, but which come with numerous underappreciated risks that should be considered by marine managers before adoption [150-152].

Even in areas where suitable bare rocky substrate exists, some site preparation and planning are necessary. Studies have shown that 'loose' corals placed at receiving sites without manual attachment have very low rates of survival [114], as coral self-attachment to the substrate is generally a slow process and many will be damaged or dislodged during storms. As such, use of prepared 'attachment aids' (e.g., Coralclip) may be necessary, particularly in high energy environments affected by waves [115]. Even in areas where wave action is less of a concern, some substrate preparation is necessary, even if using traditional direct epoxy or cement attachment (detailed below). All marine substrates, even artificial surfaces only hours old, will have a surface covered by a biofilm comprised of a living microbial community with associated exudates [187-189], and more mature 'bare' substrates will typically be home to various microalgae and invertebrates [146,190], all of which can interfere with proper adhesion. As such, areas of 'bare' substrates are not actually bare, and such surfaces must be heavily scrubbed with wire brushes to reduce the biofilm, and then chiselled to expose fresh, underlying rock to allow a strong bond with the epoxy or cement (Fig. 26). Detachment due to poor adhesion is one of the leading causes of coral mortality during relocation projects (50-65% loss of colonies [112,191]), suggesting that hyper-focused efforts on substrate preparation need to be made prior to attachment of relocated colonies in order to maximise success. Such substrate cleaning efforts can also help remove the presence of spatial competitors such as macroalgae on adjacent substrates, improving subsequent growth of transplanted colonies [192].

Fig. 26. A diver uses an underwater pneumatic drill to prepare the substrate at a receiving site for attachment of relocated coral colonies. Such an approach can provide cavities for epoxy or cement to allow a better 'grip', since biofilms on natural substrates often result in poor adhesion. Source: Erik Zobrist (CC0-PD).

Colony placement considerations

Aside from substrate considerations, care should be taken to consider the depth of relocation and the density of colony placement at the receiving site during the planning process.

In general, corals should be relocated at depths comparable to that of their donor site. Corals are physiologically acclimated to specific light conditions that occur at particular depths, such that changes in depth can result in detrimental impacts to colony health. Coral colony morphology [193], symbiont density and community structure [194,195], photosynthetic pigment composition [196], sensitivity to UV radiation [196], and various other parameters vary with depth in order to minimise light stress at shallow depths or maximise photosynthetic yield in low light of deep waters. As such, relocation of coral colonies to depths different from where they were derived at the donor site can cause substantial photo-physiological stress to coral colonies, with impacts that can last for more than six months [194] and full acclimation taking several years [197], while potentially impacting their long-term health and survivorship. This is particularly true in the Arabian Gulf, as depths shallower than 3 m are subject to extreme temperature stress during low wind conditions [55], while high turbidity limits coral growth deeper than 10 m except at offshore seamounts where surrounding clear waters support coral growth to ~30 m depth [48,54,198]. These observations suggest that extreme care should be taken to relocate corals to within a few meters of the depth from which they were obtained.

In addition to depth, planners should also consider the spatial layout of how they plan to position colonies relative to one another. One key parameter will be the density of coral colonies. Higher colony density has been suggested to facilitate reef structural integrity during storms [95,199], but at too high a density inter-colony competition for space can lead to decreased growth rates and survivorship [199,200]. However, placing colonies too far apart also has risks, as this may interfere with fertilisation success during spawning and impede reef-scale reproductive output [153], and may also make isolated colonies less attractive habitats to coral dwelling organisms that provide important ecological functions such as nutrient transfer [201]. While further research in this area is necessary, the existing data suggests that a unimodal relationship exists, where positive density effects occur at moderate densities, but negative effects occur at high densities [95,200], and this is likely to be context specific. Therefore, it is suggested that preliminary surveys of colony density at local sites should be conducted to determine the natural range and average density of colonies to use as a guide for relocation planning.

Colony attachment methods

One of the final planning stages for the active phase of a coral relocation exercise is the selection of the method of colony attachment once they have been relocated to the recipient site. Commonly used attachment methods include the use of marine glue (epoxy) or Portland cement, as well as masonry nails, cable ties or stainless-steel wires, sometimes in combination [121,128,175,192,202].

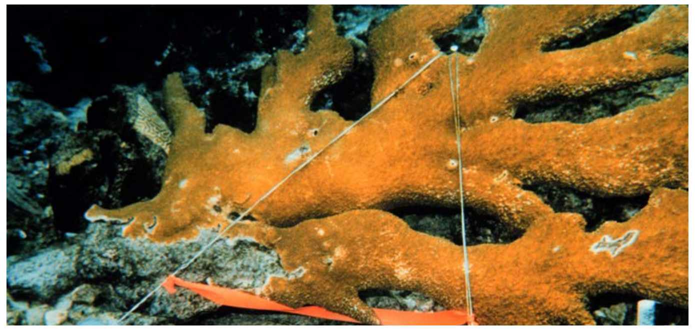


Fig. 27. Metal wires and masonry nails being used to attach elkhorn coral fragments to the reef framework of Fortuna Reef in Puerto Rico. Source: Erik Zobrist (CC-PD).

The selection of attachment methods must be made based on its potential for coral dislodgement under local wave conditions [27], with high wave-energy environments avoided as loss tends to be high regardless of attachment method in these environments [110,111]. Epoxy and cement are the most frequently used attachment methods, particularly for massive/mounding morphologies. Cable ties and wires used in combination with nails embedded into the reef substrate are commonly used for branching species such as *Acropora* table corals that tend to have only limited bare skeletal tissue for adhesive exposure after removal [121], and this approach also supports high survival rates [113]. *Acropora* table corals may be placed with their axial polyp facing upwards to speed up growth or may be placed laying down to provide a more stable base and allow new branches to develop with time [153]. Recently a new attachment approach has been developed, called the Coralclip[115], which is a simple spring-clip that can hold fragments in place in gaps in the reef framework and is easy to deploy [115].

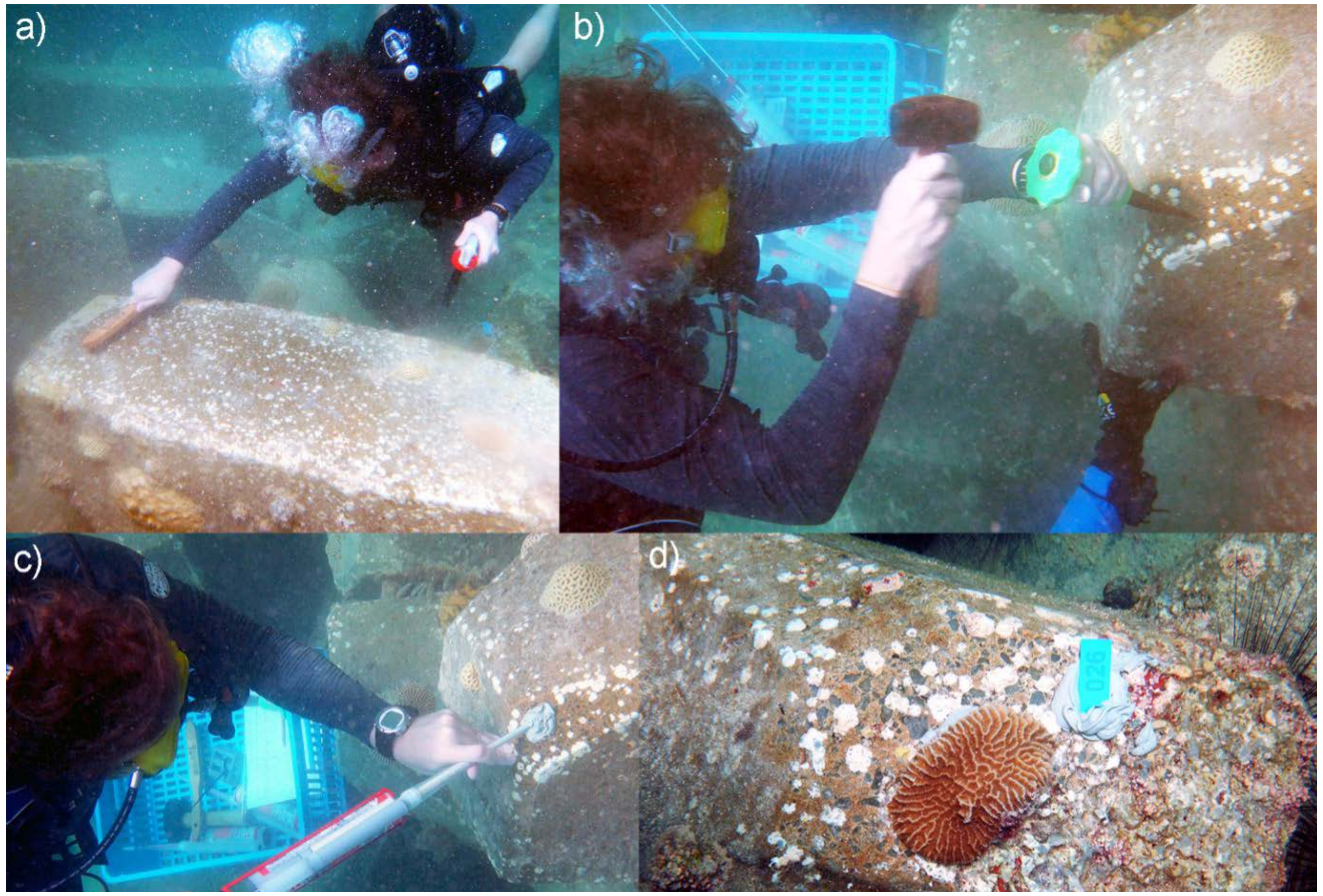


Fig. 28. Example of site preparation and attachment for a coral relocation project at Khalifa Port in Abu Dhabi, UAE, in 2020. Corals were relocated from one breakwater to another, with attachment onto concrete stabits. Here, a) wire brushes were used to clean the surface, which were then b) scored with a hammer and chisel to expose the underlying concrete, before c) an epoxy was applied to the substrate, allowing d) attachment of a coral colony and a labelled tag for long-term monitoring. Image credits: Prasanna Wijesinghe and Harry Cook.

The importance of attachment site preparation and attachment method should not be underestimated: on average only half to two-thirds of corals are estimated to survive the relocation process [106,112,191], and attachment failure in the weeks following transplantation is a leading cause of their mortality [110,192,203]. However, if colonies can remain immobile and properly attached to the reef framework for several months, their growing skeleton will begin to self-adhere and form a strong bond to the substrate, after which coral loss due to detachment is rare [110,192,204]. Regardless of attachment methods used, planners should take care to minimise displacement of existing benthos, and to limit the disruption of any existing habitat-associated communities.

Fig. 29. A researcher uses epoxy for attachment of a coral colony in the Florida Keys. However, the lack of appropriate substrate cleaning and preparation is likely to result in detachment of any colonies during the first storm. Source: NOAA (CC-PD).

7

Best practices for coral relocation: The post-relocation monitoring phase

A relocation project may only be described as successful once ecological function has been restored and a self-sustaining and resilient ecosystem has been recreated [125]. A relocated assemblage should display similar species as the donor system, represent all major functional groups, have reproductive populations and be resilient to stress [125]. To assess success, a key yet often underappreciated, part of any biodiversity offset programme is monitoring.

Hypothesis-driven and ecologically-based monitoring is a crucial step to periodically appraise the project's success and evaluate progress towards each individual SMART goal [80]. Consistent and comparable data is necessary to quantify changes over time, and to permit further intervention if necessary [125]. Monitoring increases the scientific robustness, accountability and transparency of relocation programmes and should be a central component of any coral translocation effort [129]. Funding must be allocated for this component of the programme from the outset of the planning process, and the monitoring findings should be used to help guide adaptive management of the project [130].

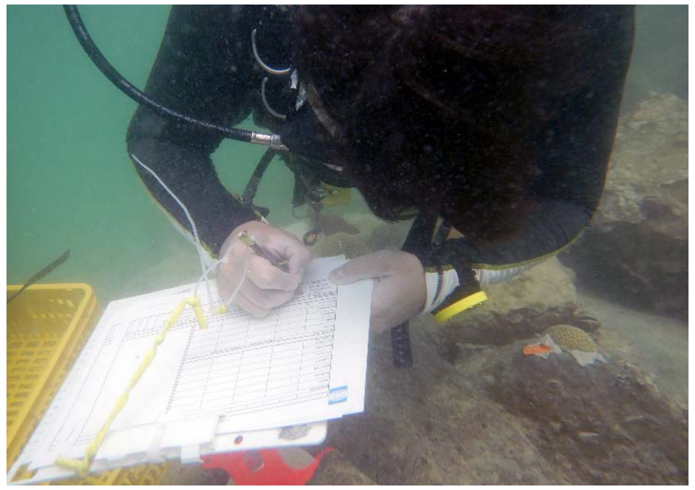


Fig. 30. Post-relocation monitoring is essential to determine whether a translocation programme has met its intended goals, and identify zwhy some relocation sites are successful while others are not. Such information should be made public to aid future coral relocation efforts. Source: Khalifa Port 2020 relocation project, John Burt.

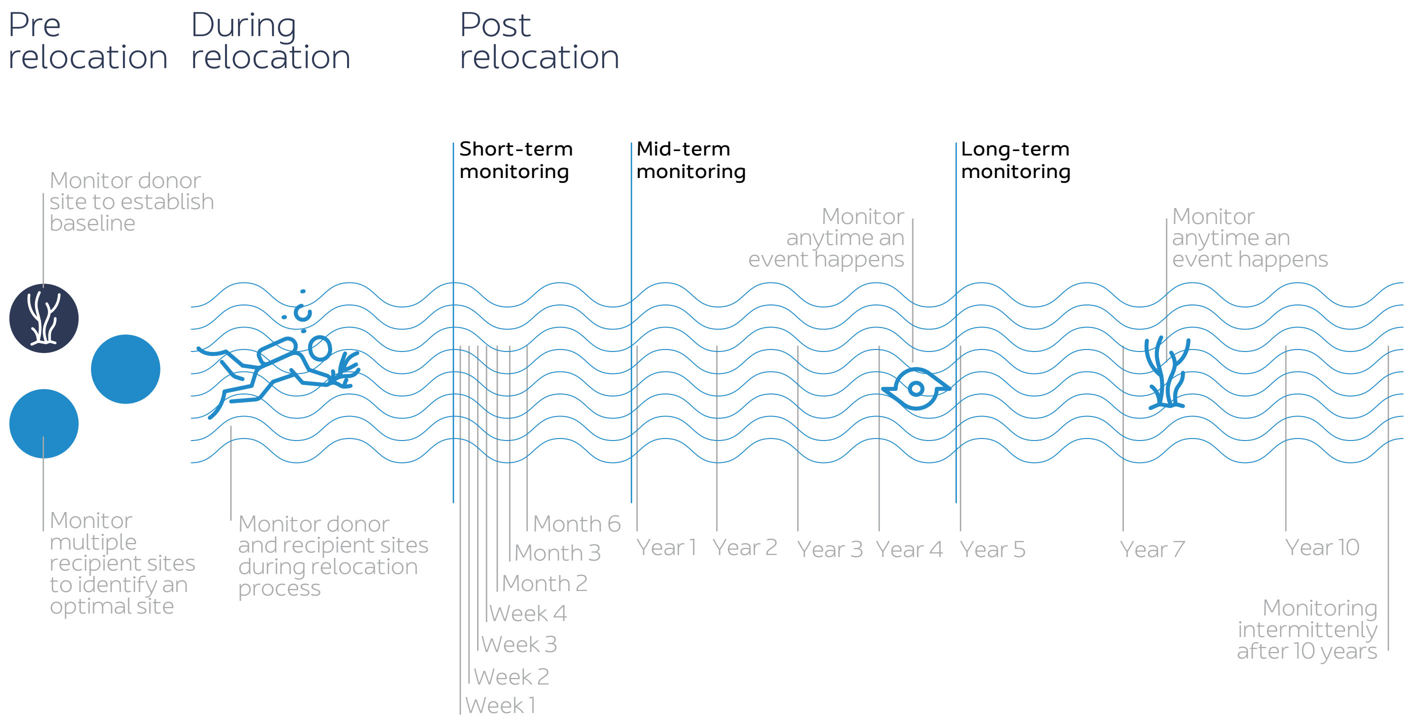
Best practice for coral relocation monitoring programmes follows the BACI (before-after, control-impact) approach. Surveys and monitoring plans should be implemented well before any coral relocation activities occur and follow the process through its implementation and then for a period of time after-the-fact to assess long-term success [162]. To ensure that patterns observed at a particular relocation site are the result of intervention and not the result of stochastic processes, such programmes should also include data not only from the donor and recipient site(s), but also at undisturbed 'reference' sites nearby the donor site where corals are left in place, as well as 'control' sites adjacent to the recipient site where non-relocated communities are monitored [162]. Ideally, monitoring should include multiple reference and control sites that are spatially interspersed around intervention sites to support identification of spatial trends alongside any temporal trends that are picked up from the long-term periodic monitoring [163,164]. Factors to be considered for monitoring in such a BACI approach are outlined in the 'best practices in coral relocation: planning phase' section of this document, with careful consideration made for the biological metrics to be catalogued that represent not only the status of individual coral colonies, but also community structural and functional metrics that should be included. Metrics that can be considered for the coral populations include coral cover and abundance, reproductive capacity (e.g. % of corals spawning) and recruitment (e.g. settlement), coral condition (e.g. colony presence/absence, % tissue loss, disease prevalence, etc.), species richness, evenness and diversity, while habitat or community metrics include invertebrate and fish community data (e.g. presence/absence, abundance/density, richness, evenness and diversity, and size-structure), measures of reef complexity (e.g. rugosity, colony/reef height), and habitat quality (e.g. water quality, sedimentation, abundance/diversity of functional groups or coral recruits, etc) [125]. Further detailed descriptions of components to consider including in intervention-based reef monitoring programmes such as coral relocation projects are provided in Goergen et al. (2020) [125], and readers are directed there for further information in developing their monitoring plans.

Fig. 31. Researchers monitoring the health of a coral colony using a diving-PAM on Saadiyat reef, Abu Dhabi. Monitoring programmes should aim to go beyond basic indicators of relocation success (e.g., survival and growth), to include more subtle signals of coral condition, such as disease, photosynthetic health, or related metrics that support an assessment of success in meeting the project goals and objectives. Source: John A. Burt.

In addition to where and what to monitor, coral relocation plans also need to determine the frequency and length of the monitoring programme. In many cases, the frequency and length of monitoring will be contingent upon the specific objectives and goals of the coral relocation programme [125], but they should also reflect the nature of the timeframes at which change is expected to occur for the corals and the associated communities at the various sites under consideration (Fig. 32). For example, post-relocation losses from anchorage detachment are more likely to occur in the first few weeks following relocation, while attainment of reproductive capacity for fragments may take several years or more; seasonal environmental processes (e.g., severe bleaching impacts and disease outbreaks are more common in summer than in winter in the Arabian Gulf 51,205) also need to be considered.

Relocation Project Monitoring Guide

Timeline



Key monitoring metrics

Measure these for both the native and relocated coral community at every monitoring instance

Coral colony

- Colony survival
- Colony size and growth
- Reproduction (evidence of sexual maturity & fecundity)
- Disease, bleaching, and predation (COTS)
- Measures of abundance (% cover, density, colony counts)

Coral assemblage

- Measures of diversity (species richness, diversity indices)
- Measures of complexity (rugosity)

Fish

- Abundance
- Biomass
- Richness
- Key functional group (parrotfish, butterflyfish)

Other benthos

- Abundance of algae, urchins and others
- % cover of algae, urchins and others

Environment

- Temperature
- Turbidity/light
- Dissolved oxygen

Fig. 32. Pre- and post-relocation monitoring is critical to assess the success of any relocation effort in meeting its goals. The survey timeframe and frequency as well as the metrics to be studied need careful consideration during the project planning phase.

By ensuring that a monitoring programme accounts for temporal dynamics, project managers provide themselves an opportunity to use adaptive management where their data can be used to apply corrective/remedial actions should any issues be identified during routine monitoring [125,133]. Monitoring therefore should incorporate short- (~12 months), mid-(1-5 years) and long-term (>5 years) timeframes [125], with the frequency of surveys higher at points during which more rapid change is expected, particularly in the period immediately following coral relocation, as well as after any major stochastic event occurs (e.g., mass bleaching or storms) (Fig. 32). While initial surveys will provide crucial information on the immediate viability of a relocation project, it is not sufficient to declare 'success' of relocation efforts in meeting their goals given the long periods that marine ecosystems need for ecosystem function to be restored [106]. Due to the slow growth rate of most corals and the timeframe needed for stabilisation of ecosystem functions, monitoring periods should be considered on decadal scales, rather than the monthly or yearly scales common to many monitoring programmes [80,90]. For instance, long-term monitoring (>5-10 years) carried out annually would be needed to determine trends in gamete production by relocated corals or changes in reef structure or rugosity, and consequent impacts on associate fishes and invertebrates [125]. Monitoring consistently is an applied research effort, where the goal is for relocated reefs to establish into self-sustaining and resilient ecosystems over time as a key outcome of the impact mitigation process [129].

Communication and dissemination of 'lessons learned' is a key final stage of the coral relocation and monitoring effort. The wealth of data collected from a robustly planned and implemented coral relocation effort can help support and guide the success of future programmes seeking to mitigate impacts to reef ecosystems. Data sharing and communication of results is seen as one of the most important challenges obstructing marine conservation and management in the Arabian Gulf [34], and mistaken approaches continue to be repeated by others when relocation practitioners fail to communicate results that might be considered 'failures' of their programme. But an unsuccessful result is not a failure – it is an opportunity to learn and to adapt for future relocation efforts. Practitioners need to not only tout the 'good news' stories that dominate the regional mass media (typically without any public data available to validate the comments), but also openly communicate their results through conferences and peer-reviewed publications where the veracity and validity of the data is interpreted by subject experts. It is only with a shared and widely communicated understanding of the challenges of coral relocation - and the solutions that work best towards mitigating these risks – that the regional coral reef management community can maximise its success in offsetting impacts from development on these valuable ecosystems.

8
Case studies from around the world

(Burt, 2021)

Location:
Abu Dhabi, UAE.

Background:
A proposed expansion of Khalifa Port further into offshore waters included a section of a 10-year-old breakwater where coral communities occurred. Relocation of corals out of the footprint area to a more distant breakwater outside of the development area was proposed as part of the offset, with a research component included to better understand factors affecting success.

Goals:
To relocate over 500 coral colonies of all genera present to a breakwater outside of the development area, with 120 of these colonies to be incorporated into a research programme.

Methods:
Prior to relocation, a research programme was designed to assess the performance (survival, condition, growth) of relocated colonies based on three treatments: species selection (3 taxa: Platygyra, Dipsastrea, and Favites), attachment method (epoxy vs. cement), and relocation depth (2-3 m vs. 6-8 m). To address these three questions, a crossed field-experiment was implemented, where 120 colonies were relocated, with 10 colonies of each species allocated to the various attachment and depth treatments. In addition, over 400 more corals were to be relocated that were not

incorporated into the research programme as part of the offset programme. All relocated corals were to be monitored for three years, with more intensive surveys at the beginning (weekly for the first month, monthly to three months, quarterly to the first year, and then annually for year 2 and 3).

Scale:
Research colonies allocated to a 30 m section of breakwater, with the additional colonies placed outside over a ca. 100 m length of breakwater. Monitored for 3 years.

Monitoring:
Monitoring at each time point included attachment success, full/partial colony survival, growth, and condition (e.g., bleaching or disease).
Outcomes: In total, 588 colonies from seven genera were relocated in late July 2020, with 120 of these allocated to the relocation research programme. Unfortunately, a severe marine heat wave occurred in the weeks after the relocation exercise with temperatures reaching 36.9°C, resulting in loss of 85% of colonies within a month of relocation. Comparisons between naturally occurring corals on the breakwater and relocated corals showed that this mortality level was consistent across both groups, indicating that losses were not due to the relocation activity itself. Despite the outcome, some valuable information was obtained from the monitoring. Survival of colonies placed deeper (6-8 m) was five-fold higher than colonies that were placed at shallower (2-3 m), indicating the importance of depth for attenuating heat stress on relocated corals. Depth also played a role in attachment success. Regardless of attachment method, virtually all relocated corals (whether live or deceased from bleaching) remained attached to the substrate when relocated to deeper parts of the breakwater (92% attached), while detachment loss was much higher for corals places in the shallows, but this was primarily only for corals attached with epoxy (epoxy: 50% attachment after 1 year; cement: 95% attachment after one year at 2-3 m depth). Monitoring continues at the time of writing.

Cost:
Undisclosed.

Challenges & lessons learned:
The most significant challenge that faces this coral relocation programme was the timing of the coral relocation, occurring just prior to the onset of a severe marine heat wave. While comparisons to the natural coral communities showed that this event would have been catastrophic regardless of relocation status, it does underscore the importance of relocating coral during 'shoulder' seasons to allow time for healing and repair prior to the stress of summer or winter temperatures. The results also showed that placement of corals deeper (6-8 m) and attachment with cement are more likely to result in higher survival of colonies placed on breakwater habitats.

Considerations:
The data presented above represent the results from the first of the three-year monitoring programme, so further data will help to establish whether the observed patterns stay true. Due to the heavy losses of corals from bleaching, statistical analyses of the resulting data will nonetheless remain a challenge due to sample size limitations.

(Seguin et al., 2008)

Location:
Bal Haf, Yemen.

Background:
The construction of a liquefied natural gas plant and pipeline was scheduled to damage 3 sites displaying high coral and fish density and diversity. Impacts included the building of a cooling pipeline and jetty, the deployment of concrete blocks for shoreline protection purposes and warm seawater discharge at an outfall location. Coral transplantation was proposed as a mitigation action of the planned infrastructure works.

Goals:
To relocate a subset (value unreported) of coral colonies that would be impacted by the construction works to safe alternative nearby sites.

Methods:
A baseline survey identified coral species composition at the donor sites. 3 recipient sites were selected for transplantation interventions due to their proximity to the donor sites while remaining outside of the direct impact zone, similar depth range and comparable water parameters. A selection of coral colonies in the impact zone were selected with priority given to large, rare, healthy and slow-growing specimens totalling 1495 colonies. Small colonies were removed with hammers and chisels and placed in plastic baskets, which were then loaded onto a boat and ferried to the relocation sites. Colonies were frequently splashed with water to reduce surface stress. Medium and large colonies were displaced with crowbars and arranged in large floating steel baskets which were then towed submerged to their final destination. 140 large Porites species bommies were drilled in-situ and fixed with steel screws within their calcium carbonate framework. Lift bags were attached to the screws to shuttle the large coral boulders to the recipient sites. Colonies were fixed to the substrate with cement with the exception of fragile Acropora branching species which were affixed with epoxy.

Scale:
Spatial scale unreported, 5 monitoring surveys over the course of 14 months.

Monitoring:
A dozen coral colonies per restoration site were investigated over time for changes in their survival, growth and health (disease occurrence).

Outcomes:
The overall survival of relocated colonies was 91% 1-year post-intervention with some anecdotal evidence of growth. Coral transplant mortality was attributed to sedimentation, predation by fishes,

physical disturbances by fishermen, competition with an invasive sponge and barnacles, and high wave action. Massive coral morphologies appeared to tolerate the transplantation process better than branching species.

Cost:
<1% of the cost of construction works (value unreported).

Challenges & lessons learned:
Large swells immediately following monsoon season caused breakage and detachment in a significant number of transplants (including large coral bommies), which may be avoided by limiting transplantation activities until this seasonal period has passed or choosing less exposed recipient sites. Fish predation also seemed to be exacerbated when coral transplants displayed signs of stress, therefore authors recommend a more careful selection process when collecting transplant material. Necrosis was observed at the site displaying the highest levels of sedimentation. Authors also infer that barnacle infestation on Porites colonies was related to high sedimentation which highlights the need to select more appropriate relocation recipient sites.

Considerations:
Only a subset of the original coral communities were transplanted, and large areas of thriving reef (original coral density unreported) were most likely destroyed by the marine works. The limited monitoring period and very small pool of monitored colonies doesn't allow for a definite evaluation of project success, especially at the high sedimentation and high exposure transplant locations. Fishes and invertebrates were not studied aside from anecdotal reports of corallivory and competition. Baseline surveys of proposed recipient sites in particular are lacking and may have prevented the transplantation of fragile colonies where invasive invertebrates were widespread.

(Deb et al., 2014)

Location:
North-East Qatar.

Background:
The Barzan Gas Project pipeline was anticipated to affect shallow coral reef communities during construction by physical removal due to trenching activities and enhanced sedimentation. RasGas Company Limited developed a coral management, relocation, and monitoring plan involving the relocation of threatened colonies to a suitable site to acquire the state's environmental clearance.

Goals:
To identify or construct a suitable transplantation site and to relocate 4% of at-risk coral colonies.

Methods:
An initial benthic environmental survey was carried out to investigate coral density, size, health and species composition along the pipeline and to assess the suitability of coral communities for relocation works. Environmental parameters including temperature, pH, salinity, turbidity, dissolved oxygen and water depth were sampled at the donor and potential recipient sites. Potential recipient sites were assessed based on the following criteria: substrate type, topographic relief, dominant biota, coral presence/absence and percentage cover, and urchin presence/absence. Due to a lack of suitable natural sites for coral re-attachment, an artificial reef of 550 quarried boulders was deployed on sandy substrate. The recipient site was selected due to its proximity to a healthy reference reef and its appropriate water depth. Corals were selected for their size (>10cm), ease of removal and overall health and removed with hammers and chisels from the donor site. 1693 coral colonies were relocated from the pipeline corridor to the limestone boulders and re-attached with a cement mixture. A deep and a shallow nearby natural reef reference sites were selected for comparison through time.

Scale:
Spatial scale of ~720 m^2, biannual surveys within a 5-year monitoring programme.

Monitoring:
~10% of relocated colonies as well as 25 naturally occurring colonies at each reference site were tagged for monitoring purposes. The following metrics were investigated as part of the monitoring programme; transplanted coral colony attachment status, tagged colony health (bleaching, tissue loss, algal growth), benthic colonisation, reef fish assemblage, sediment accumulation, sea urchin density and thermal trends (with in-situ loggers).

Outcomes:
Coral health declined with time at the reattachment

site with the majority of colonies (80%) displaying signs of stress. Algal overgrowth on the boulders was identified as the main source of stress to relocated corals. Similar signs of low coral health were observed on the tagged corals at natural reference sites which were attributed to the highly fluctuating natural environmental conditions in the Arabian Gulf. Authors report anecdotal sightings of coral recruitment at the artificial reef site. Urchin density was low at the relocation site when compared to densities reported in the literature for this region.

Cost:
Unreported.

Challenges & lessons learned:
Limestone boulders may not be the most suitable artificial substrate for coral relocation due to a lack of small interstitial spaces within the rock matrix itself which may have decreased overall coral colony attachment.

Considerations:
Based on numbers recorded, more than 38,000 coral colonies were lost due to the marine works described at this location which is a less than ideal metric considering the "no net loss" policy that ought to be employed. Of the corals that were relocated, colony health was degraded over time. More encouraging results may have been obtained if transplantation efforts were focused on areas where algae were not the dominant benthic biota.

(ter Hofstede et al., 2016)

Location:
Coral Harbour, New Providence, Bahamas.

Background:
Dredging of an access channel in Coral Harbour was expected to damage several patches of coral reef by physical destruction, increased sedimentation and turbidity. Contractual requirements necessitated the relocation of these colonies out of the direct zone of impact.

Goals:
To relocate all viable coral colonies (>10cm, including large coral boulders) and associated invertebrates outside of the impact zone.

Methods:
7 recipient locations near Coral Harbour with similar environmental parameters were selected. 1523 coral colonies were detached with hammers and chisels at their base. The size of transplants ranged from 5-61 cm. Octocorals, sponges, sea anemones, and echinoderms were relocated alongside coral colonies (abundance unreported). Large boulder corals were relocated with a vessel-bound crane while the remaining smaller colonies were towed in a submerged container. Coral colonies were re-attached with cement mixtures and marked with permanent tags.

Scale:
Spatial scale unreported, 14 months monitoring period.

Monitoring:
Pre-relocation benthic surveys were conducted to assess general reef composition (i.e., coral % cover etc). Monitoring metrics included detachment rates, survival rates, health condition (bleaching, disease, predation scars) and size of all relocated colonies.

Outcomes:
A 91% survival rate was reported for all transplanted colonies after 14 months. Of these surviving colonies, 82% were in good health while other displayed bleaching, predation scars and partial tissue mortality. Growth rate outcomes were unclear at this point. Changes to benthic metrics in regard to baseline were unreported.

Cost:
Unreported.

Challenges & lessons learned: The general good health of donor colonies and pristine recipient sites were recognised as high contributors to project success. Recipient sites mimicked the donor site's environmental parameters and observed low anthropogenic stressors. High survival rates were also partially attributed to the seasonal timing of the relocation works; winter relocations reduced high temperature stress and allowed colonies to recover prior to hurricane season. Other success factors included reduced transportation stress with submerged relocation containers and good adhesion to the new substrate.

Considerations:
The temporal scale of monitoring was limited (14 months), thus it is not possible to assess long-term project success. Survival of relocated invertebrates was not reported and a formal investigation of fish assemblages and associated ecosystem processes was lacking.

(Kotb, 2016)

Location:
Al-Dirreh Bay/Aqaba Marine Park, Aqaba, Jordan.

Background:
Plans for the development of a modernized port on Al-Dirreh Bay threatened a diverse coral reef area and popular dive site. To mitigate and compensate for these harmful impacts on coral reefs, the Aqaba Special Economic Zone Authority approved the relocation of at-risk colonies to degraded sites within the Aqaba Marine Park.

Goals:
To test the success of this relocation method as a mitigation measure to coastal infrastructure development.

Methods:
Recipient sites within the Aqaba Marine Park were selected due to their low coral cover. A nearby control site was used to compare growth rates between transplanted and natural coral colonies. Environmental data (temperature, tidal range, currents, salinity) was provided by the Aqaba Marine Science Station. ~7000 coral colonies were detached from Al-Dirreh with hammers and chisels and placed in floating cages. Submerged cages were towed by barges to recipient sites in Aqaba Marine Park. Colonies of various species with healthy appearances were selected for transplantation and special care was taken to avoid damaging live tissue. Colonies were attached to hard substrates with marine cement.

Scale:
Spatial scale unreported, 2-year monitoring study with biannual surveys.

Monitoring:
Survival and growth rate of transplanted colonies were investigated over a 2-year period. A subsample of 1096 colonies was investigated for survival metrics while a subsample of 160 colonies was selected for growth rate explorations and compared to 48 tagged natural coral colonies at a nearby control site.

Outcomes:
Authors reported an overall survival rate of 87%, with massive colonies displaying higher survival than branching colonies. Growth rates per species were comparable at the translocation site and at the control natural reef site.

Cost:
Unreported.

Challenges & lessons learned:
High survival and growth rates were attributed to

recipient sites displaying similar environmental parameters to donor site, low transportation and handling stress and overall health of selected transplants. Authors recommend the set-up of a nursery area within donor colonies to generate new fragments and enhance restoration outputs (although other authors have argued that coral nurseries substantially increase cost and effort without additional benefits over direct attachment in recipient sites [114]).

Considerations:
No description of total corals lost to development was provided and a baseline study of the donor site and pre-relocation recipient sites was lacking. Coral species richness at the transplant sites versus control site was not investigated and fish and invertebrate assemblages were not assessed.

(Rodgers et al., 2017)

Location:
Kane'ohe Bay, Moku o Lo'e Island, Hawai'i.

Background:
Several mature coral colonies (abundance unreported) were scheduled for destruction due to the clearing of vessel obstructions in a navigation channel.

Goals:
To relocate large coral heads to a nearby dredged sandy patch reef site.

Methods:
The recipient site was selected due to its proximity to the impacted channel, suitable depth, and low coral cover. Obstructing corals were dislodged with a pry bar and towed submerged to the receiving site. Special care was taken to exclude colonies with invasive algal overgrowth. The method of attaching corals to the bare sandy substrate is unreported.

Scale:
Spatial scale of relocation site was ~200 m2, monitoring period of 11 years with data collected across 3 discrete survey years.

Monitoring:
Both the donor and recipient sites coral cover and species composition were investigated prior to relocation, with special focus on invasive species of sponge and algae. Fish populations including abundance, biomass and species richness were assessed at the relocation site post-transplantation.

Outcomes:
Spatial complexity, fish abundance, fish biomass and species richness increased significantly at the relocation site. The fish assemblage was composed mainly of herbivorous species. The donor site was able to recover naturally from translocation activities.

Cost:
Unreported.

Challenges & lessons learned:
The use of large, sexually mature coral colonies in relocation activities was shown to enhance project success. Special care to limit the spread of invasive algae was also highly recommended for future endeavours. Rapid water temperature increases were shown to rapidly reduce coral cover.

Considerations:
While the use of large colonies limited adverse sediment impacts, translocation of coral colonies to sandy or silty substrate is not usually recommended as fine sediment may inhibit natural coral settlement.

9

Acknowledgements

Primary funding for the development of this document was provided by AD Ports Group, and their support is gratefully acknowledged. John Burt was also partially supported by the NYUAD Center for Interacting Urban Networks (CITIES) and the Mubadala Arabian Center for Climate and Environmental Sciences (Mubadala ACCESS), funded by Tamkeen under the NYUAD Research Institute Awards CG001 and CG009, respectively.

10

References

1. Moberg, F. and C. Folke, Ecological goods and services of coral reef ecosystems. Ecological Economics, 1999. **29**(2): p. 215-233.

2. Costanza, R., et al., The value of the world›s ecosystem services and natural capital. Nature, 1997. **387**(6630): p. 253-260.

3. de Groot, R., et al., Global estimates of the value of ecosystems and their services in monetary units. Ecosystem Services, 2012. **1**(1): p. 50-61.

4. Hoegh-Guldberg, O., et al., Coral Reef Ecosystems under Climate Change and Ocean Acidification. Frontiers in Marine Science, 2017. **4**(158): p. .

5. Fisher, R., et al., Species Richness on Coral Reefs and the Pursuit of Convergent Global Estimates. Current Biology, 2015. **25**(4): p. 500-505.

6. Hatcher, B.G., Coral reef primary productivity: A beggar›s banquet. Trends in Ecology & Evolution, 1988. **3**(5): p. 106-111.

7. Veron, J., Corals of the world. 2000, Townsville: Australian Institute of Marine Science.

8. Pratchett, M.S., et al., Spatial, temporal and taxonomic variation in coral growth—implications for the structure and function of coral reef ecosystems. Oceanography and Marine Biology: An Annual Review, 2015. **53**: p. 215-295.

9. Baird, A.H., J.R. Guest, and B.L. Willis, Systematic and Biogeographical Patterns in the Reproductive Biology of Scleractinian Corals. Annual Review of Ecology, Evolution, and Systematics, 2009. **40**(1): p. 551-571.

10. Harrison, P. and C. Wallace, Reproduction, dispersal and recruitment of scleractinian corals, in Coral Reefs, Ecosystems of the World, Z. Dubinsky, Editor. 1990, Elsevier Science: Amsterdam, NL.

11. Sebens, K. and K. DeRiemer, Diel cycles of expansion and contraction in coral reef anthozoans. Marine Biology, 1977. **43**(3): p. 247-256.

12. Oakley, C.A. and S.K. Davy, Cell Biology of Coral Bleaching, in Coral Bleaching: Patterns, Processes, Causes and Consequences, M.J.H. van Oppen and J.M. Lough, Editors. 2018, Springer International Publishing: Cham. p. 189-211.

13. Muscatine, L. and J.W. Porter, Reef Corals: Mutualistic Symbioses Adapted to Nutrient-Poor Environments. BioScience, 1977. **27**(7): p. 454-460.

14. Houlbrèque, F. and C. Ferrier-Pagès, Heterotrophy in Tropical Scleractinian Corals. Biological Reviews, 2009. **84**(1): p. 1-17.

15. Winters, G., et al., Photographic assessment of coral chlorophyll contents: Implications for ecophysiological studies and coral monitoring. Journal of Experimental Marine Biology and Ecology, 2009. **380**(1): p. 25-35.

16.Dullo, W.-C., Coral growth and reef growth: a brief review. Facies, 2005. 51(1): p. 33-48.

17.Spalding, M., E. Green, and C. Ravilious, World atlas of coral reefs. 2001, Berkley: University of California Press. 416.

18. UNEP-WCMC, Global distribution of warm-water coral reefs, Version 4.1, in Millennium Coral Reef Mapping Project. 2021, UN Environment Programme World Conservation Monitoring Centre: Cambridge, UK.

19. Veron, J.E.N., et al. Corals of the World: Coral Stucture and Growth (Fig. 1 by Geoff Kelly). 2022 27/10/2022]; Available from: http://www.coralsoftheworld.org/page/structure-and-growth/.

20. Pandolfi, J.M., et al., Global trajectories of the long-term decline of coral reef ecosystems. Science, 2003. **301**(5635): p. 955-958.

21. Hoegh-Guldberg, O., et al., Coral reefs under rapid

climate change and ocean acidification. Science, 2007. **318**: p. 1737–1742.

22. Glynn, P.W., Coral reef bleaching: facts, hypotheses and implications. Global Change Biology, 1996. **2**(6): p. 495-509.

23. Brown, B.E., Coral bleaching: causes and consequences. Coral Reefs, 1997. **16**(1): p. S129-S138.

24. Hughes, T., et al., Phase shifts, herbivory, and the resilience of coral reefs to climate change. Current Biology, 2007. **17**(4): p. 360-365.

25. Souter, D., et al., Executive summary, in Status of Coral Reefs of the World: 2020, P.S. Souter D, Wicquart J, Logan M, Obura D, Staub F, Editor. 2021, Global Coral Reef Monitoring Network & United Nations Environment Programme: Lausanne, Swizerland. p. 14-19.

26. Carpenter, K.E., et al., One-third of reef-building corals face elevated extinction risk from climate change and local impacts. Science, 2008. **321**(5888): p. 560-563.

27. Zimmer, B., Coral reef restoration: an overview, in Coral reef restoration handbook, W.F. Precht, Editor. 2006, CRC Press: Boca Raton, Florida. p. 39-59.

28. Burt, J., et al., Are artificial reefs surrogates of natural habitats for corals and fish in Dubai, United Arab Emirates? Coral Reefs, 2009. **28**(3): p. 663-675.

29. Vaughan, G.O., N. Al-Mansoori, and J. Burt, The Arabian Gulf, in World Seas: An Environmental Evaluation, second edition, C. Sheppard, Editor. 2019, Elsevier Science: Amsterdam, NL. p. 1-23.

30. Riegl, B. and S. Purkis, Coral reefs of the Gulf: adaptation to climatic extremes. Coral Reefs of the World. Vol. 3. 2012, Amsterdam, Netherlands: Springer Science+Business Media B. V. 379.

31. Grandcourt, E., Reef fish and fisheries in the Gulf, in Coral Reefs of the Gulf: Adaptation to climatic extremes, B.M. Riegl and S. Purkis, Editors. 2012, Springer Netherlands. p. 127-161.

32. Buchanan, J.R., et al., Living on the edge: Vulnerability of coral-dependent fishes in the Gulf. Marine Pollution Bulletin, 2016. **105**(2): p. 480-488.

33. Grandcourt, E.M., et al., The abundance, status and bio-economic production potential of coral reef fisheries resources in Abu Dhabi (technical report for project 02-20-0002-11 & 02-21-0006-11). 2011, Abu Dhabi, UAE: Environment Agency – Abu Dhabi.

34. van Lavieren, H., et al., Managing the growing impacts of development on fragile coastal and marine systems: Lessons from the Gulf. 2011, A Policy Report, United Nations University - Institute for Water, Environment, and Health. Hamilton, ON, Canada.

35. Burt, J., H. van Lavieren, and D. Feary, Persian Gulf reefs: an important asset for climate science in urgent need of protection. Ocean Challenge, 2014. **20**: p. 49-56.

36. Coles, S., Coral species diversity and environmental factors in the Arabian Gulf and the Gulf of Oman: a comparison to the Indo-Pacific region. Atoll Research Bulletin, 2003. **507**: p. 1-19.

37. de Verneil, A., et al., Summer oxygen dynamics on a southern Arabian Gulf coral reef. Frontiers in Marine Science, 2021. **8**(1676): p. 1676.

38. Bouwmeester, J., et al., Coral and Reef Fish Communities in the Thermally Extreme Persian/Arabian Gulf: Insights into Potential Climate Change Effects, in Perspectives on the Marine Animal Forests of the World, S. Rossi and L. Bramanti, Editors. 2021, Springer International Publishing: Cham. p. 63-86.

39. Price, A., Studies on the echinoderm fauna of the western Arabian Gulf. Journal of Natural History, 1981. **15**: p. 1-15.

40. Riegl, B.M., et al., Present limits to heat-adaptability in corals and population-level responses to climate extremes. PLoS One, 2011. **6**(9): p. e24802.

41. Smith, E.G., et al., Signatures of selection underpinning rapid coral adaptation to the world›s warmest reefs. Science Advances, 2022. 8(2): p. eabl7287.

42. Howells, E.J., et al., Host adaptation and unexpected symbiont partners enable reef-building corals to tolerate extreme temperatures. Global Change Biology, 2016. **22**(8): p. 2702-2714.

43. Burt, J., et al., Insights from extreme coral reefs in a changing world. Coral Reefs, 2020. **39**(3): p. 495-507.

44. Vaughan, G.O. and J.A. Burt, The changing dynamics of coral reef science in Arabia. Marine Pollution Bulletin, 2016. **105**(2): p. 441-458

45. Howells, E.J., et al., Enhancing the heat tolerance of reef-building corals to future warming. Science Advances, 2021. **7**(34): p. eabg6070.

46. Howells, E.J., et al., Challenges of sperm cryopreservation in transferring heat adaptation of corals across ocean basins. PeerJ, 2022. **10**: p. e13395.

47. Coles, S.L. and B.M. Riegl, Thermal tolerances of reef corals in the Gulf: A review of the potential for increasing coral survival and adaptation to climate change through assisted translocation. Marine Pollution Bulletin, 2013. **72**(2): p. 232-332.

48. Bouwmeester, J., et al., Spatial patterns of reef fishes and corals in the thermally extreme waters of Qatar. Frontiers in Marine Science, 2022. **9**.

49. Bauman, A., et al., Multiple environmental factors influence the spatial distribution and structure of reef communities in the northeastern Arabian Peninsula. Marine Pollution Bulletin, 2012. 72(2): p. 302-312.

50. Burt, J., S. Al-Harthi, and A. Al-Cibahy, Long-term impacts of bleaching events on the world's warmest reefs. Marine Environmental Research, 2011. **72**(4): p. 225-229.

51. Riegl, B., et al., Population collapse dynamics in Acropora downingi, an Arabian/Persian Gulf ecosystem-engineering coral, linked to rising temperature. Global Change Biology, 2018. **24**: p. 2447–2462.

52. Burt, J., et al., Chapter 4. Status and trends of coral reefs of the ROPME Sea Area, in Status of Coral Reefs of the World: 2020, D. Souter, et al., Editors. 2021, Global Coral Reef Monitoring Network & United Nations Environment Programme: Lausanne, Swizerland. p. 1-13.

53. Riegl, B., Effects of the 1996 and 1998 positive sea-surface temperature anomalies on corals, coral diseases and fish in the Arabian Gulf (Dubai, UAE). Marine Biology, 2002. **140**: p. 29-40.

54. Burt, J., et al., Causes and consequences of the 2017 coral bleaching event in the southern Persian/Arabian Gulf. Coral Reefs, 2019. **38**(4): p. 567-589.

55. Paparella, F., et al., Coral Bleaching in the Persian/Arabian Gulf Is Modulated by Summer Winds. Frontiers in Marine Science, 2019. **6**(205): p. 1-15.

56. Sheppard, C., et al., Environmental concerns for the future of Gulf coral reefs, in Coral reefs of the Gulf: adaptation to climatic extremes, B.M. Riegl and S. Purkis, Editors. 2012, Springer Science+Business Media B. V. p. 349-373.

57. Burt, J., The environmental costs of coastal urbanization in the Arabian Gulf. City: analysis of urban trends, culture, theory, policy, action, 2014. **18**(6): p. 760-770.

58. Burt, J.A. and A. Bartholomew, Towards more sustainable coastal development in the Arabian Gulf: Opportunities for ecological engineering in an urbanized seascape. Marine Pollution Bulletin, 2019. **142**: p. 93-102.

59. Burt, J., A. Bartholomew, and P. Usseglio, Recovery of corals a decade after bleaching in Dubai, United Arab Emirates. Marine Biology, 2008. **154**(1): p. 27-36.

60. Erftemeijer, P.L.A., et al., Environmental impacts of dredging and other sediment disturbances on corals: A review. Marine Pollution Bulletin, 2012. **64**(9): p. 1737-1765.

61. Sale, P.F., et al., The growing need for sustainable ecological management of marine communities of the Persian Gulf. Ambio, 2011. **40**(1): p. 4-17.

62. Sheppard, C., Coral reefs in the Gulf are mostly

dead now, but can we do anything about it? Marine Pollution Bulletin, 2016. **105**(2): p. 593-598.

63. Fanning, L.M., et al., Applying the ecosystem services - EBM framework to sustainably manage Qatar›s coral reefs and seagrass beds. Ocean & Coastal Management, 2021. **205**: p. 1-16.

64. Mateos-Molina, D., et al., Synthesis and evaluation of coastal and marine biodiversity spatial information in the United Arab Emirates for ecosystem-based management. Marine Pollution Bulletin, 2021. **167**: p. 112319.

65. Al-Azri, N.S., et al., Comparative evaluation of EIA systems in the Gulf Cooperation Council States. Impact Assessment and Project Appraisal, 2014. **32**(2): p. 136-149.

66. Van Lavieren, H. and R. Klaus, An effective regional Marine Protected Area network for the ROPME Sea Area: Unrealistic vision or realistic possibility? Marine Pollution Bulletin, 2013. **32**(2): p. 389-405.

67. Naser, H.A., The role of environmental impact assessment in protecting coastal and marine environments in rapidly developing islands: The case of Bahrain, Arabian Gulf. Ocean & Coastal Management, 2015. **104**: p. 159-169.

68. Ben-Romdhane, H., et al., Coral Reefs of Abu Dhabi, United Arab Emirates: Analysis of Management Approaches in Light of International Best Practices and a Changing Climate. Frontiers in Marine Science, 2020. **7**(541).

69. ADUPC, Plan Maritime 2030–Abu Dhabi Coastal and Marine Framework Plan–Charette 1 Proceedings Book–Existing Conditions, Constraints and Opportunities. Abu Dhabi Urban Planning Council (ADUPC), 2014.

70. Butler, J.D., et al., A benthic habitat sensitivity analysis of Qatar›s coastal zone. Marine Pollution Bulletin, 2021. **167**: p. 112333.

71. Mateos-Molina, D., et al., Applying an integrated approach to coastal marine habitat mapping in the north-western United Arab Emirates. Marine Environmental Research, 2020: p. 105095.

72. Burt, J.A., et al., Improving management of future coastal development in Qatar through ecosystem-based management approaches. Ocean & Coastal Management, 2017. **148**: p. 171-181.

73. O'Higgins, T.G., M. Lago, and T.H. DeWitt, Ecosystem-based management, ecosystem services and aquatic biodiversity: Theory, tools and applications. 2020: Springer Nature.

74. Virtanen, E.A., A. Moilanen, and M. Viitasalo, Marine connectivity in spatial conservation planning: analogues from the terrestrial realm. Landscape Ecology, 2020. **35**(5): p. 1021-1034.

75. Jones, K.R., et al., Spatial analysis to inform the mitigation hierarchy. Conservation Science and Practice, 2022. **4**(6): p. e12686.

76. Ekstrom, J., L. Bennun, and R. Mitchell, A cross-sector guide for implementing the Mitigation Hierarchy. Cross Sector Biodiversity Initiative, Cambridge, 2015.

77. Phalan, B., et al., Avoiding impacts on biodiversity through strengthening the first stage of the mitigation hierarchy. Oryx, 2018. **52**(2): p. 316-324.

78. Brownlie, S. and J. Treweek, The mitigation hierarchy and beyond, in Sustainability assessment: applications and opportunities, R. Gibson, Editor. 2016, Routledge: Oxfordshire, UK. p. 225-246.

79. Swangjang, K. and S. Cumkhett, 16 - Mitigation hierarchy; an effectiveness of project control mechanism, in Handbook of Advanced Approaches Towards Pollution Prevention and Control, R.O.A. Rahman and C.M. Hussain, Editors. 2021, Elsevier. p. 325-342.

80. Rodgers, K.u.S., et al., Effectiveness of coral relocation as a mitigation strategy in Kāne'ohe Bay, Hawai'i. PeerJ, 2017. **5**: p. e3346.

81. Kotb, M.M., Coral translocation and farming as mitigation and conservation measures for coastal development in the Red Sea: Aqaba case study, Jordan. Environmental Earth Sciences, 2016. **75**(5): p. 1-8.

82. Gomez, E., R. Dizon, and A. Edwards, Methods of coral transplantation. Reef Rehabilitation, 2010: p. 99.

83. ter Hofstede, R., et al. Monitoring and evaluation of coral transplantation to mitigate the impact of dredging works. in Proceedings of the 13th International Coral Reef Symposium, Honolulu, HA. 2016.

84. Yu, S., et al., Towards a biodiversity offsetting approach for coastal land reclamation: Coastal management implications. Biological Conservation, 2017. **214**: p. 35-45.

85. Niner, H.J., et al., A global snapshot of marine biodiversity offsetting policy. Marine Policy, 2017. **81**: p. 368-374.

86. Gibbons, P., et al., A Loss-Gain Calculator for Biodiversity Offsets and the Circumstances in Which No Net Loss Is Feasible. Conservation Letters, 2016. **9**(4): p. 252-259.

87. Maron, M., et al., Faustian bargains? Restoration realities in the context of biodiversity offset policies. Biological Conservation, 2012. **155**: p. 141-148.

88. Bull, J.W., et al., Biodiversity offsets in theory and practice. Oryx, 2013. **47**(3): p. 369-380.

89. Curran, M., S. Hellweg, and J. Beck, Is there any empirical support for biodiversity offset policy? Ecological Applications, 2014. **24**(4): p. 617-632.

90. Jacob, C., et al., Marine ecosystem restoration and biodiversity offset. Ecological Engineering, 2018. **120**: p. 585-594.

91. Jokiel, P. and S. Coles, Response of Hawaiian and other Indo-Pacific reef corals to elevated temperature. Coral Reefs, 1990. **8**: p. 155-162.

92. Jokiel, P., et al., Review of coral reef restoration and mitigation in Hawaii and the U.S.-Affiliated Pacific Islands, in Coral reef restoration handbook: the rehabilitation of an ecosystem under siege, W. Precht, Editor. 2006, CRC Press: Boca Raton, FL. p. 271-290.

93. Bellwood, D.R., et al., Confronting the coral reef crisis. Nature, 2004. **429**(6994): p. 827-833.

94. Shantz, A.A., et al., Fish-derived nutrient hotspots shape coral reef benthic communities. Ecol Appl, 2015. **25**(8): p. 2142-52.

95. Shaver, E.C. and B.R. Silliman, Time to cash in on positive interactions for coral restoration. PeerJ, 2017. **5**: p. e3499.

96. Glynn, P.W. and I.C. Enochs, Invertebrates and Their Roles in Coral Reef Ecosystems, in Coral Reefs: An Ecosystem in Transition, Z. Dubinsky and N. Stambler, Editors. 2011, Springer Netherlands: Dordrecht. p. 273-325.

97. Stier, A.C., et al., Guard crabs alleviate deleterious effects of vermetid snails on a branching coral. Coral Reefs, 2010. **29**(4): p. 1019-1022.

98. Stewart, H.L., et al., Determinants of the onset and strength of mutualistic interactions between branching corals and associate crabs. Marine Ecology Progress Series, 2013. **493**: p. 155-163.

99. Stachowicz, J.J. and M.E. Hay, Mutualism and Coral Persistence: The Role of Herbivore Resistance to Algal Chemical Defense. Ecology, 1999. **80**(6): p. 2085-2101.

100. Ladd, M.C. and A.A. Shantz, Trophic interactions in coral reef restoration: A review. Food Webs, 2020. 24: p. e00149.

101. Frias-Torres, S. and C. van de Geer, Testing animal-assisted cleaning prior to transplantation in coral reef restoration. PeerJ, 2015. 3: p. e1287.

102. Kaufman, L.S., If you build it, will they come? Toward a concrete basis for coral reef gardening, in Coral reef restoration handbook, W.F. Precht, Editor. 2006, CRC Press: Boca Raton, Florida. p. 119-142.

103. Seraphim, M.J., et al., Interactions between coral restoration and fish assemblages: implications for reef management. J Fish Biol, 2020. 97(3): p. 633-655.

104. Boström-Einarsson, L., et al., Coral restoration – A systematic review of current methods, successes,

failures and future directions. PLOS ONE, 2020. 15(1): p. e0226631.

105.Bayraktarov, E., et al., Motivations, success, and cost of coral reef restoration. Restoration Ecology, 2019. 27(5): p. 981-991.

106.Bayraktarov, E., et al., The cost and feasibility of marine coastal restoration. Ecological Applications, 2016. 26(4): p. 1055-1074.

107.Seguin, F., et al. Large coral transplantation in Bal Haf (Yemen): an opportunity to save corals during the construction of a Liquefied Natural Gas plant using innovative techniques. in Proceedings of the 11th International Coral Reef Symposium. 2008. Ft. Lauderdale, Florida.

108.Symons, L.C., A. Stratton, and W. Goodwin, Streamlined injury assessment and restoration planning in the US National Marine Sanctuaries, in Coral reef restoration handbook, W.F. Precht, Editor. 2006, CRC Press: Boca Raton, Florida. p. 167-192.

109.Gittings, S.R., The recovery process in a mechanically damaged coral reef community. 1988, Texas A&M University: Ann Arbor. p. 245.

110. Clark, S. and A.J. Edwards, Coral transplantation as an aid to reef rehabilitation: evaluation of a case study in the Maldive Islands. Coral Reefs, 1995. **14**(4): p. 201-213.

111. Edwards, A. and S. Clark, Coral transplantation: a useful management tool or misguided meddling? Marine Pollution Bulletin, 1998. **37**(8-12): p. 474-487.

112. Garrison, V.H. and G. Ward, Transplantation of storm-generated coral fragments to enhance Caribbean coral reefs: A successful method but not a solution. Revista de Biologia Tropical, 2012. **60**: p. 59-70.

113. Goergen, E.A. and D.S. Gilliam, Outplanting technique, host genotype, and site affect the initial success of outplanted Acropora cervicornis. PeerJ, 2018. **6**: p. e4433.

114. Forrester, G.E., et al., Comparing the Efficiency of Nursery and Direct Transplanting Methods for Restoring Endangered Corals. Ecological Restoration, 2019. **37**(2): p. 81-89.

115. Suggett, D.J., et al., Coralclip®: a low-cost solution for rapid and targeted out-planting of coral at scale. Restoration Ecology, 2020. **28**(2): p. 289-296.

116. Deb, K., A. McCarthy, and B. Harkanson. Coral Relocation as Habitat Mitigation for Impacts From the Barzan Gas Project Pipeline Construction, Offshore Qatar. in SPE International Conference on Health, Safety, and Environment. 2014. Society of Petroleum Engineers.

117. Okubo, N., T. Motokawa, and M. Omori, When fragmented coral spawn? Effect of size and timing on survivorship and fecundity of fragmentation in Acropora formosa. Marine Biology, 2007. **151**(1): p. 353-363.

118. Shutler, S.K., et al., Compensatory restoration: how much is enough? Legal, economic, and ecological considerations, in Coral reef restoration handbook, W.F. Precht, Editor. 2006, CRC Press: Boca Raton, Florida. p. 77-94.

119. Casey, J.M., S.R. Connolly, and T.D. Ainsworth, Coral transplantation triggers shift in microbiome and promotion of coral disease associated potential pathogens. Scientific Reports, 2015. **5**(1): p. 11903.

120.Hein, M., et al., Coral Reef Restoration as a strategy to improve ecosystem services - A guide to coral restoration methods. Nairobi, Kenya: United Nations Environment Programme, 2020.

121. Edwards, A.J., Reef rehabilitation manual. 2010, St Lucia, Australia: Coral Reef Targeted Research & Capacity Building for Management Program. 166.

122. Gayle, P.M.H., P. Wilson-Kelly, and S. Green, Transplantation of benthic species to mitigate impacts of coastal development in Jamaica. Revista De Biologia Tropical, 2005. **53**(Suppl. 1): p. 105-115.

123.Takeda, S., et al., Mitigation of coral ecosystem service-related social issues: evidence from a coastal development project in a developing country. Impact Assessment and Project Appraisal, 2021. **39**(1): p. 36-50.

124.Nanajkar, M., K. De, and B. Ingole, Coral reef restoration - A way forward to offset the coastal development impacts on Indian coral reefs. Marine Pollution Bulletin, 2019. **149**: p. 110504.

125.Goergen, E.A., et al., Coral reef restoration monitoring guide: Methods to evaluate restoration success from local to ecosystem scales. 2020.

126.Precht, W.F., Coral reef restoration handbook. 2006: CRC press.

127.Miller, M.W. and A.M. Szmant, Lessons learned from experimental key-species restoration, in Coral reef restoration handbook, W.F. Precht, Editor. 2006, CRC Press: Boca Raton, Florida. p. 219.

128.Edwards, A.J. and E.D. Gomez, Reef restoration concepts and guidelines: making sensible management choices in the face of uncertainty. 2007, St. Lucia: Capacity Building for Management Programme/Coral Reef Targeted Research. 38.

129.Hein, M.Y., et al., Perspectives on the use of coral reef restoration as a strategy to support and improve reef ecosystem services. Frontiers in Marine Science, 2021. **8**(299).

130.Precht, W.F. and M. Robbart, Coral reef restoration: the rehabilitation of an ecosystem under siege, in Coral reef restoration handbook, W.F. Precht, Editor. 2006, CRC Press: Boca Raton, Florida. p. 1-24.

131. Shaver, E.C., et al., A Manager's Guide to Coral Reef Restoration Planning and Design. 2020: NOAA Technical Memorandum CRCP 36. 1-128.

132.Doran, G.T., There's a S.M.A.R.T. way to write management's goals and objectives. Management review, 1981. **70**(11): p. 35-36.

133.Wapnick, C. and A. McCarthy, Monitoring the efficacy of reef restoration projects: where are we and where do we need to go?, in Coral reef restoration handbook, W.F. Precht, Editor. 2006, CRC Press: Boca Raton, Florida. p. 339.

134.Vaughan, G. and J. Burt, Seasonal variation in reef fish communities in the environmentally extreme southern Arabian Gulf, in European Coral Reef Symposium. 2017, International Society for Reef Studies: Oxford University, UK.

135.Coles, S. and A. Tarr, Reef fish assemblages in the western Arabian Gulf: A geographically isolated population in an extreme environment. Bulletin of Marine Science, 1990. **47**(3): p. 696-720.

136.Burt, J., et al., The influence of wave exposure on coral community development on man-made breakwater reefs, with a comparison to a natural reef. Bulletin of Marine Science, 2010. **86**(4): p. 839-859.

137.Biggs, B.C., Harnessing Natural Recovery Processes to Improve Restoration Outcomes: An Experimental Assessment of Sponge-Mediated Coral Reef Restoration. PLOS ONE, 2013. **8**(6): p. e64945.

138.Fox, H.E., et al., Recovery in rubble fields: long-term impacts of blast fishing. Marine Pollution Bulletin, 2003. **46**(8): p. 1024-1031.

139.Venera-Ponton, D., et al., Macroalgae reduce growth of juvenile corals but protect them from parrotfish damage. Marine Ecology Progress Series, 2011. 421: p. 109-115.

140.Bonaldo, R.M. and M.E. Hay, Seaweed-Coral Interactions: Variance in Seaweed Allelopathy, Coral Susceptibility, and Potential Effects on Coral Resilience. PLOS ONE, 2014. 9(1): p. e85786.

141.Tanner, J.E., Competition between scleractinian corals and macroalgae: An experimental investigation of coral growth, survival and reproduction. Journal of Experimental Marine Biology and Ecology, 1995. **190**(2): p. 151-168.

142.Morley, D.M., et al., Environmental enhancement gone awry: characterization of an artificial reef constructed from waste vehicle tires. Environmental Problems in Coastal Regions, 2008. **7**: p. 73-87.

143.Sherman, R.L. and R.E. Spieler, Tires: Unstable materials for artificial reef construction. Transactions on Ecology and the Environment, 2006. **88**: p. 215-223.

144.Bohnsack, J.A. and D.L. Sutherland, Artificial Reef Research: A Review with Recommendations for Future Priorities. Bulletin of Marine Science, 1985. 37(1): p. 11-39.

145.Tallman, J., Aesthetic components of ecological restoration, in Coral reef restoration handbook, W.F. Precht, Editor. 2006, CRC Press: Boca Raton, Florida. p. 193.

146.Burt, J., et al., Coral recruitment and early benthic community development on several materials used in the construction of artificial reefs and breakwaters. Journal of Experimental Marine Biology and Ecology, 2009. **373**: p. 72-78.

147.Williams, S.L., et al., Large-scale coral reef rehabilitation after blast fishing in Indonesia. Restoration ecology, 2019. **27**(2): p. 447-456.

148.Crawford, A., et al., Architecture for coral restoration: Using clay-based digital fabrication to overcome bottlenecks to coral larval propagation, in Structures and Architecture A Viable Urban Perspective? 2022, CRC Press. p. 458-466.

149.Burt, J., A. Bartholomew, and D. Feary, Man-made structures as artificial reefs in the Gulf, in Coral reefs of the Gulf: adaptation to climatic extremes, B. Riegl and S. Purkis, Editors. 2012, Springer Science+Business Media B. V. p. 171-186.

150.Feary, D., J. Burt, and A. Bartholomew, Artificial marine habitats in the Arabian Gulf: review of current use, benefits and management implications. Ocean & Coastal Management, 2011. **54**: p. 742-749.

151. Bartholomew, A., J.A. Burt, and L.B. Firth, Artificial reefs in the Arabian Gulf: Benefits, challenges and recommendations for policy-makers. Regional Studies in Marine Science, 2022(102723): p. 1-23

152.Burt, J., A. Bartholomew, and L. Firth, Policy and management considerations for artificial reefs in the Arabian Gulf. Sheikh Saud bin Saqr Al Qasimi Foundation for Policy Research, Policy Paper 51, 2021: p. 1-31.

153.Bonito, V.B., A coral gardener's guide to implementing ecologically-relevant coral restoration strategies. Reef Explorer Technical report. 2021.

154.Riegl, B. and G. Branch, Effects of sediment on the energy budgets of four scleractinian (Bourne 1900) and five alcyonacean (Lamouroux 1816) corals. Journal of Experimental Marine Biology and Ecology, 1995. **186**(2): p. 259-275.

155.Shaver, E.C., et al., Effects of predation and nutrient enrichment on the success and microbiome of a foundational coral. Ecology, 2017. **98**(3): p. 830-839.

156.Ceccarelli, D.M., et al., Rehabilitation of coral reefs through removal of macroalgae: state of knowledge and considerations for management and implementation. Restoration Ecology, 2018. **26**(5): p. 827-838.

157.Frias-Torres, S., et al., Reef fishes recruited at midwater coral nurseries consume biofouling and reduce cleaning time in Seychelles, Indian Ocean. African Journal of Marine Science, 2015. **37**(3): p. 421-426.

158.Cano, I., et al., Effects of herbivory by the urchin Diadema antillarum on early restoration success of the coral Acropora cervicornis in the central Caribbean. Journal of Experimental Marine Biology and Ecology, 2021. **539**: p. 151541.

159.Stewart, H.L., et al., Symbiotic crabs maintain coral health by clearing sediments. Coral Reefs, 2006. **25**(4): p. 609-615.

160.Rouzé, H., et al., Juvenile Trapezia spp. crabs can increase juvenile host coral survival by protection from predation. Marine Ecology Progress Series, 2014. **515**: p. 151-159.

161. Ladd, M.C., et al., Harnessing ecological processes to facilitate coral restoration. Frontiers in Ecology and the Environment, 2018. **16**(4): p. 239-247.

162.Green, R.H., Sampling design and statistical methods for environmental biologists. 1979: John Wiley & Sons.

163.Underwood, A.J., Beyond BACI - the detection of environmental impacts on populations in the real, but variable, world. Journal of Experimental Marine Biology and Ecology, 1992. **161**(2): p. 145-178.

164.Underwood, A.J., On beyond BACI - sampling designs that might reliably detect environmental disturbances. Ecological Applications, 1994. **4**(1): p. 3-15.

165.Clements, C.S. and M.E. Hay, Biodiversity enhances coral growth, tissue survivorship and suppression of macroalgae. Nature ecology & evolution, 2019. **3**(2): p. 178-182.

166.Darling, E.S., et al., Evaluating life-history strategies of reef corals from species traits. Ecology Letters, 2012. **15**(12): p. 1378-1386.

167.Kerry, J. and D. Bellwood, The effect of coral morphology on shelter selection by coral reef fishes. Coral Reefs, 2012. **31**(2): p. 415-424.

168.Yap, H.T., et al., Physiological and ecological aspects of coral transplantation. Journal of Experimental Marine Biology and Ecology, 1998. **229**(1): p. 69-84.

169.Shlesinger, T. and R. van Woesik, Different population trajectories of two reef-building corals with similar life-history traits. J Anim Ecol, 2021. **90**(5): p. 1379-1389.

170.Page, C.A., E.M. Muller, and D.E. Vaughan, Microfragmenting for the successful restoration of slow growing massive corals. Ecological Engineering, 2018. **123**: p. 86-94.

171. Schlecker, L., et al., Mechanisms and potential immune tradeoffs of accelerated coral growth induced by microfragmentation. PeerJ, 2022. **10**: p. e13158.

172. Koval, G., et al., Fish predation hinders the success of coral restoration efforts using fragmented massive corals. PeerJ, 2020. **8**: p. e9978.

173.Mostrales, T.P.I., R.N. Rollon, and W.Y. Licuanan, Evaluation of the performance and cost-effectiveness of coral microfragments in covering artificial habitats. Ecological Engineering, 2022. **184**: p. 106770.

174.ter Hofstede, R., Feeding ecology of the angelfish species Pomacanthus asfur and Pomacanthus maculosus, in Marine Biology. 1998, University of Groningen: Netherlands. p. 32.

175.Kenny, I., et al. Coral Relocation: A mitigation tool for dredging works in Jamaica. in International Coral Reef Symposium. 2012. Cairns, Australia: ICRS.

176.McKeon, C.S., et al., Multiple defender effects: synergistic coral defense by mutualist crustaceans. Oecologia, 2012. **169**(4): p. 1095-1103.

177.McKeon, C.S. and J.M. Moore, Species and size diversity in protective services offered by coral guard-crabs. PeerJ, 2014. **2**: p. e574.

178.McCarrick, E., Dubai coral moved. Time Out Dubai, 2009: p. https://www.timeoutdubai.com/things-to-do/things-to-do-features/9508-dubai-coral-moved.

179.Frewin, J., Dubai tourism gets boost from $10m coral reef relocation. BBC News, 2013. **Accessed at http://www.bbc.co.uk/news/business-24297821 on 20 Nov 2013.**

180.Li, K., Contract No. PI2/2020 Environmental Monitoring Works for Lei Yue Mun Waterfront Enhancement Project Certification of Coral Translocation Plan (Version 5.0). 2021, Wellab Limited: Hong Kong. p. https://www.lymwep.com/images/data/Coral_Translocation_Plan_v5.0_certified_verified.pdf.

181. Buckee, J. and C. Blount, Long-term survival of large relocated <i>Porites</i> colonies at the Cocos (Keeling) Islands. Pacific Conservation Biology, 2022. **28**(5): p. 455-456.

182.Lennon, D. and J. Walch. RAPID RELOCATION OF NEARSHORE CORALS OUT OF A DREDGE ZONE SAUDI ARABIA. in International Conference on Artificial Reefs and Related Aquatic Habitats. 2009. Curitiba, Brazil.

183.Riegl, B., et al., Environmental constraints for reef building in the Gulf, in Coral reefs of the Gulf: adaptation to climatic extremes, B.M. Riegl and S.J. Purkis, Editors. 2012, Springer Science+Business Media B. V. p. 187-224.

184.Coles, S.L. and Y.H. Fadlallah, Reef coral survival and mortality at low-temperatures in the Arabian Gulf - new species-specific lower temperature limits. Coral Reefs, 1991. **9**(4): p. 231-237.

185.Shinn, E., Coral reef recovery in Florida and the Persian

Gulf. Environmental Geology, 1976. 1: p. 241-254.

186. Thoppil, P.G. and P.J. Hogan, Persian Gulf response to a wintertime shamal wind event. Deep Sea Research Part I: Oceanographic Research Papers, 2010. **57**(8): p. 946-955.

187. Apilanez, I., A. Gutierrez, and M. Diaz, Effect of surface materials on initial biofilm development. Bioresource Technology, 1998. **66**(3): p. 225-230.

188. Chan, B.K.K., W.K.S. Chan, and G. Walker, Patterns of biofilm succession on a sheltered rocky shore in Hong Kong. Biofouling, 2003. **19**(6): p. 371-380.

189. Stoodley, P., et al., Biofilms as complex differentiated communities. Annu. Rev. Microbiol., 2002. **56**: p. 187-209.

190. Burt, J., A. Bartholomew, and P. Sale, Benthic development on large-scale artificial reefs: a comparison of communities among breakwaters of different age and natural reefs. Ecological Engineering, 2011. **37**: p. 191-198.

191. Tagliafico, A., et al., A potential method for improving coral self-attachment. Restoration Ecology, 2018. **26**(6): p. 1082-1090.

192. Forrester, G.E., et al., Evaluating Methods for Transplanting Endangered Elkhorn Corals in the Virgin Islands. Restoration Ecology, 2011. 19(3): p. 299-306.

193. Einbinder, S., et al., Changes in morphology and diet of the coral Stylophora pistillata along a depth gradient. Marine Ecology Progress Series, 2009. **381**: p. 167-174.

194. Cohen, I. and Z. Dubinsky, Long term photoacclimation responses of the coral Stylophora pistillata to reciprocal deep to shallow transplantation: photosynthesis and calcification. Frontiers in Marine Science, 2015. **2**.

195. Iglesias-Prieto, R., et al., Different algal symbionts explain the vertical distribution of dominant reef corals in the eastern Pacific. Proceedings of the Royal Society of London. Series B: Biological Sciences, 2004. **271**(1549): p. 1757-1763.

196. Shick, J.M., et al., Depth-dependent responses to solar ultraviolet radiation and oxidative stress in the zooxanthellate coral Acropora microphthalma. Marine Biology, 1995. **122**(1): p. 41-51.

197. Ben-Zvi, O., et al., Photophysiology of a mesophotic coral 3 years after transplantation to a shallow environment. Coral Reefs, 2020. **39**(4): p. 903-913

198. Riegl, B., Climate change and coral reefs: different effects in two high-latitude areas (Arabian Gulf, South Africa). Coral Reefs, 2003. **22**.

199. Griffin, J.N., et al., Density-dependent effects on initial growth of a branching coral under restoration. Restoration Ecology, 2015. **23**(3): p. 197-200

200. Ladd, M.C., et al., Density Dependence Drives Habitat Production and Survivorship of Acropora cervicornis Used for Restoration on a Caribbean Coral Reef. Frontiers in Marine Science, 2016. **3**.

201. Huntington, B.E., et al., Facilitation in Caribbean coral reefs: high densities of staghorn coral foster greater coral condition and reef fish composition. Oecologia, 2017. **184**(1): p. 247-257.

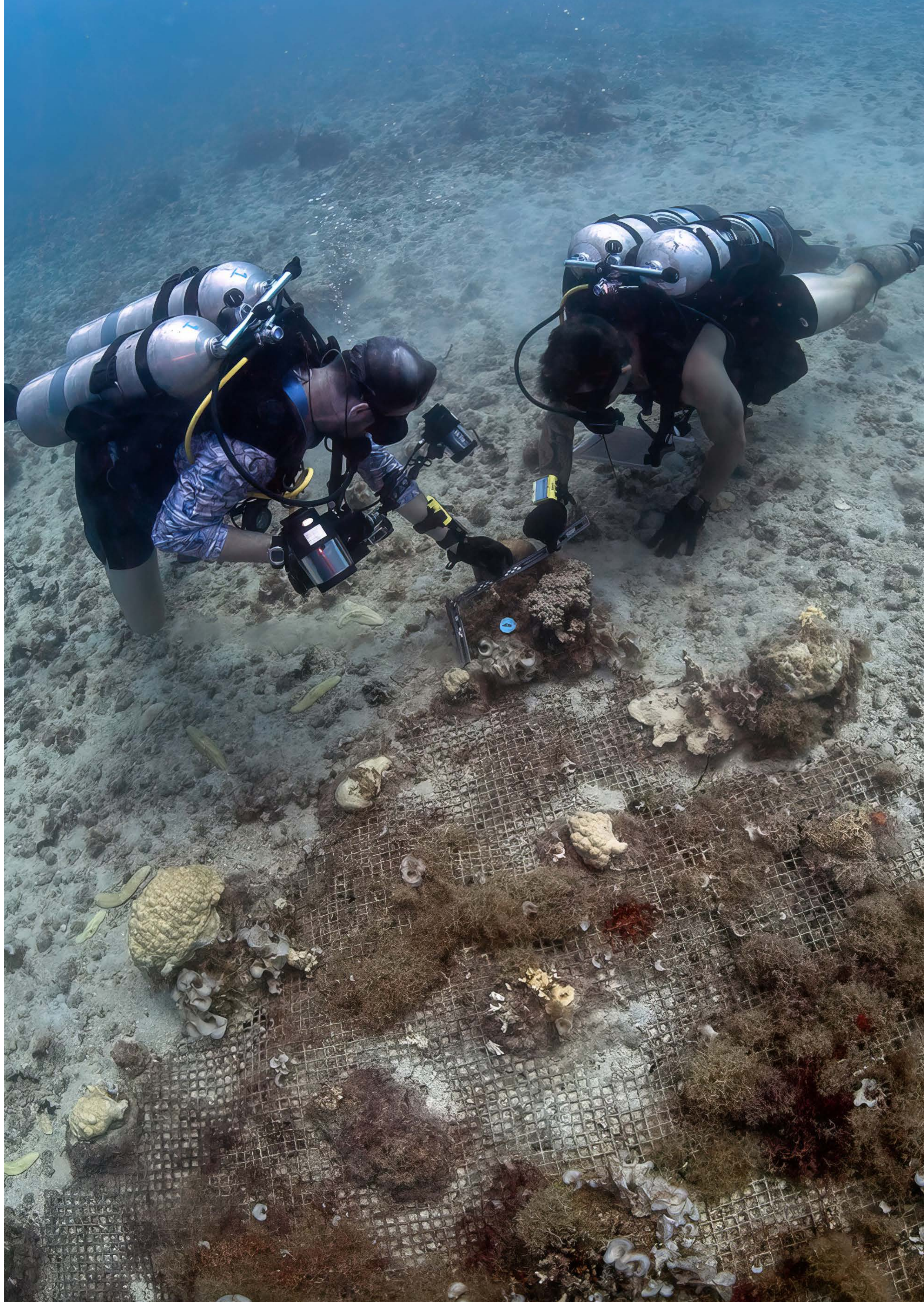
202. Omori, M., Coral restoration research and technical developments: what we have learned so far. Marine Biology Research, 2019. **15**(7): p. 377-409.

203. Bongiorni, L., et al., First step in the restoration of a highly degraded coral reef (Singapore) by in situ coral intensive farming. Aquaculture, 2011. **322-323**: p. 191-200.

204. Guzman, H.M., Restoration of Coral Reefs in Pacific Costa-Rica. Conservation Biology, 1991. 5(2): p. 189-195.

205. Howells, E., et al., Annual outbreaks of coral disease coincide with extreme seasonal warming. Coral Reefs, 2020. **39**(3): p. 771-781

206. Burt, J.A. Khalifa Port Coral Relocation Project: Year 1 Follow-up Monitoring Report. Report submitted to Abu Dhabi Ports, 12 Dec. 2021. 21pp.



Get in touch

adportsgroup.com

For more information please email **innovation@adports.ae**