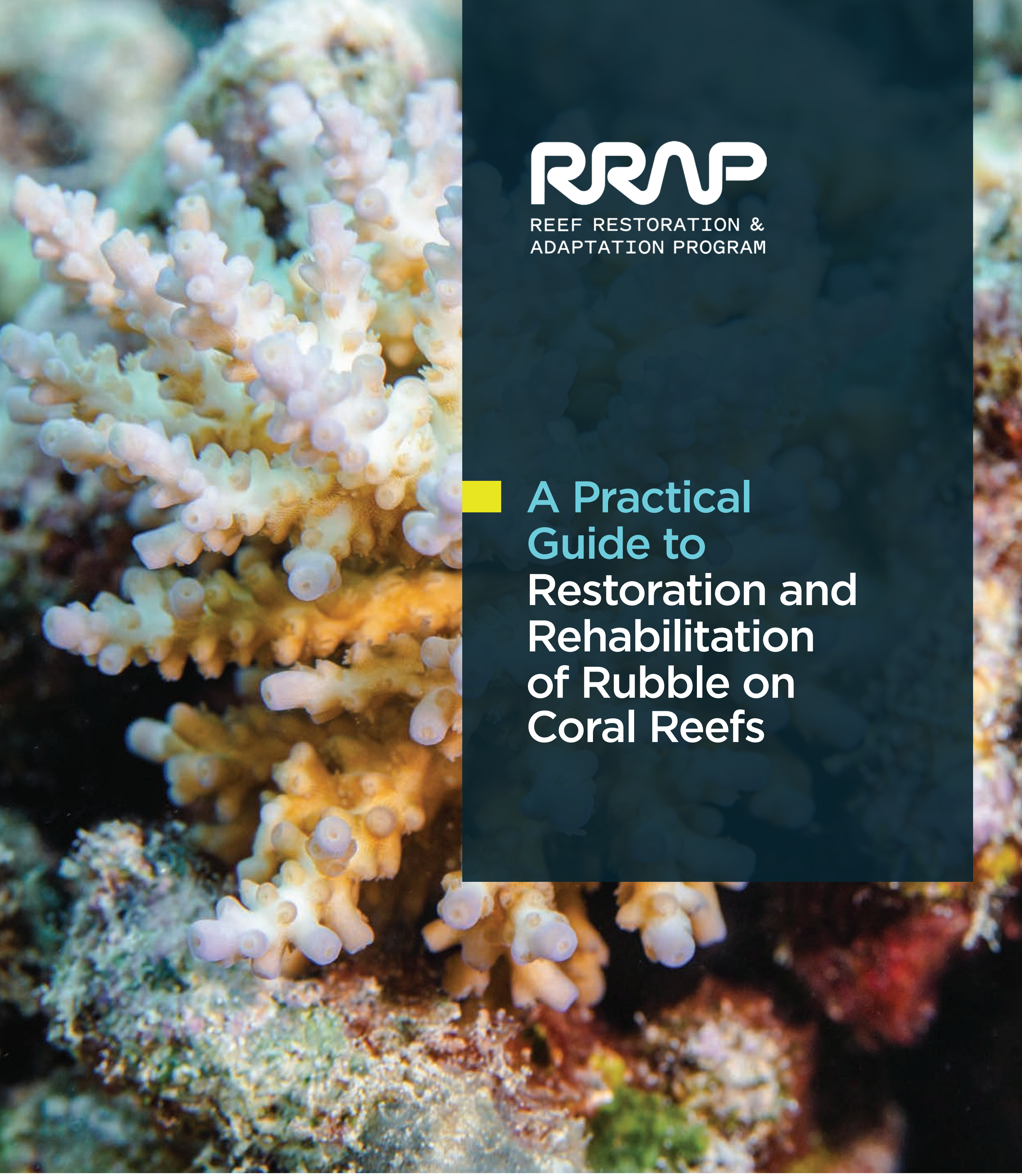

RRAP

REEF RESTORATION & ADAPTATION PROGRAM

A Practical Guide to Restoration and Rehabilitation of Rubble on Coral Reefs

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A Practical Guide to Restoration and Rehabilitation of Rubble on Coral Reefs

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Peter Mumby

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For more information on the Reef Restoration and Adaptation Program (RRAP), please visit:

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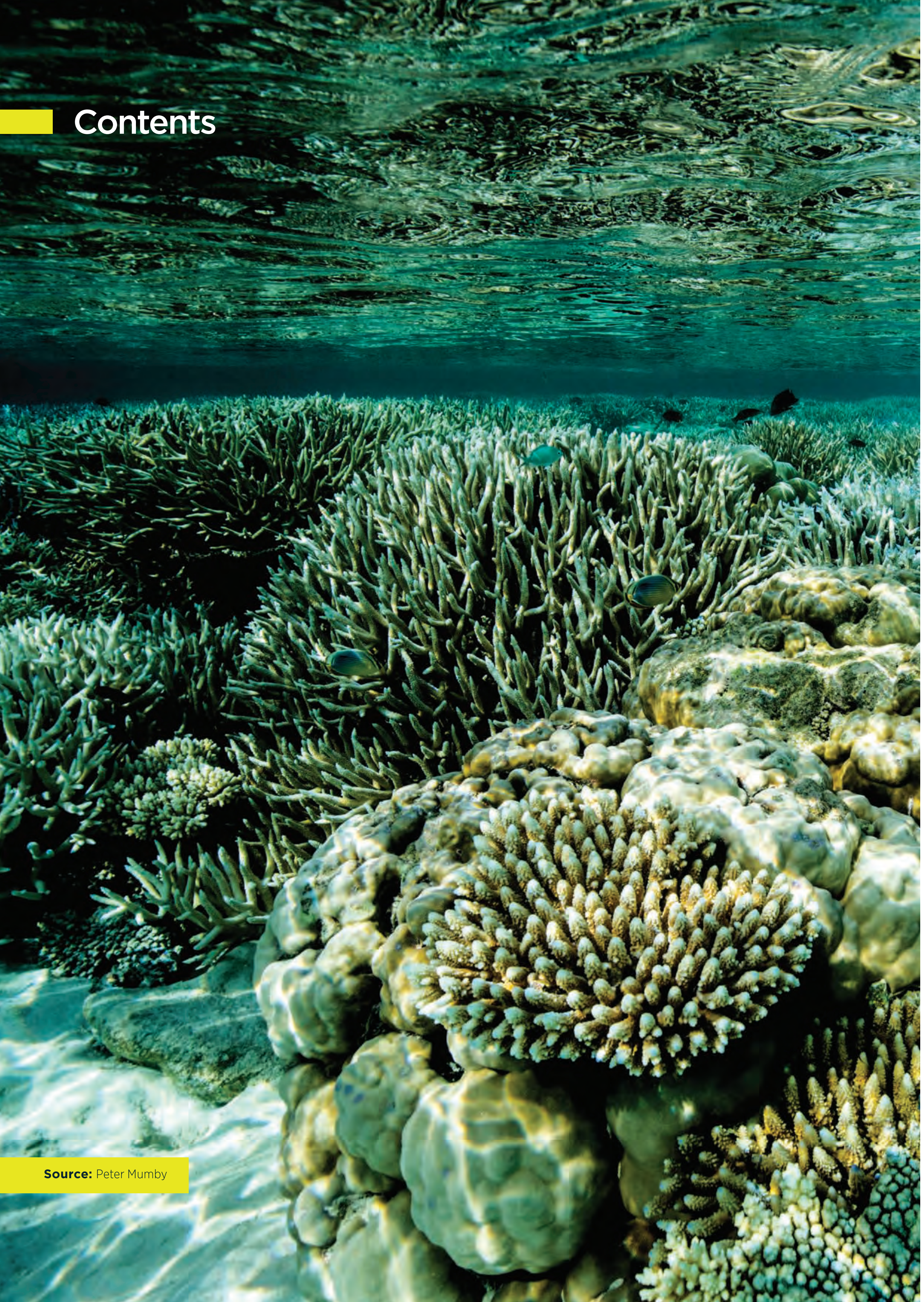

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Executive Summary

Coral reefs are home to at least **25% of marine species,** and offer essential ecosystem goods and services, contributing a substantial **US$2.7 trillion** annually to the global economy.

Climate change and human activities present increasing threats to coral reefs. Disturbances such as marine heatwaves are predicted to be more frequent and intense into the Anthropocene.

As a result, rubble is likely to be generated and mobilised more often, shrinking recovery windows for coral reefs. Coral reefs will become increasingly vulnerable to the persistence of loose rubble beds.

Rubble and reef recovery

Rubble is not always a considered an impediment to reef recovery.

It is a natural component of the reef and plays a critical role in the cycle of coral reef erosion, sedimentation and accretion. In certain environmental conditions, immobile rubble beds can constitute a suitable settlement substrate for coral recruits, supporting reef recovery and accretion. Rubble beds also provide important invertebrate habitats, and support food chains and the health of adjacent reefs.

However, rubble beds can also significantly hinder reef recovery when rubble is are continually or periodically mobilised. When rubble is mobilised, coral recruits are subjected to abrasion and smothering. Loose rubble beds, where pieces are not interlocked, can remain in a degraded state for decades to centuries.

Current rubble stabilisation efforts and limitations

Rubble stabilisation interventions can be broadly classified into four categories:

1. **Direct manipulation of the substrate,** which involves removing rearranging, and/or reattaching rubble to stabilise the substrate.
2. **Addition of structures to restrict rubble movement,** where structures are introduced to pin down rubble or block its downslope movement.
3. **Addition of structures to provide an alternative substrate,** which offers elevated, stable surfaces that encourage coral recruitment.
4. **Propagation of corals and sponges,** which involves coral transplantation and gardening to kick-start reef recovery when in combination with methods, as well as sponge seeding to aid in rubble binding.

The most commonly used methods include: 1) rubble removal followed by coral and rubble reattachment (capping rubble with cement and then reattaching dislodged corals), and 2) the addition of rocks, metal, or concrete structures to stabilise rubble.

One of the key limitations of stabilisation methods is their high costs, usually coupled with low scalability. Many stabilisation methods are also not monitored, particularly over long time periods.

Essential elements for effective rubble stabilisation

Like all restoration interventions, rubble stabilisation should be considered as one component of a resilience-based management framework for degraded reefs.

It is not a silver bullet for all problems and should be considered in conjunction with the management of other environmental stressors.

A degraded reef can be evaluated in terms of its historical condition, the reasons for coral decline, and obstacles to recovery. This information will help to determine:

1. whether intervention is suitable and appropriate at the site,
2. whether rubble stabilisation will be effective, and;
3. whether additional steps are required before proceeding.

Rubble stabilisation interventions are generally suitable for locations where reef recovery is limited by the instability of disturbed persistent rubble, provided that other factors of reef degradation, such as poor water quality, have already been addressed.

The most appropriate stabilisation method(s) will depend on project goals, environmental conditions, and socio-economic considerations. In some cases, a combination of methods may be necessary and effective.

A carefully designed, science-based, and long-term monitoring program is highly recommended to capture data before, upon and after deployment of rubble stabilisation interventions. It is important that long-term monitoring is incorporated into project budgets and workplans. Ideally, this program would include a range of ecological, social, and economic metrics.

Purpose of the document and the Rubble Stabilisation Intervention toolbox

The guidelines aim to consolidate current knowledge in the field of rubble stabilisation.

It encourages proactive measures and can inform decision-making when planning a rubble stabilisation project.

The Rubble Stabilisation Intervention toolbox includes two expert-based Bayesian Belief Networks that summarises the conditional probabilities of success and benefits based on chosen stabilisation methods and environmental conditions. These networks incorporate observations from past projects across multiple countries and expert opinions, providing users with information for decision-making to better achieve their project goals.

How to use these guidelines

The guidelines encapsulate **state-of-the-art knowledge on rubble stabilisation,** drawing from a number of sources including published papers, case studies, and expert data from around the globe.

We aim to provide a comprehensive resource that supports decision-making for our target audience, which includes practitioners, tourism operators, managers, and anyone seeking to understand and apply rubble stabilisation techniques for restoring degraded coral reefs.

While some of the case studies are derived from the Great Barrier Reef (GBR), the considerations and principles outlined in this guide may be applied or adapted to other locations facing similar challenges. Indeed, some of the scenarios we consider, such as the rubble problems created by blast fishing, are far more applicable in other parts of the world.

The guide is structured into 3 main sections:

1. The Background section

Lays the foundation for understanding the trends, importance, and fundamental mechanisms of rubble stabilisation.

It provides the necessarycontext for the rubble 'problem' and the rationale for rubble stabilisation, answering the 'what' and 'why'.

2. Rubble stabilisation: From concept to impact

Provides guidance on the key stages of a rubble stabilisation project, answering the 'how'.

It starts with the **planning** subsection, outlining the key factors to consider in determining the suitability of restoration and the most appropriate method aligned with project objectives.

Following the planning is the **implementation** stage, where the chosen methods are put into action. For each method, this subsection discusses the steps involved in implementation, advantages and disadvantages, expected outcomes, and the ideal conditions for success. Please note that some interventions in these guidelines have not been systematically tested and some findings are anecdotal. Readers should carefully assess the applicability of the information to their specific circumstances and site environment.

Finally, the **monitoring and evaluating project success** subsection provides advice on how to establish an effective monitoring program that assesses the impact of a stabilisation project.

3. The RRAP Rubble Stabilisation Intervention Toolbox section

Provides an introduction and a step-by-step guide to the decision-making tools developed for rubble stabilisation.

Background

This section aims to introduce the problem of **rubble on coral reefs** and discuss current and projected **trends of rubble generation and mobilisation** to improve understanding from a management perspective.

What is rubble?

'Rubble' is an umbrella term for fragments of coral or reef rock generated predominantly by physical processes that break off parts of coral skeletons and reef framework (Kenyon et al., 2023a; Rasser & Riegl, 2002).

Biological and chemical processes that cause abrasion and weakening of the reef framework, such as bioerosion and acidification, also promote breakage, indirectly contributing to the formation of rubble.

When disturbances such as cyclones, warming events, disease or predator outbreaks, and human activities damage the reef, pieces of coral and reef rock break off, forming what is called 'rubble.' Most of these rubble pieces are dead, but live fragments are also common in rubble beds, especially in the aftermath of a recent disturbance. However, live fragments may die quickly or over time if they do not attach to a stable substrate (Bowden-Kerby, 2001; Kenyon et al., 2020; Lewis et al., 2022). While rubble can be generated by human-induced disturbances, it is also naturally generated on reefs.

Rubble is an instrumental part of the natural cycles on coral reefs of erosion and accretion, which influence reef sedimentary budgets (Lange et al., 2024; Nuñez Lendo et al., 2024; Rasser & Riegl, 2002). Rubble can naturally collect in depositional areas such as grooves in a spur-and-groove system, where corals are normally absent (Rogers et al., 2013; Shannon et al., 2013). It can support the recovery and accretion of the reef through the transport and contribution of live fragments to other areas, and can contribute to the structural development of shallow fore-reefs and reef crests through cementation over time. Rubble beds also support a high biodiversity of sessile and motile marine invertebrates, which are integral to reef food webs (Wolfe et al., 2023; Wolfe et al., 2021), and vertebrates, including the larval stages of certain fish species (Laurie Raymundo, University of Guam, pers. comm.).

Figure 1. Close-up photo of coral rubble taken on Heron Reef, Great Barrier Reef. Source: Tania Kenyon, The University of Queensland

The morphology and sizes of rubble pieces vary, depending on the type and magnitude of the disturbance, as well as the pre-disturbance coral species composition at the site (**Figure 2**) (Wolfe et al., 2021). The majority of rubble originates from fast-growing branching corals, such as *Acropora spp.*, as they are often more vulnerable to bleaching and physical damage compared to other morphologies such as massive corals (Loya et al., 2001; Scoffin, 1993). The breakage of *Acropora* corals results in rubble pieces with branching morphologies, though this can change over time as pieces are further broken down. Environmental factors, including hydrodynamics and depth, also play a role in shaping rubble characteristics (Wolfe et al., 2021).

For example, the pattern and intensity of damage caused by disturbances can vary across depth gradients (Harmelin-Vivien & Laboute, 1986; Woodley et al., 1981), resulting in rubble with different sizes.

At present, there are no standardised measures to quantify and describe rubble, as the interpretations of rubble vary across studies (Wolfe et al., 2021). However, readers can refer to Kenyon et al. (2024) for a detailed analysis of on rubble typologies on the GBR. Typically, rubble pieces measure between 1 and 10 cm in length in shallow reef rubble beds (Kenyon et al., 2023a; Wolfe et al., 2021), but can range from just slightly larger than sand (over 2 mm) to large boulders (over 1 m).

Box 1

The biodiversity of rubble beds

Although they may appear "dead" at first glance, rubble habitats are a hotbed of biodiversity. Rubble beds host a diverse range of cryptic organisms and microbial communities that contribute to various essential ecosystem functions (Wolfe et al., 2021). In fact, over 95% of the surfaces and framework cavities of rubble can be occupied by sessile organisms, which is 8 times greater than what is visible on the surface.

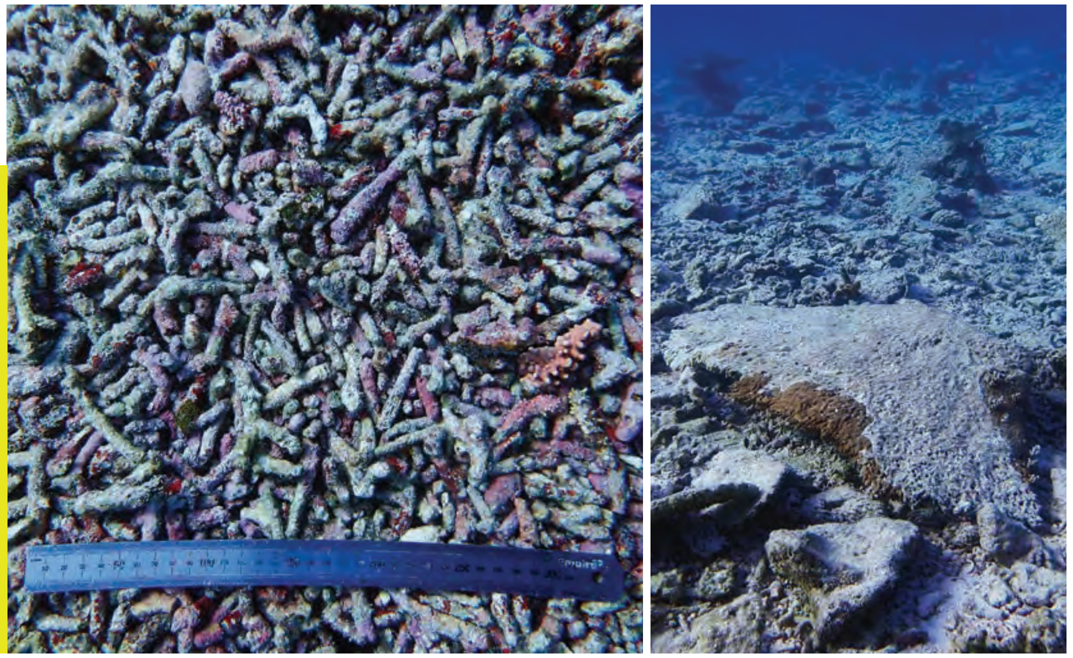


Figure 2. Rubble beds with pieces of vastly different morphologies – small and mostly unbranched rubble (left), and plate rubble (right). Source: Tania Kenyon, The University of Queensland

Why does rubble cause problems for coral reefs?

One of the key factors influencing reef recovery is the condition of the substrate, including but not limited to its stability (Gouezo et al., 2021).

The stability of rubble substrates is influenced by numerous factors (see section **Factors affecting rubble stabilisation**). When rubble beds are stable (e.g., through low hydrodynamic energy and/or interlocking between pieces), they can serve as a foundation for new corals to settle on and undergo sustained growth (Yadav et al., 2016). Rubble pieces can be highly desirable for coral recruits, offering sheltered crevices and a biofilm that encourages settlement (Babcock & Mundy, 1996; Edmunds et al., 2004; Tebben et al., 2015).

Nevertheless, even if pieces are relatively stable, some rubble beds may have environmental and ecological conditions that are unsuitable for coral survival.

For example, in a study conducted on Heron Reef, coral settlement was lower on rubble recruitment tiles in loose rubble habitats compared to interlocked rubble and hard carbonate areas, even when the rubble pieces themselves were stabilised (Roima Paewai-Huggins, The University of Queensland, pers. comm.) Rubble beds, regardless of stability, can have differing levels of deposited sediment, turbulence, predation and/or algal competition compared to adjacent hard carbonate reef areas (Kenyon et al., 2023a). For example, free-stream flow can be higher but with less turbulence over rubble, as the reduced structural complexity of rubble creates less drag (Guihen et al., 2013). This reduction in turbulence can in turn result in higher deposited sediment loads in rubble beds. Predation can also be higher in rubble areas than adjacent reef following disturbances (Lewis & Wainwright, 1985; Wilson et al., 2006). Ecological phase-shifts, for example, from coral-dominated to algal-dominated states, are possible in these rubble beds even when pieces are stable (Kenyon et al., 2023a).

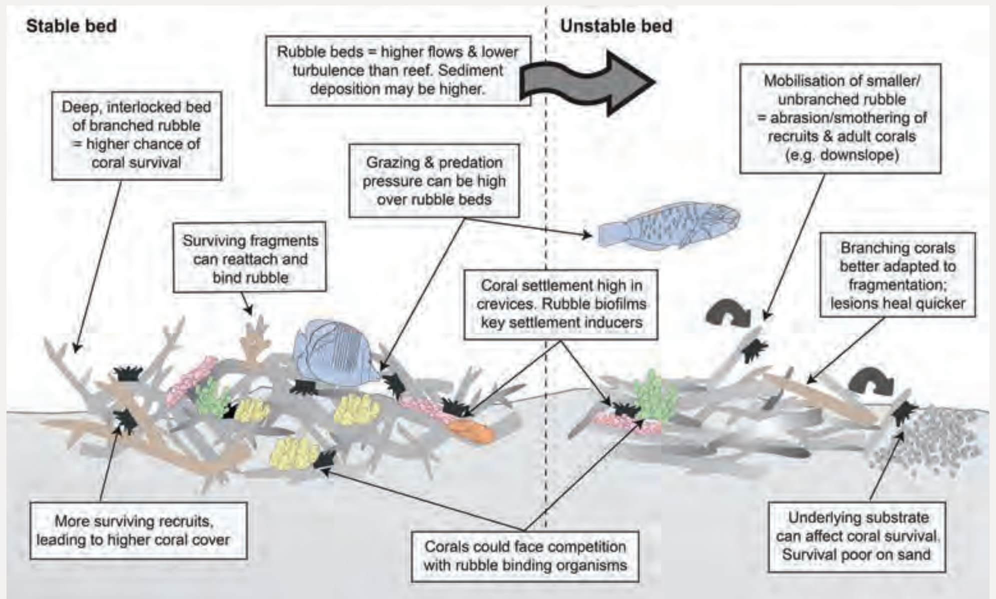


Figure 3. Consequences of rubble generation, mobility, and binding for coral recruitment. Adapted from "Coral rubble dynamics in the Anthropocene and implications for reef recovery" by Kenyon et al. (2023a).

Clearly, inhibited recovery in rubble beds can be attributed not only to mobility but also other environmental and ecological factors.

Rubble beds can become 'problematic' when pieces remain unstable for an extended period, hindering coral settlement and growth. While outcomes for stable rubble beds are more nuanced, the presence of 'loose' (not interlocked) and mobile rubble beds in areas where they should not be always spell slow reef recovery following disturbances (Figure 3). The surfaces of loose rubble are typically dominated by turf algae and macroalgae, which can hinder the growth of crustose coralline algae (CCA) (Yadav et al., 2016).

As coral larvae are drawn to CCA through chemical and microbial signals, recruits may be less likely to settle on loose rubble pieces than other substrates (Harrington et al., 2004). Even if recruits do successfully settle onto loose rubble beds, frequent mobilisation causes abrasion, sand scour, and smothering, reducing survival (Brown & Dunne, 1988; Clark & Edwards, 1995). In the Maldives, survival rates were lower for corals settling <0.5 m above the seabed due to sand scour (Clark & Edwards, 1994).

Box 2

What is coral recruitment and why does it affect resilience?

Coral recruitment refers to the process of new juvenile corals joining the reef community (Edwards, 2010).

It is a three-stage process involving:

1) the arrival of larvae from spawning events or brooding,
2) the settlement and attachment of juveniles and/or fragments, and;
3) the growth of settled juveniles and/or fragments.

Numerous small (0.5-5 cm) corals on the reef are indicative of a healthy recruitment process. Although, in rubble areas, larger corals might still be absent, suggesting that corals are arriving and settling to the rubble area, but not surviving beyond a certain size/age.

If recruitment and survival are insufficient to replace dying adult colonies, coral cover will decline over time and the coral community may change. The resilience of a coral reef ecosystem is influenced by coral recruitment. Ecological resilience is broadly defined as the ability of a system to absorbchanges and persist in the face of disturbances (Holling, 1973). Coral reefs with higher recruitment rates are more resilient because they can recover faster from disturbances. Processes that promote, enhance, and accelerate recruitment improve the resilience of coral reefs and are critical for the conservation and management of coral reefs in the wake of climate change (Anthony et al., 2015)

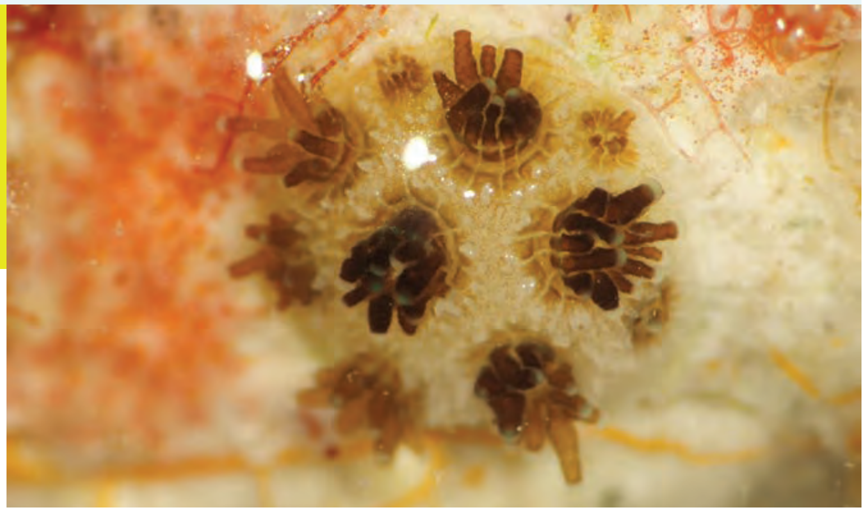


Figure 4. *Acropora spp.* recruit of approximately 1 mm in diameter observed under a microscope. Source: Roima Paewai-Huggins, The University of Queensland

In addition to the impacts on attached coral recruits, live coral fragments in the rubble bed also experience mortality or stunted growth owing to frequent mobilisation and abrasion (Kenyon et al., 2020). Kenyon et al. (2020) demonstrated that for fragments of both *Porites rus* and *Pocillopora verrucosa*, proportions of bleached and dead tissue increased over time when frequently abraded, and all fragments died from smothering after five days overturned into sand. Corals that are growing downslope from loose rubble beds can be smothered by rubble rolling down the slope (Harmelin-Vivien, 1994). As a result, these 'loose', mobile rubble beds create a significant bottleneck for reef recovery and, in many cases, persist in this state for decades or even centuries (Dollar & Tribble, 1993; Fox et al., 2003; Riegl, 2001).

Overall, our understanding of coral recruitment dynamics in rubble beds indicates that interventions are likely to be necessary if rubble beds are:

1) unstable, and;
2) if conditions are unfavourable for coral survival in the bed, regardless of stability (e.g., where sand may smother newly settled corals).

On the other hand, if rubble remains stable, and conditions favour coral settlement, growth and survival, there may be no need for intervention, as the reef has the potential to recover naturally on its own.

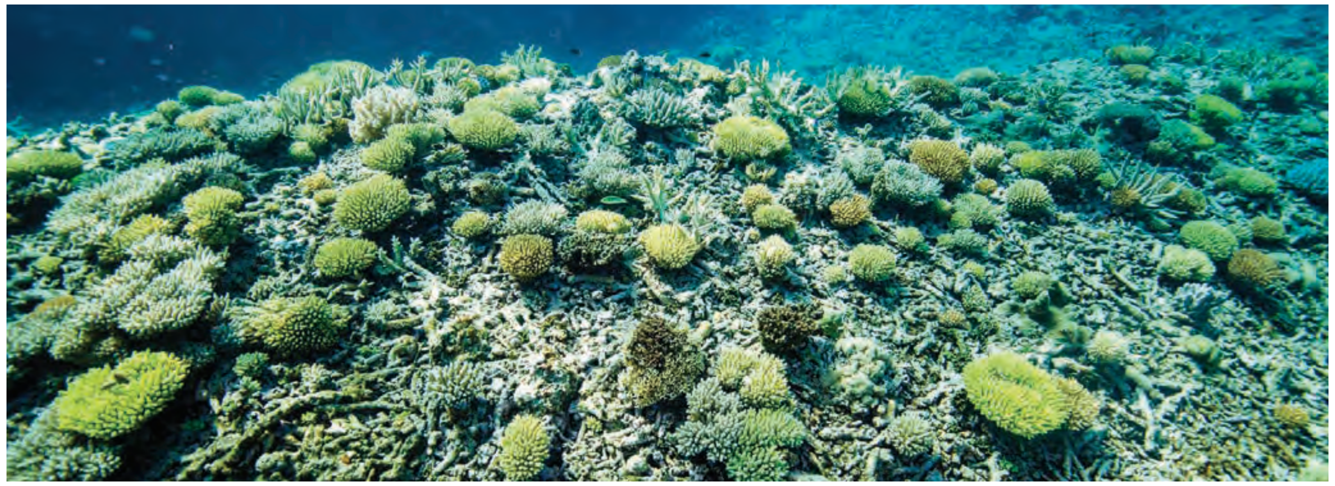


Figure 5. Live corals attached onto rubble beds. Source: Peter Mumby

Types of rubble beds

Despite the absence of a universal standard for measuring individual rubble pieces or defining rubble beds, ongoing research aims to develop metrics for characterising rubble beds (Paewai-Huggins, in prep.) and classifications to support management (Dodgen, in prep.).

To make appropriate whether rubble beds should be restored, it is critical to know whether the bed is:

- **an undisturbed persistent** feature within a reef, not associated with reef degradation,
- **a disturbed transient** feature formed by a disturbance (e.g., cyclones, ship groundings, blast fishing, etc.) that will naturally recover to its pre-disturbance state; or
- **a disturbed persistent** feature formed by a disturbance that will not return to its pre-disturbance state.

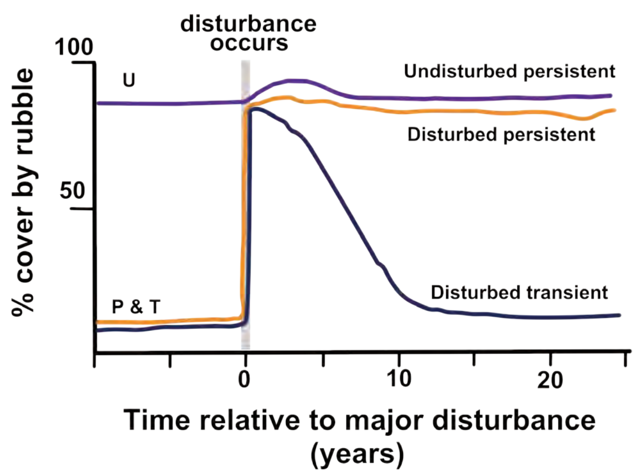
Undisturbed persistent rubble beds

Undisturbed persistent rubble beds are those that have existed for a long time without any known sources of disturbance that caused their formation. This type of rubble should not be considered an indicator of degradation or poor reef health. Just as a healthy forest will always contain some dead and dying trees, coral reefs will always have areas of rubble.

Undisturbed persistent rubble often occurs in the following areas:

- At the seaward edge of reef slopes, referred to as the fore reef talus, where it collects as dead coral fragments are washed down-slope (Hughes, 1999). However, disturbed rubble beds can exist in these locations. If there is prior knowledge to indicate high coral cover in this zone, and that area is now rubble, it is likely to be disturbed.
- In the back reef or reef flat, behind reef crests, where fragments are washed by waves that crash over the reef crest and can form (e.g., rubble subzone of Jell and Webb (2012), rubble-dominated reef flats at One Tree Island, Shannon et al. (2013); Thornborough (2012)).
- Within the grooves of spur and groove formations (Duce et al., 2016)

Figure 6. Trends for rubble cover over time for undisturbed persistent (U), disturbed transient (T), and disturbed persistent (P) rubble beds. Importantly, U would exist independent of a disturbance due to local conditions (exposure to water energy, slope, reef community composition), whereas T and P are formed because of a disturbance. P undergoes an ecological phase shift to ongoing high rubble cover, whereas T has a trajectory towards recovery to pre-disturbance levels of rubble cover. Source: Tanya Dodgen, Queensland University of Technology



Importantly, areas of undisturbed persistent rubble are unlikely to have supported high coral cover in the past, and therefore do not indicate any long-term decline in coral cover or reef growth. If restoration were undertaken in these areas, it would likely get buried by on-going rubble deposition. Further, undisturbed persistent rubble is a unique and important habitat for a diverse range of organisms, including small crustaceans and cryptic fish, which are key players in reef trophodynamics, and sessile flora and fauna including turf algae, crustose coralline algae, sponges, ascidians, serpulid worms, and anemones, among others (Brandl et al., 2018; Kenyon, 2021; Kramer et al., 2014; Wolfe et al., 2021). For these reasons, it is **not recommended** to treat undisturbed persistent rubble as a restoration target.

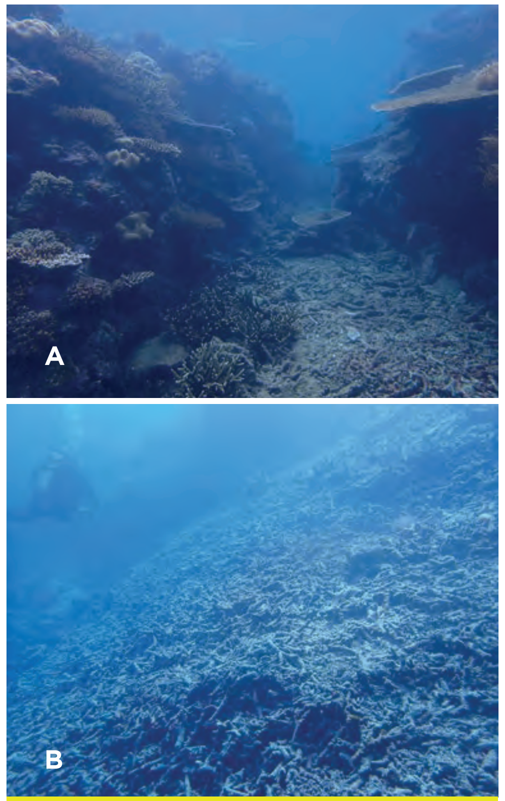


Figure 7. Above: Photos of undisturbed persistent rubble beds **(a)** in a groove of a spur-and-groove system (Moore Reef, GBR) and **(b)** at the foot of a forereef slope as talus (Davies Reef, GBR). Note that undisturbed persistent rubble beds are largely determined by geomorphology. Source: Tanya Dodgen, Queensland University of Technology

Disturbed transient rubble beds

Unlike undisturbed rubble, disturbed rubble beds - whether transient or persistent - are formed by a disturbance (or combination of disturbances). However disturbed transient rubble beds show evidence of recovery within a year or two following a disturbance and can recover without human intervention within 5 to 10 years.

For example, Shinn (1976) recorded coral reefs in Florida rapidly recovering from being "severely devastated" by Hurricanes Donna (1960) and Betsy (1965). Following both hurricanes, the observed reefs regrew within two years, after which the signs of storm damage were almost unnoticeable. Rubble generated by hurricanes in Hawaii and the Florida Keys was also observed to recover to pre-disturbance levels of coral cover within less than a decade (Dollar & Tribble, 1993; Shinn, 1976). Fossil records in Jamaica provide examples of ancient reefs that went through several cycles of destruction and re-growth, showing that reefs were resilient to multiple disturbances over time (Perry, 2001). Like undisturbed persistent rubble, disturbed transient rubble can confer environmental benefits. For example, storms have been observed to expand coral cover into new locations through the transport of rubble, including living coral fragments, to new sites (Shinn, 1976). For further description of disturbed transient rubble beds, see **"Natural rubble bed recovery"** section.

If a reef is likely to recover without intervention within 1 to 10 years of a disturbance, investing in restoration in these locations may be unnecessary. Ideally, one would have information about coral cover prior to an observed disturbance to be able to monitor an area and say whether it is on a recovery trajectory (see section **Monitoring and evaluating project success**). Intervention, may, however, speed the recovery of disturbed transient beds, which may be desirable in a popular tourist site for example.

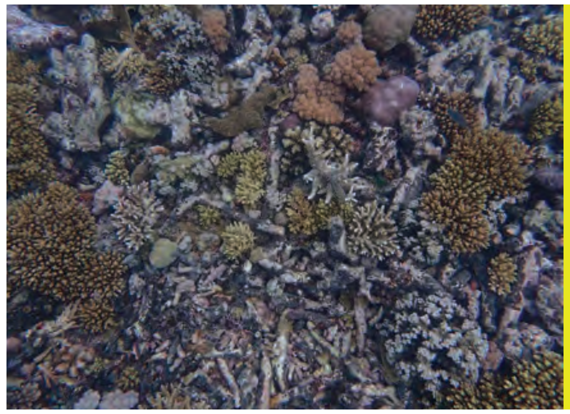


Figure 8. Photo of a disturbed transient rubble bed. Hard corals can be observed growing and binding on the rubble bed. Photo taken on Moore Reef, GBR near the Reef Magic Pontoon in January 2024. Source: Tanya Dodgen, Queensland University of Technology

Disturbed persistent rubble beds

In contrast to transient rubble beds, disturbed persistent rubble beds persist for decades or represent a "phase shift" where an area that was once dominated by living reef has permanently lost hard corals.

Examples include a blast-fished reef in Indonesia, which showed no signs of recovery over 17 years of observation (Fox et al., 2019). Similarly, blast-fished Acroporid reefs in the Philippines showed no signs of hard coral recovery a decade after blast fishing was stopped (Cruz et al., 2014). Reefs in the Caribbean Sea have undergone repetitive increased disturbance regimes since the 1990s. Where overfishing of herbivores is high, many have undergone a phase shift towards macroalgal domination (Jackson et al., 2014). For more examples of disturbed persistent rubble beds, refer to **Table 1** in the **"Frequent disturbances, slow recovery"** section.

Disturbed persistent rubble is an indicator that an area of reef could benefit from active restoration. If the conditions that caused the reef to degrade in the first place can also be improved (e.g. ceasing blast fishing or improving water quality), stabilising rubble can be an effective way to encourage coral re-growth and recovery (e.g. Fox et al. (2019); Fox et al. (2005)).

Distinguishing between disturbed transient and disturbed persistent rubble

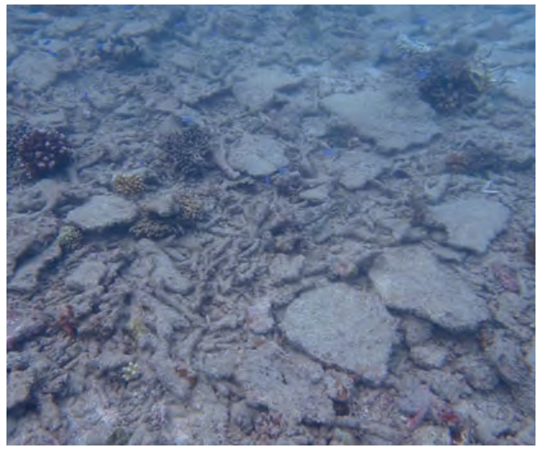
At present, it is challenging to predict whether a disturbed rubble bed will follow a transient or persistent trajectory, because these types of rubble beds can only be accurately differentiated through long-term monitoring. For now, we must rely on monitoring to determine whether rubble shows signs of recovery over time as a single observation cannot indicate progress. Further research is needed to predict rubble bed trajectories reliably based on surveys conducted at a single point in time (see section **Monitoring and evaluating project success**).

Distinguishing between disturbed transient and persistent rubble beds can optimise resource allocation, directing efforts to persistent beds, which will not recover without human intervention. While long-term monitoring is the gold standard, certain metrics can provide clues to distinguish between these types. Using rubble-specific metrics (see rapid rubble assessment in **Appendix A** and detailed rubble assessment in **Appendix B**) to study rubble bed types, linking their physical characteristics with c oral growth and survival, can help to assess natural recovery potential and guide decision-making. For example, rubble beds that are very thick, with larger rubble pieces, and evidence of live corals, are much more likely to recover naturally, as shown on the GBR (Kenyon et al., 2024).

Left: Figure 9. Photo of a disturbed persistent rubble bed. The rubble pieces are relatively small, and few hard corals can be observed. Photo taken on Moore Reef, GBR near the Reef Magic Pontoon in March 2024.

Right: Figure 10. Rubble bed resulting from Cyclone Jasper in December 2023. At the time of writing, in July 2024, it is unclear whether this disturbed rubble bed is transient or persistent. More time is needed to determine its trajectory. In the early post-disturbance stage, disturbed transient and persistent rubble beds can look similar. Photo taken on Moore Reef, GBR near the Reef Magic Pontoon in March 2024.

Source: Tanya Dodgen, Queensland University of Technology



Emerging trends of rubble generation and persistence on coral reefs

Coral reefs face growing threats from climate change, with disturbances becoming more frequent and intense (Hoegh-Guldberg, 1999; Hoegh-Guldberg et al., 2007; Hughes et al., 2018; Hughes et al., 2003).

Disturbances including extreme weather events, rising sea surface temperatures, and human activities such as ship groundings and blast fishing substantially damage coral reefs, leading to their degradation and the generation of vast amounts of rubble (Cheal et al., 2017; Hughes et al., 2017; Riegl, 2001). **Table 1** presents case studies of disturbance-generated rubble fields and shows how, after years or decades, there are little to no signs of recovery.

Table 1. Case studies of rubble fields and their effects on reef recovery (Kenyon et al., 2023a)

Location	Disturbance	Time after disturbance (years)	Effects on reef recovery	References
North Malé Atoll, Maldives	Coral mining	16	Low coral cover (0.5%) at mined sites that are dominated by rubble as opposed to control sites (11-60%). Rubble beds also experience low coral and reef fish diversity.	Brown & Dunne (1988)
West coast of the island of Hawaii	Intense storm in 1980	12	Coral cover in disturbed sites only increased by 5% from 10% in 12 years. The authors estimated that the reefs' recovery to pre-storm conditions would occur within a timeframe of 40 to 70 years, depending on whether the growth follows an exponential or linear pattern.	Dollar & Tribble (1993)
Komodo National Park and Bunaken National Park, Indonesia	Past chronic blast fishing	around 7-50	Low coral cover (4.7%) in rubble beds and no significant natural recovery observed over 5 years of monitoring since 1998	Fox et al. (2003)
Calagcalag Marine Protected Area, central Philippines	Blast fishing	22	Low hard coral cover (6-10%) and coral recruit survival rates (6%) were observed in rubble beds, contrasting with the 40-47% coral cover in reference sites.	Raymundo et al. (2007)
Biscayne National Park, Florida, USA	Ship grounding	13-17	Lower juvenile coral density (0.34-1.03/m^2) were observed in rubble beds, contrasting with the reference sites (2.0–6.5/m^2).	Cameron et al. (2016)
Bahia de Tallaboa, Puerto Rico	Ship grounding	7	Coral recruit density (0/m^2) and survival (0%) were consistently lower on the rubble site compared to the reference site (density: 7/m^2; survival: 77%).	Viehman et al. (2018)
Malakal Bay, Palau	Crown-of-thorns starfish outbreak in 1979	25	Coral cover remains low (13%) in unstable rubble beds.	Victor (2008)
Seychelles	Bleaching event in 1998	14	Low adult coral cover (10%) in unstable rubble beds compared to nearby healthy sites (30%) despite having high juvenile coral density.	Chong-Seng et al. (2014)
Havannah reef, Great Barrier Reef, Australia	Bleaching and cyclones from 1998 to 2000	6	Significantly lower juvenile coral persistence (10%) in unconsolidated rubble compared to algal-dominated rubble beds and bommie habitats (57%).	Johns et al. (2018)
Three central atolls of South Malé, Felidhoo and Ari, Maldives	Bleaching event in 1998	8	Hard coral cover ranged from 12% to 37%, still significantly lower compared to pre-disturbance levels. There was also a high proportion of rubble and sand (15- 65%).	Lasagna et al. (2008)

Ship groundings

The rise in maritime traffic contributes to an increased risk of ship groundings, escalating the threat to coral reefs.

Maritime traffic worldwide has quadrupled between 1992 and 2012, with the most significant growth in the Indian Ocean and Chinese seas (Tournadre, 2014). Asia is one of the world-leaders in maritime freight, with ports loading about 42% of total goods worldwide. The Oceania region accounted for 1.4 billion tons of loaded and discharged cargo in 2021 alone (UNCTAD, 2024). Although the COVID-19 pandemic caused a temporary decline, post-pandemic seaborne trade is rebounding and projected to grow at 2.1% annually from 2024 to 2028 (United Nations Conference on Trade Development, 2023). The increase in ship traffic and seaborne trade amplifies the potential impact on marine ecosystems through ship groundings, animal collisions, and pollution.

Vessel groundings on coral reefs can cause different types of damage, stemming from activities such as improper anchoring, running aground, vessel movement while aground, and collateral damage during salvage attempts (Challenger, 2006) (**Figure 11**– see more damaged substrate photos in **case study 1**). The extent of damage is determined by factors including speed on impact, size and draft of the grounded vessel, and the reef environment, such as the topography and depth, as well as the benthic composition. Upon contact with the reef, the vessel may damage or destroy coral colonies, crack reef rock structures, and flatten habitats, quickly generating rubble. Additionally, grounded vessels can introduce chemical contaminants including antifoulants (**Figure 11c**), fuel or oil onto substrates, which may inhibit coral growth and settlement (Negri et al., 2002), further hindering reef recovery. A recent environmental impact study recommended efforts for the complete removal of damaged reef material following ship groundings due to toxic contamination with antifoulants (Advisian, 2020).

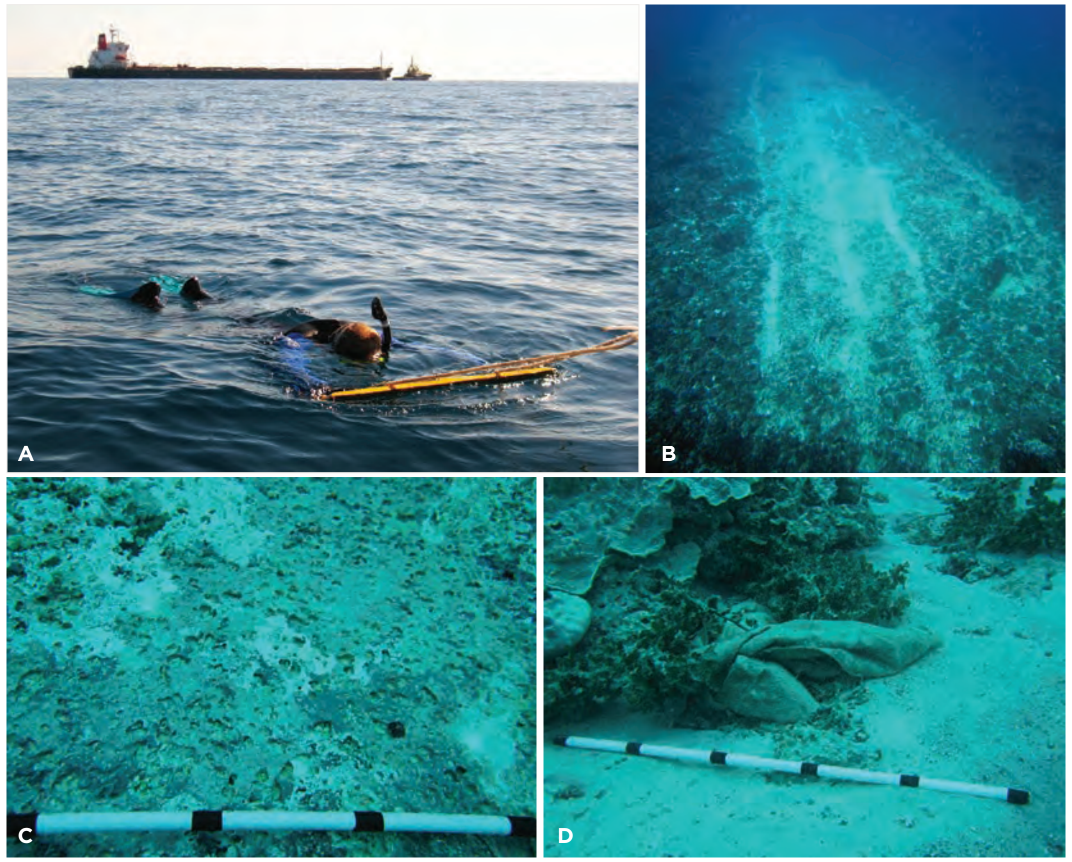


Figure 11.
Photos showing:

a) A researcher using a manta tow to view damage to the area near the final resting location of the Shen Neng, on Douglas Shoal in background;

b) Anchor damage to substrate close to the initial grounding site;

c) Antifouling paint on reef; and

d) Material debris, in the area which was the final resting location of ship.

Source: © Commonwealth of Australia (Reef Authority) 2012

Photographer: P. Marshall

Many countries have established legal mechanisms for ship groundings, often covering damage assessments, restoration plans, and monitoring. These measures ensure that responsible parties are held accountable for the resulting damage and will fund restoration and/or remediation efforts. For example, on the GBR, there is a notable risk of ship groundings due to heavy maritime traffic to specific ports (**Figure 12**). Australia's economy relies heavily on shipping, and the increase in bulk cargo exports has led to more international vessels navigating the sensitive waters of the GBRMP, Torres Strait, and the Coral Sea, heightening the risk of ship-sourced pollution and damage (AMSA, 2014). Past reporting has indicated that foreign-owned bulk carriers have taken shortcuts within the GBR for efficiency, increasing the risk of accidents and environmental damage (Connolly & Henley, 2010).

In order to mitigate these risks within the GBRMP, the Reef Authority collaborates with Maritime Safety Queensland (MSQ) and AMSA to regulate ship activities, lift standards, and maximise compliance with regulatory requirements through a series of preventive and preparatory measures and response actions (GBRMPA, 2022c). This extensive collaborative effort includes measures such as the ReefRep and ReefVTS systems, Designated Shipping Areas, mandatory grounding reporting, the National Plan for Maritime Environmental Emergencies,
and the recognition of the area as a Marine Park (1975); a World Heritage Area (1981) and a Particularly Sensitive Sea Area (IMO 1990) (AMSA, 2020, 2024; GBRMPA, 2022c; MSQ, 2024).

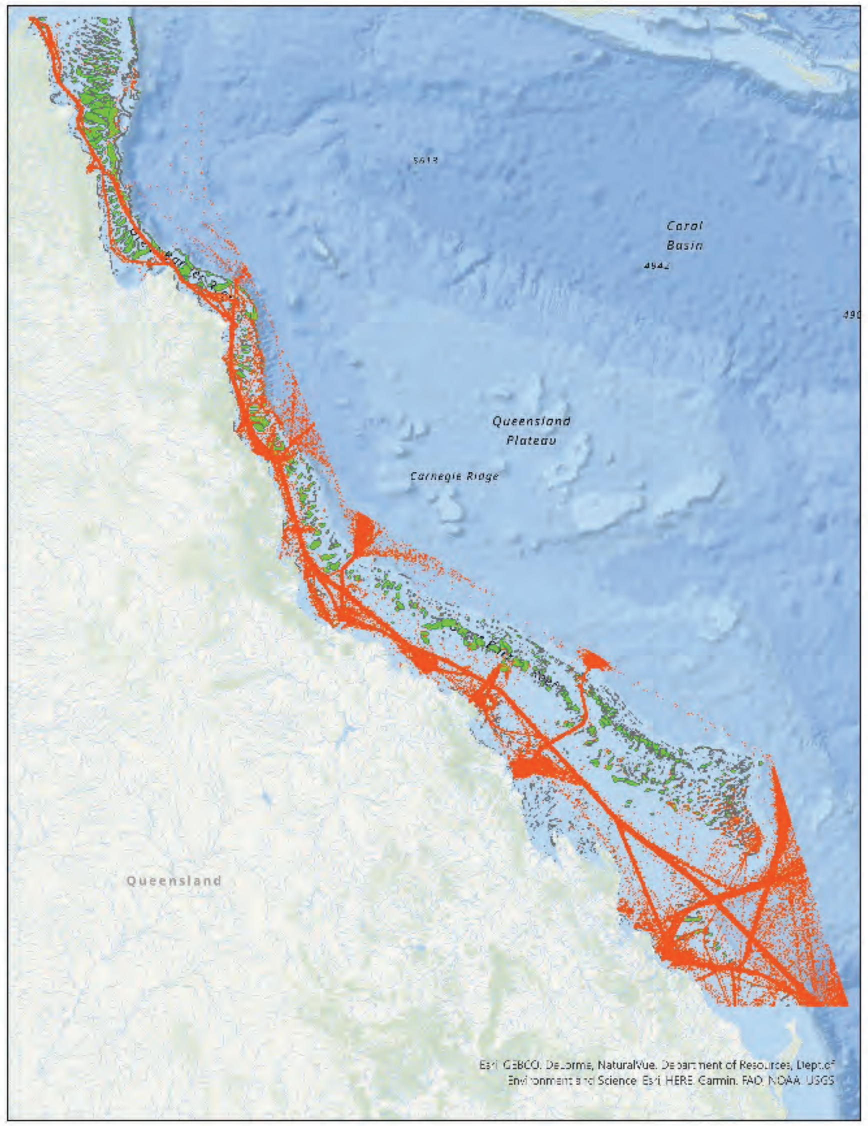


Figure 12.
Ship tracks (red) within the Great Barrier Reef Marine Park. The shipping tracks represent total monthly records from 2019 to 2021, with each point within the dataset representing a vessel position report. Data extracted from AMSA Track Data 2019-2021.

Source: Julio Salcedo-Castro

Blast fishing

Blast fishing, also known as fish bombing or dynamite fishing, is a destructive practice that is widespread in Southeast Asia and some other parts of the world, despite being illegal (Fox et al., 2000; Fox & Caldwell, 2006).

This method has been adopted extensively as a result of rapid population growth in these regions, where food security and economic necessity over-rides consideration of environmental sustainability. The main ingredients for bombs include fertilizers and pesticide pellets, which are accessible and inexpensive (McManus, 1997). A single fish bomb can yield up to 45 kg of fish, nearly 24 times more than the catch from traditional hook-and-line methods (Kissol, 2012; Wood & Ng, 2016; Wood et al., 2004). It is a low-cost, low-effort way, often practiced by less experienced fishers as a quick means of boosting short-term catches for food and earn quick money.

However, the practice of using homemade bombs destroys the reef framework, generating vast amounts of rubble. In Tun Sakaran Marine Park (Sabah, Malaysia), for example, an average of at least 40 blasts was recorded daily, which led to the destruction of 75 km of reefs in a year (Robin Philippo, Tropical Research and Conservation Centre (TRACC), pers. comm.). Sites damaged by bombs made from pesticide pellets can be completely devoid of life, with no signs even of algae or other early colonisers (Kee Alfian Bin Abdul Adzis, MISC Berhad, pers. comm.).

Despite awareness of this issue, law enforcement struggles to prosecute perpetrators due to the difficulty in detecting and linking the crime with the perpetrators (Abdul Adzis, pers. comm.).

Word-of-mouth does not constitute sufficient evidence, and individuals may also be deterred from reporting due to the fear of potential retaliation from fishers. Even when incidents are reported through official channels, the extensive paperwork required for enforcement discourages people from pursuing the matter. Furthermore, fishers have adopted strategies such as dropping bombs in deeper waters to avoid detection and using less explosives to ensure that blasted fish are indistinguishable from traditionally fished ones to a prospective buyer at market (Abdul Adzis, pers. comm.).

Geopolitical complexities further complicate the issue of blast fishing. Fishers, many of whom come from marginalized or stateless communities such as the Bajau (also known as Sea Gypsies), may source materials from various countries and travel across borders, making regulation difficult. Without formal recognition from their governments, these communities face precarious economic conditions and denied access to legitimate work, pushing them toward destructive fishing practices as a quick way to provide for their families. As such, there is an urgent need for enforcement mechanisms that not only address illegal fishing practices but also consider the underlying socio-economic and geopolitical drivers. Effective cross-border collaboration is also needed, especially considering the possibility of organised efforts of bomb production and distribution networks. Although United Nations Sustainable Development Goal 14 aims to effectively end destructive fishing practices by 2020, progress is not advancing at the necessary speed or scale, highlighting the need for coordinated global action (United Nations, 2024).

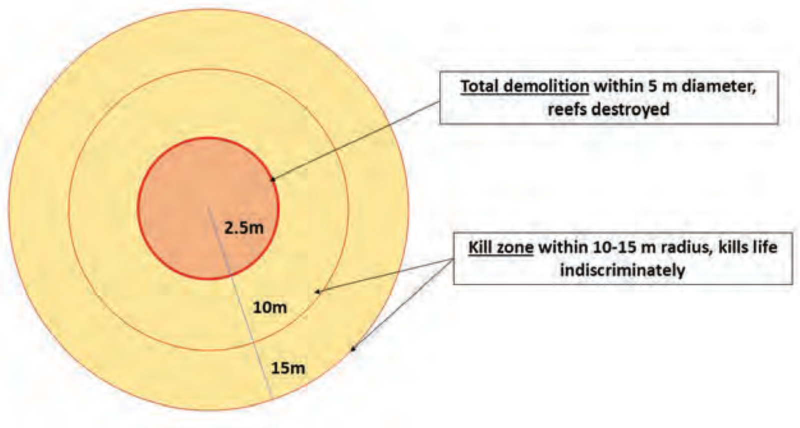


Figure 13. Blast fishing and the damages it causes. Source: Robin Philippo, TRACC Borneo; (McManus, 1997)

Extreme weather events

Extreme weather events like hurricanes and tropical cyclones, which are projected to intensify due to climate change (Cheal et al., 2017; Knutson et al., 2020), are key drivers of rubble generation (Scoffin, 1993).

Cyclone trends vary by region, but most studies predict a decrease in frequency and a higher proportion of intense cyclones (Knutson et al., 2020). When a storm crosses a coral reef, storm-induced waves and currents exert significant mechanical forces on coral colonies, breaking them into rubble (Harmelin-Vivien, 1994). Powerful forces can even tear apart the reef matrix itself. Dislodged corals and rubble pieces can be transported to other parts of the reef where they can cause further damage. Shallower areas are more susceptible to mechanical damage, yet severe storms can also impact deeper areas by deepening bottom current velocities, thus affecting a larger depth range. In addition to mechanical damage, storm-associated heavy rainfall and flooding can also lower salinity, increase water turbidity, and nutrient levels (Harmelin-Vivien, 1994).

These conditions can lead to coral mortality and eventual break down into rubble. These weather events can thus cause patchy damage or total destruction of reefs, leave behind rubble fields of varying size (Highsmith et al., 1980; Woodley et al., 1981).

As well as generating rubble, extreme weather events can mobilise and re-distribute pre-existing rubble fields, making these areas unstable. The speed of water movement near the sea bed, referred to "near-bed wave orbital velocity" (*U*) can increase significantly during storms. During a cyclone, *U* can reach 13 m/s, and very large, boulder-sized rubble can be thrown from reefs onto shore (Etienne & Paris, 2010; Hubbard, 1992; Keen et al., 2004; Madin, 2004; Nandasena et al., 2011; Tsutsumi et al., 2000). Thus, smaller rubble pieces will most certainly be mobilised during these events, depending on their level of interlocking and binding (also see section **Factors affecting rubble stabilisation and mobilisation**).

Figure 14. Broken coral, primarily elkhorn coral (*Acropora palmata*), near San Juan, Puerto Rico after Hurricanes Irma and Maria in 2017. Source: Sean Griffin

Marine heatwaves

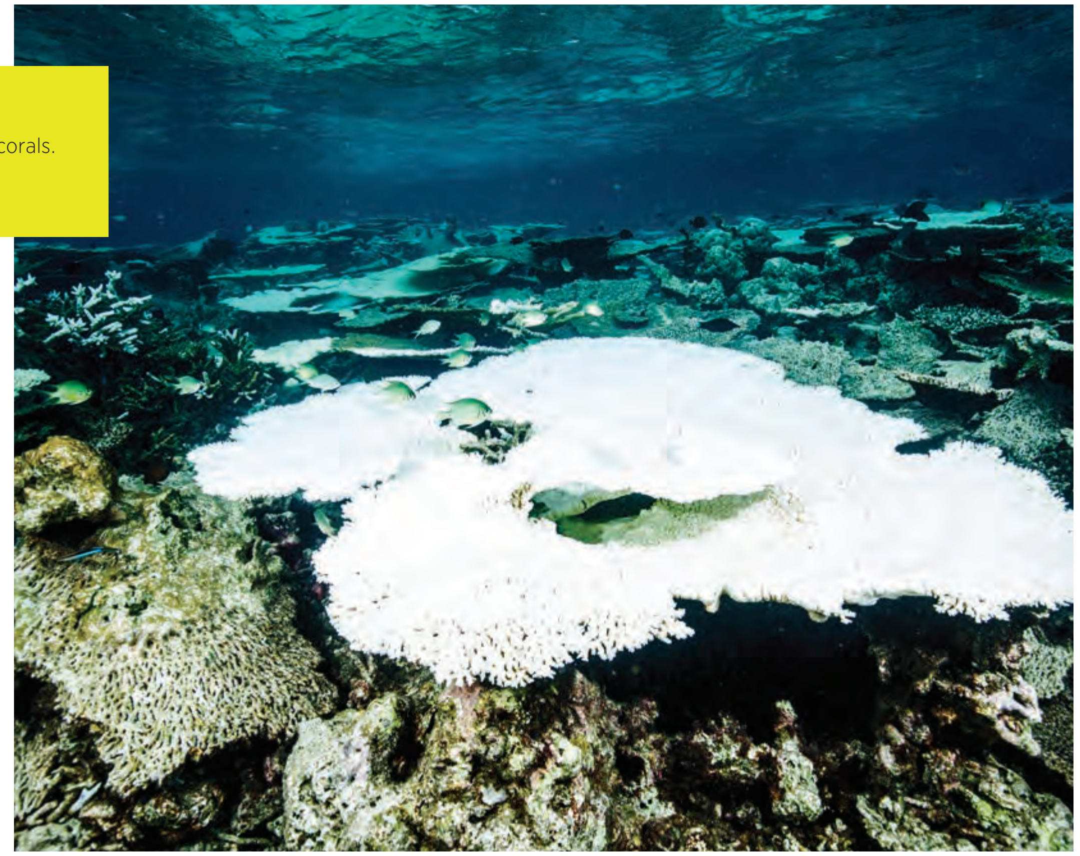
Marine heatwaves can cause mass coral bleaching events and widespread coral mortality (Eakin et al., 2019; Hughes et al., 2018; Hughes et al., 2017; Sully et al., 2019).

Globally, bleaching events resulted in the loss of an estimated 11,700 km^2 of reef area from 2009 to 2018 (Edwards et al., 2024). The intensity and frequency of marine heatwaves is increasing, with many regions expected to experience constant heat by late 21st century (Oliver et al., 2019). As a result, mass bleaching events are becoming more frequent, with widespread impacts to reef ecosystems (Hoegh-Guldberg, 1999; Hughes et al., 2017).

Corals that die from bleaching can remain standing but are susceptible to bioerosion and fragmentation into rubble without the protection of the tissues (Leggat et al., 2019). Morais et al. (2022b) showed that ~80% of 143 colonies killed from bleaching had completely broken down within 60 months. This process of degradation contributes to the generation of large amounts of rubble following severe bleaching-related mortality events.

Mitigating climate change and ocean warming is crucial for reducing coral mortality and subsequent rubble generation from bleaching events. For example, a recent study showed that limiting global warming to 1.5°C above pre-industrial levels could reduce the frequency of mass bleaching events in the GBR to about three per decade, highlighting the potential for genetic adaptation provided that bleaching severity remains low (McWhorter et al., 2022b). Furthermore, climate refugia—local areas offering some relief from warming— are only effective until global temperatures rise beyond approximately 3°C (McWhorter et al., 2022a). Therefore, investing in emission reductions is crucial for minimizing rubble generation and ensuring the long-term health and resilience of coral reef ecosystems.

Figure 15.
Bleached colonies of table corals.
Source: Peter Mumby



Diseases and predation

Like bleaching, coral disease and predation contribute to rubble generation by killing corals that then break down over time.

Coral disease can cause lesions and tissue loss, impact coral reproduction and growth, and result in widespread mortality (Harvell et al., 2007; Loya et al., 2001). In some regions of the Caribbean, White Band Disease caused the dominant species, *Acropora cervicornis*, to be reduced from 70% coral cover in 1986 to 0% in 1993 (Aronson & Precht, 1997).

To date, 40 diseases have been identified worldwide in various ocean basins (22 in the Atlantic, 9 in the Indo-Pacific, and 9 in other oceans) and affect 200 species of reef-building corals (Morais et al., 2022a). Outbreaks are associated with both local stressors (e.g. poor water quality) and global stressors (e.g. rising global sea surface temperatures). Coral disease is projected to become more prevalent with rising temperatures. A conservative model predicts that 76.8% of corals worldwide will be diseased by 2100 under the business-as-usual climate projection (Burke et al., 2023).

Similar to coral diseases, predation by corallivores such as crown-of-thorns starfish (CoTS) and the snail, *Drupella spp.*, can also cause tissue loss, exposing the coral skeleton and making it susceptible to infection and degradation (Renzi et al., 2022). CoTS are endemic to the Indo-Pacific region and thus a natural part of the ecosystem. Yet, they are significant predators of reef-building corals and outbreaks can lead to substantial coral loss (Birkeland & Lucas, 1990).

The future of CoTS populations and their impacts are unclear. Rising sea surface temperatures and increased food availability from freshwater run-offs may favour CoTS (Uthicke et al., 2015), but long-term reductions in coral cover also reduce food availability (Castro-Sanguino et al., 2023). CoTS can acclimate to warmer conditions and change feeding preferences under altered conditions. A recent study showed that CoTS has increased performance at higher temperatures (~30°C), leading to population irruptions and increased coral predation (Lang et al., 2022). There are extensive efforts to control CoTS population, mainly through physical removal and lethal injections (Pratchett & Cumming, 2019). On the GBR, the Reef Authority's Crown of Thorn Starfish Control Program identified priority reefs for CoTS control and has culled over a million CoTS since its establishment in 2012 (Williamson, 2023).

Current efforts are projected to reduce the number of reefs affected by CoTS outbreaks by 50%–65% each year, which translates to an increase in healthy coral area in the GBR by 5-7% per decade (Castro-Sanguino et al., 2023). In places like the Maldives, Indonesia, and Japan, CoTS are killed routinely on resort reefs and popular tourist destinations (Uthicke et al., 2023). However, these efforts are often too small in scale to impact populations significantly.

Frequent disturbances, slow recovery

Degraded reefs that are dominated by rubble may require several years to centuries to fully recover (Alcala & Gomez, 1979; Dollar & Tribble, 1993; Riegl & Luke, 1999) (**Table 1**).

Yet, the intervals between disturbances (recovery windows) are shrinking, and widespread areas of rubble-dominated reefs with minimal coral growth could thus become more common.

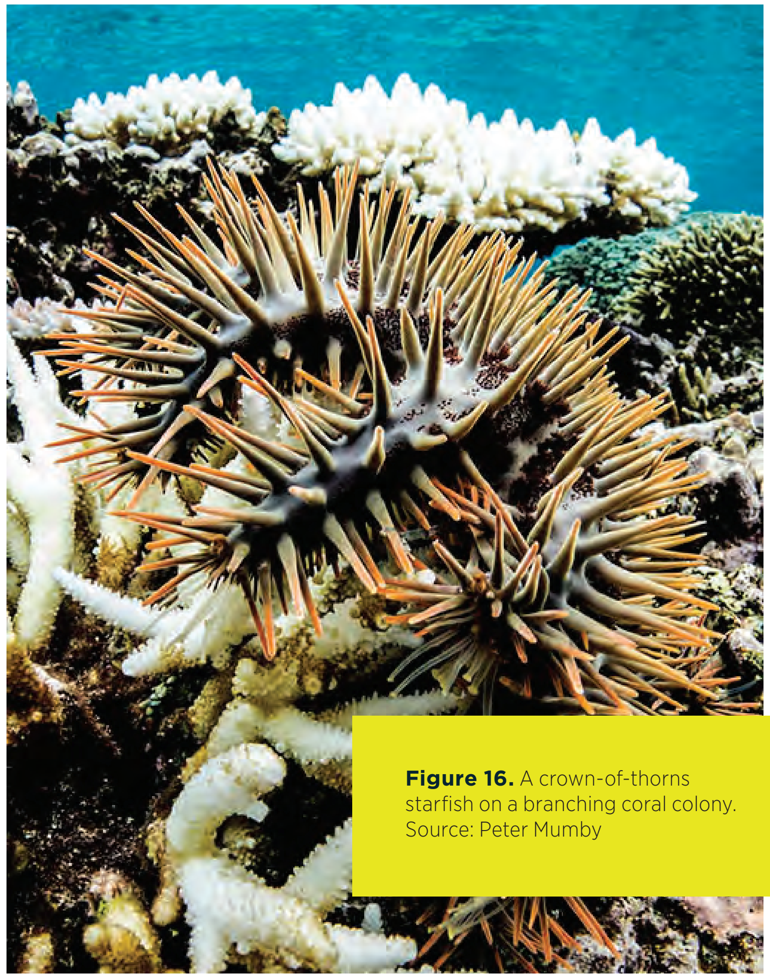


Figure 16. A crown-of-thorns starfish on a branching coral colony. Source: Peter Mumby

In focus:

How severe is the rubble problem on the Great Barrier Reef?

To address the rubble problem effectively, the first step is to gain a comprehensive understanding of its extent and distribution on the GBR.

We have a limited understanding of the current spatial extent of rubble at a regional scale in the GBR and across the globe. The identification of problematic rubble beds formed by acute disturbances (disturbed rubble beds) would require extensive field surveys that have not yet been implemented at the scale of the GBR. Remote sensing techniques, such as satellite imagery, have been employed to map benthic composition across the GBR (Roelfsema et al., 2018). This work categorised all reef areas shallower than 10 m as either rock, rubble, sand, or coral/algae. Remote sensing can identify some large, shallow rubble beds when they comprise a geological feature as they often do on reef flats. However, satellite remote sensing cannot distinguish rubble beds from hard substrate (live or dead) on the vast majority of reefs, and is, therefore, not an appropriate data source to evaluate the extent of rubble caused by reef damage. It follows that these maps cannot also distinguish between undisturbed and disturbed rubble beds (see section Types of rubble beds). Currently, remote sensing technology excludes rubble beds on reef slopes in deeper waters and rubble on inshore reefs due to visibility constraints. Rubble beds smaller than the map resolution are also excluded. Thus, rubble may be more prevalent than determined using these techniques, given its limitations. For now, in-water assessments are required to identify problematic rubble at smaller scales (site-specific or limited to individual reefs). Acoustic remote sensing (sonar) can provide information on seabed roughness and hardness (Bejarano et al., 2010) but its ability to map rubble beds explicitly remains in its infancy.

The GBR is subject to multiple environmental pressures, including more frequent CoTS outbreaks, marine heatwaves, and intense cyclones, which could increase its vulnerability to problematic rubble beds. In the past, CoTS outbreaks have led to a significant 42% decline in coral cover on the GBR between 1985 and 2012 (De'ath et al., 2012). Recent model simulations further estimated that coral populations declined by one-third from 2008 to 2020, driven by bleaching, cyclones, and CoTS predation, with less than 20% of the GBR maintaining coral cover above 30% by 2020 (Bozec et al., 2022). In addition, there have already been 5 mass bleaching events in recent years on the GBR in 2016, 2017, 2020, 2022, and 2024 (GBRMPA, 2022a, 2024). The cumulative impacts of bleaching events are concerning, as the short intervals between these events leave little time for corals to recover. On top of CoTS and bleaching, a study by Cheal et al. (2017) revealed significant ecological impacts following three closely spaced and unusually intense cyclones - Hamish (2009), Yasi (2011), and Ita (2014). Coral cover plummeted to record lows for up to 5 years post-disturbance and over a distance of at least 1500 km, and with the central-southern region suffering the most. Although coral cover at some locations in the Whitsundays and Townsville region has bounced back to higher levels than record pre-cyclones (AIMS, 2017, 2021), it dropped again due to the recent bleaching events (AIMS, 2023).

A recent study projected cyclone damage to GBR reefs from 2025 to 2100 under four climate scenarios (historical, optimal, expected, and pessimistic), identifying reef areas that are more susceptible to damage (Keppens, 2024; Keppens et al., in prep.). Cyclone-induced reef damage is categorized as moderate (30% of a reef's surface), high (50%), and severe (70%). The study finds that nearly all mid- and outer-shelf reefs will sustain moderate damage throughout the century across all scenarios, while inner-shelf reefs are more sensitive. By the century's end, over 75% of the GBR is expected to endure moderate reef damage. High reef damage is relatively minimal for inner-shelf reefs but affects most outer-shelf reefs over time. By 2100, the percentage of GBR reefs with high damage ranges from 25% under optimal conditions to 38% under pessimistic conditions. Moreover, outer-shelf reefs are projected to endure extreme damage, notably concentrated in the central region due to its location in the cyclone activity hotspot, persisting across most years and reefs even under optimal climate conditions.

By 2100, 6% to 11% of GBR reefs are expected to experience this extreme damage, depending on the climate scenario. Overall, the study underscores that the Great Barrier Reef will face significant cyclone impacts throughout this century, regardless of climate conditions, suggesting ongoing rubble generation and potential increases under pessimistic scenarios. It is important to note that there is a geographic bias in cyclone intensities towards the northern GBR, potentially overestimating the damage in that area. Efforts are currently focused on addressing this bias and optimization of the cyclone-induced damage function will be integrated in the near future (Maurie Keppens, Ghent University and The University of Queensland, pers. comm.).

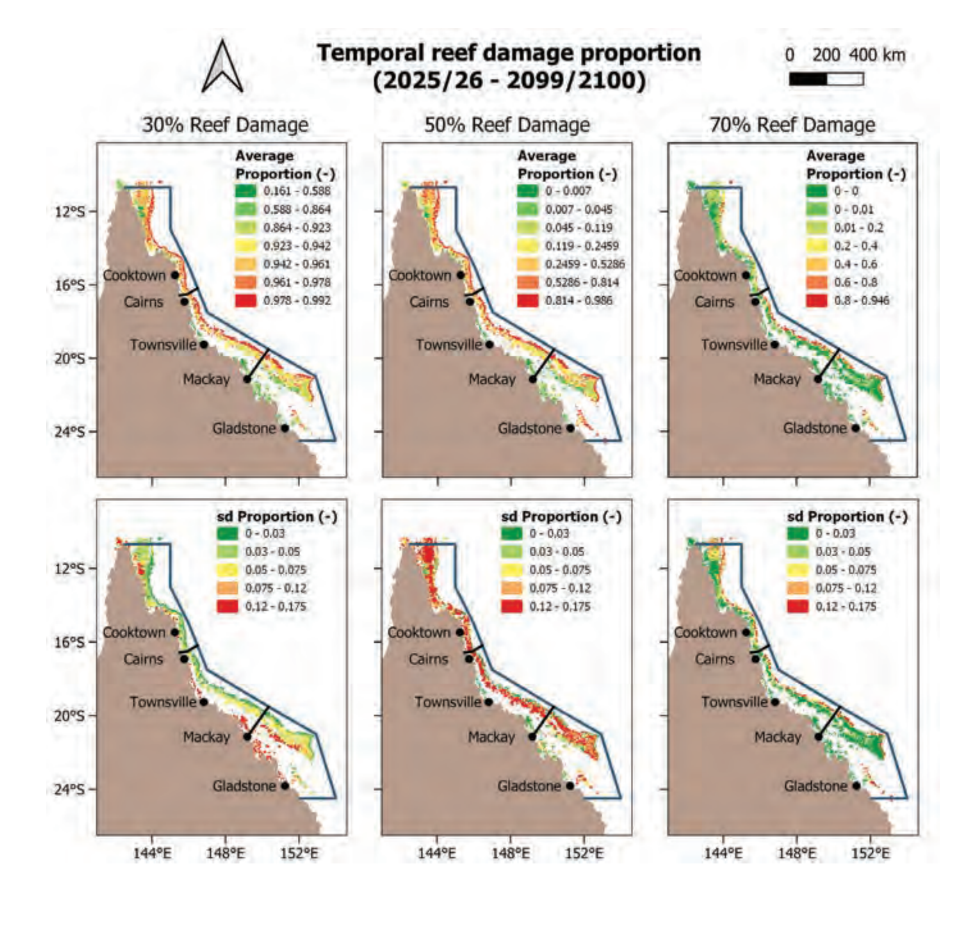


Figure 17.
The mean and standard deviation of the 1000 temporal proportions established for every reef, spanning the period 2025/26 to 2099/2100, during which a reef experiences damage, across three tiers of reef damage (30%, 50%, and 70%). Colour intervals were based on equal count (quantile). The maps represent projections under the historical scenario. For further details, refer to Keppens, 2024. Source: Keppens 2024; Maurie Keppens, Ghent University and The University of Queensland

Vulnerable sections of the GBR - Hydrodynamic regimes

The central to southern outer reef region of the GBR is predicted to be more likely to experience high cyclonic wave energy and therefore is likely to be more susceptible to rubble movement (**Figure 18**) (Cheung et al., in prep). When a cyclone is proximal to or hits the reef, it increases water movement near the sea bed that can break off pieces of coral and mobilise rubble (see section **Extreme weather events**). Some areas of a reef might be more or less affected by cyclones, and the amount of damage will be dictated by factors such as cyclone intensity, forward speed, spatial extent, reef aspect to cyclonic winds and waves, relative position of a reef to a cyclone track, and coral growth forms on the reef.

The potential impacts of cyclones on rubble mobilisation have been estimated and mapped for each individual reef across the GBR (Cheung et al., in prep).

Using on-reef wave climate simulations based on over 1,500 synthetic future tropical cyclone tracks (Callaghan et al., 2020) and annual cyclone rates (Wolff et al., 2016), the average proportion of each reef experiencing damaging near-bed wave orbital velocity has been estimated. In general, reefs on the outer shelf of the central and southern regions have the highest proportion of areas impacted by a cyclone. These outer reefs are more vulnerable to cyclone damage possibly due to the patchier arrangement of the fewer and smaller outer reefs in the central GBR regions (Sansoleimani et al., 2022) (**Figure 18**).

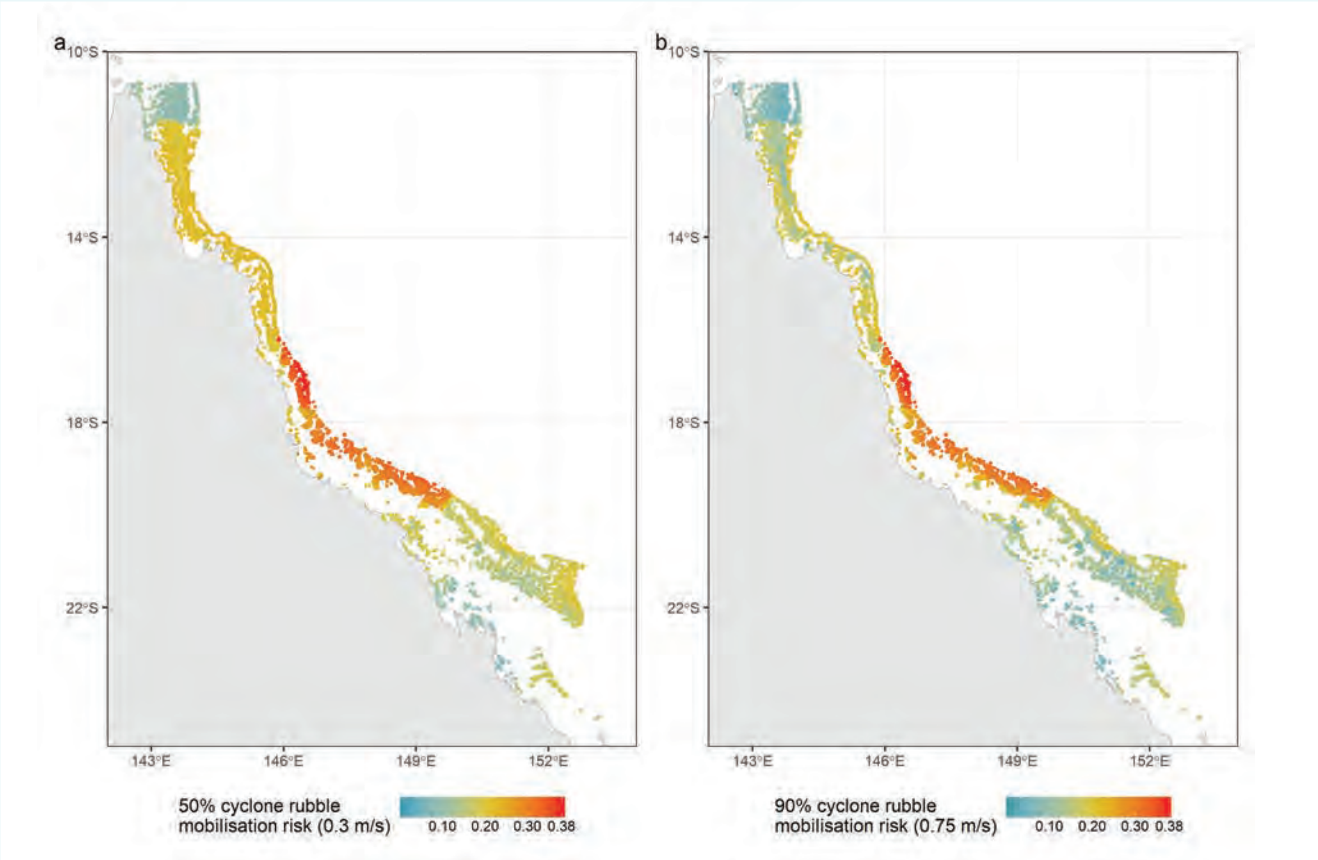


Figure 18. Maps showing the average proportion of reefs having a 50% **(a)** and 90% chance **(b)** of rubble mobilisation given the annual cyclone rate (Cheung et al., in prep; Wolff et al., 2016). If the average proportion of a reef impacted is higher, the reef appears red. This means that when a cyclone hits, a larger part of the reef will experience near-bed flows (*U*) high enough to cause rubble movement. Source: Mandy Cheung, The University of Queensland

Another study identified locations on the GBR where rubble may become a persistence problem using simulations of historical wave velocities and rubble binding functions (Sjahruddin et al., in prep). Researchers developed an interactive map on ArcGIS Online (**https://arcg.is/O5PXK1**) to highlight both GBR-wide and reef-specific locations where the binding between rubble breaks constantly, creating an unstable substrate that hinders reef recovery.

Three key variables were generated from the simulations (**Figure 19**):

a) the 90th percentile of maximum near-bed wave orbital velocity (U_{max}),

b) time to reach benchmark stability; and

c) the duration of recovery windows (time proportion – %, meaning the standardised proportion of time during the simulated period when conditions allow the rubble bed to recover).

A higher 90th percentile U_{max} indicates greater hydrodynamic energy at a site, which suggests higher wave-induced disturbance. The second variable shows the time required for rubble to reach a stable benchmark level, with a larger value indicating slower stabilisation. Sites with shorter recovery window time proportions are less likely to have stable rubble beds under adverse weather conditions, as the rubble binds may not have accumulated enough strength to remain intact.

Practitioners may prioritise sites with longer recovery windows and longer time to reach the stability benchmark. These sites may require intervention because the rubble bed takes longer to recover naturally, and disturbances occur less frequently, which increases the chances of successful interventions. For example, **flat structures** may be less effective in high-energy environments with short recovery windows, as they are prone to being buried or dislodged.

From **Figure 19**, rubble persistence appears to be a widespread problem across the GBR, with generally shorter recovery windows in the central and southern regions, mainly concentrated in the border of Townsville/Whitsunday and Mackay/Capricorn management area. Some of these sites also experience relatively greater wave energy (**Figure 19a**) and never reached benchmark stability (null values) (**Figure 19b**). Locations with high U_{max}, great number of days to benchmark stability, and short recovery windows tend to overlap, highlighting areas where rubble persistence is a significant problem.

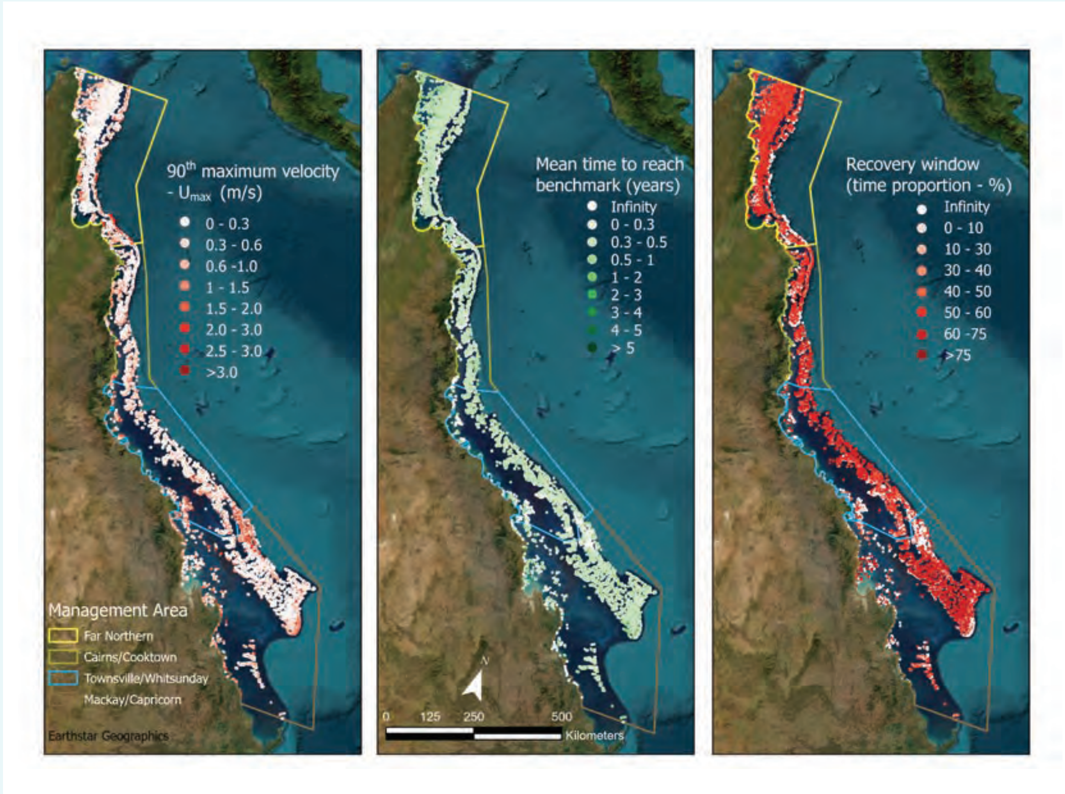


Figure 19.
Maps showing the:
a) 90th percentile U_{max};
b) mean time to reach benchmark (years); and
c) recovery window (time proportion - %) across the GBR, indicating the spatial differences in vulnerability to rubble persistence at the GBR scale.

A 'Null' value in (b) indicates areas that never achieve benchmark stability, while 'Null' in (c) indicates the absence of a recovery window.

Source: Fikri Sjahruddin, The University of Queensland

To examine locations within a reef where rubble may be persistent, users may zoom in on the interactive map to view reefs of interest (https://arcg.is/O5PXK1). For example, in Figure 20, the 90th percentile of Umax is typically highest on exposed reef slopes. These areas also take the longest to reach benchmark stability and have the shortest recovery windows. Some of these areas also have "null" values for time to reach stability benchmark, indicating that rubble binds keep breaking before it reaches a stable threshold.

This suggests that restoration efforts may be less effective in these locations due to frequent and intense disturbances. Note that Figure 19 and Figure 20 presented here are currently in development and may be subject to changes. For the most up-to-date information, please refer to the online version of the maps. More details will be available in the paper in preparation by Sjahruddin et al.

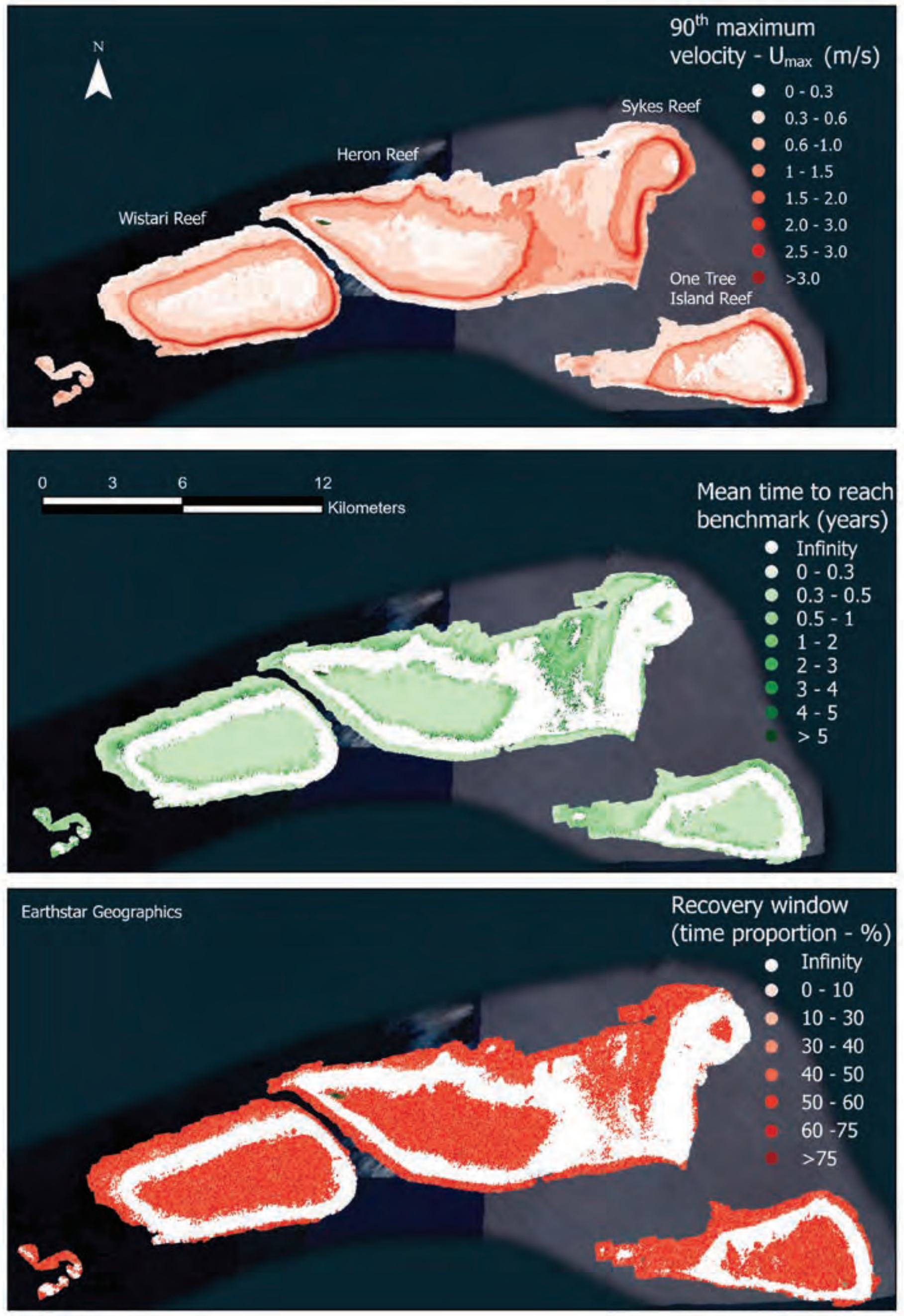


Figure 20.
Maps showing the:
a) 90th percentile U_{max};
b) mean time to reach benchmark (years); and
c) recovery window (time proportion - %) across Heron Reef, GBR, indicating the fine-scale spatial differences in vulnerability to rubble persistence within areef.

A 'Null' value in (b) indicates areas that never achieve benchmark stability, while 'null' in (c) indicates the absence of a recovery window.

Source: Fikri Sjahruddin, The University of Queensland

Vulnerable sections of the GBR – Disturbance profiles

The GBR exists in a multi-hazard environment and rubble generation can be intensified in regions where two or more drivers may exist (e.g., cyclones and cyclonic wave energy, marine heatwaves, CoTS). An approach then is to understand where the greatest confluence of drivers exists that lead to rubble generation on the GBR. Bryan et al. (in prep.) considered seven key drivers of rubble generation relevant to the GBR, including direct drivers (cyclones, waves and/or tsunamis, and ship groundings), as well as indirect or pre-conditioning drivers (bleaching and CoTS invasions).

Vulnerability scores were calculated for each individual reef within the GBR. The central to southern GBR (from the Whitsundays to Lady Musgrave) was found to have the highest vulnerability due to the combined risks of tropical cyclones, waves, CoTS, and ship traffic, with a secondary area from Cape Melville to Lizard Island also at risk due to combined risks from tropical cyclones and bleaching (Figure 21).

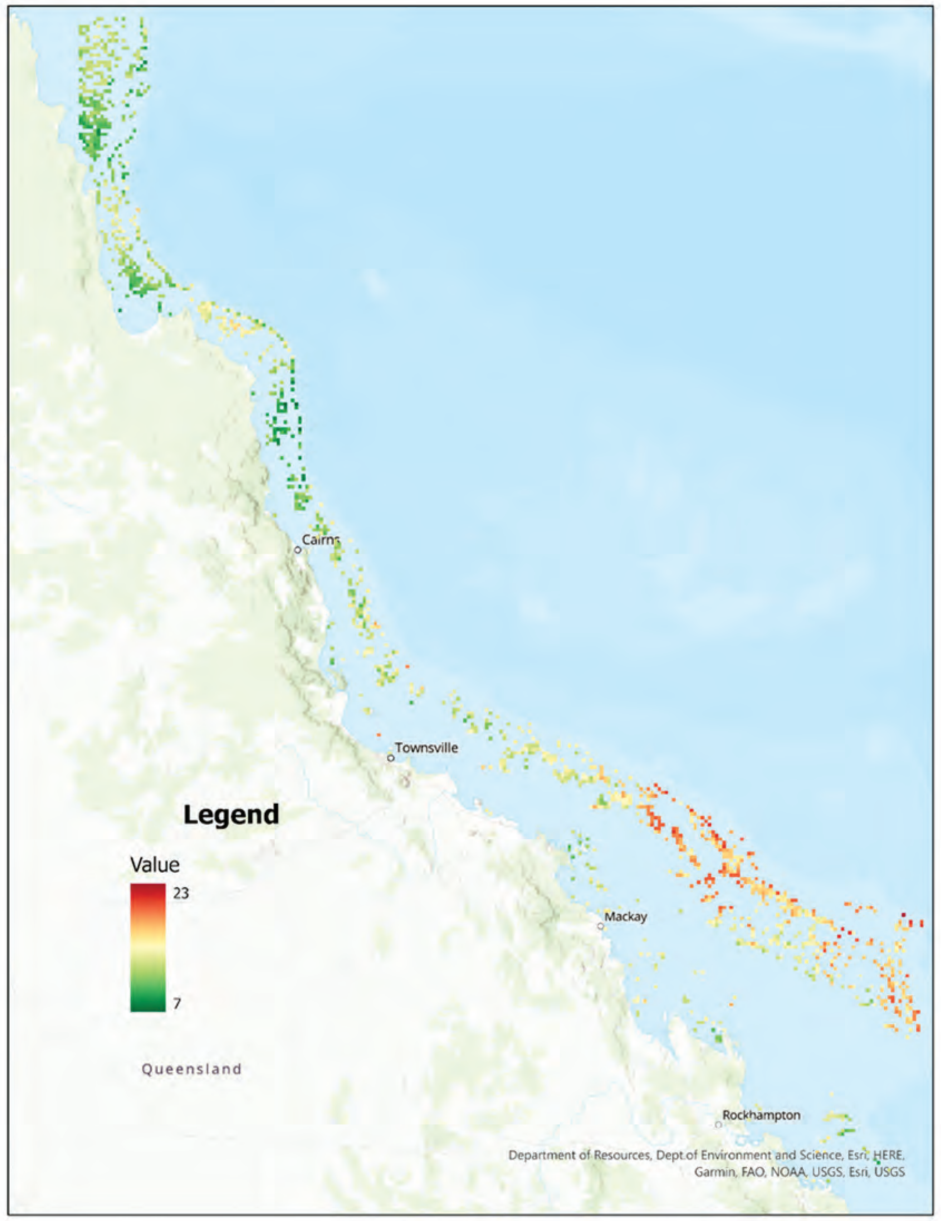


Figure 21.
Map showing vulnerability to future rubble generation across the GBR. Vulnerability scores were calculated based on direct rubble generating drivers and rubble pre-conditioning drivers. The highest values (i.e. orange-red coloured regions) indicate the greater superposition of these main rubble generating processes.

Source: Julio Salcedo-Castro & Scott Bryan, Queensland University of Technology

Vulnerable sections of the GBR – Topography

Following rubble generation, it is important to understand where rubble can accumulate and potentially hinder reef recovery. Leung and Mumby (2024) identified reefs at risk of rubble accumulation on the GBR using remote sensing data and GIS analysis. Transects were generated along reef slopes, and changes in depth along these transects were extracted (**Figure 22**). An algorithm was then used to predict accumulation sites on the transects based on slope angles, local topography, and problematic rubble bed thickness.

For each reef, the percentage of transects with problematic rubble cover (over 30%, 40%, and 50%) was calculated to determine the reefs' susceptibility to rubble. It was suggested that around 20% of the 1,706 sampled shallow offshore reefs on the GBR have topographic features that could lead to an accumulation of at least 30% rubble cover across the reef slope (**Figure 23**).

Furthermore, they found that 47 km (or 3%) of the reef slopes, primarily in the southern region, contain areas that could reach 50% rubble cover. However, the high rubble cover modelled in the study, while possible, may not be a common occurrence and warrants further investigation.

> Overall, the central to southern regions are potentially the most vulnerable to problematic rubble due to their hydrodynamic regimes, disturbance profiles, and topography.

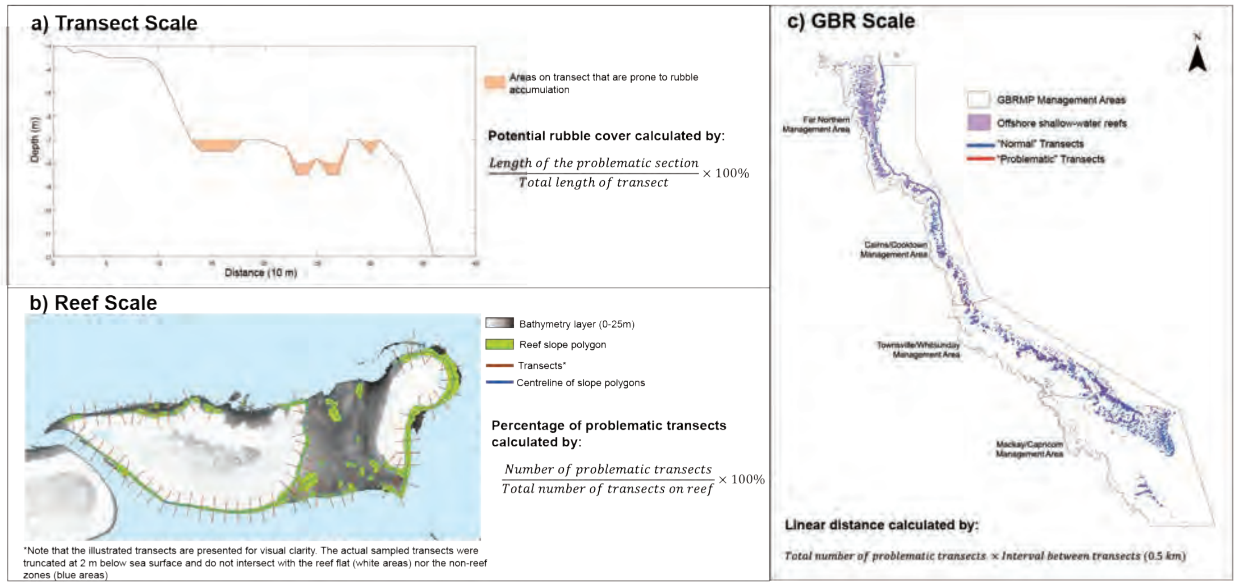


Figure 22.
Potential rubble accumulation is shown at three scales: transect **(a)**, reef **(b)**, and GBR **(c)**. a) shows an example transect profile with areas where rubble may accumulate. (b) uses Heron Reef to show how these transects align with reef slopes, and (c) presents an example distribution of transects across the GBR. Adapted from "Mapping the susceptibility of reefs to rubble accumulation across the Great Barrier Reef" by (Leung & Mumby, 2024).

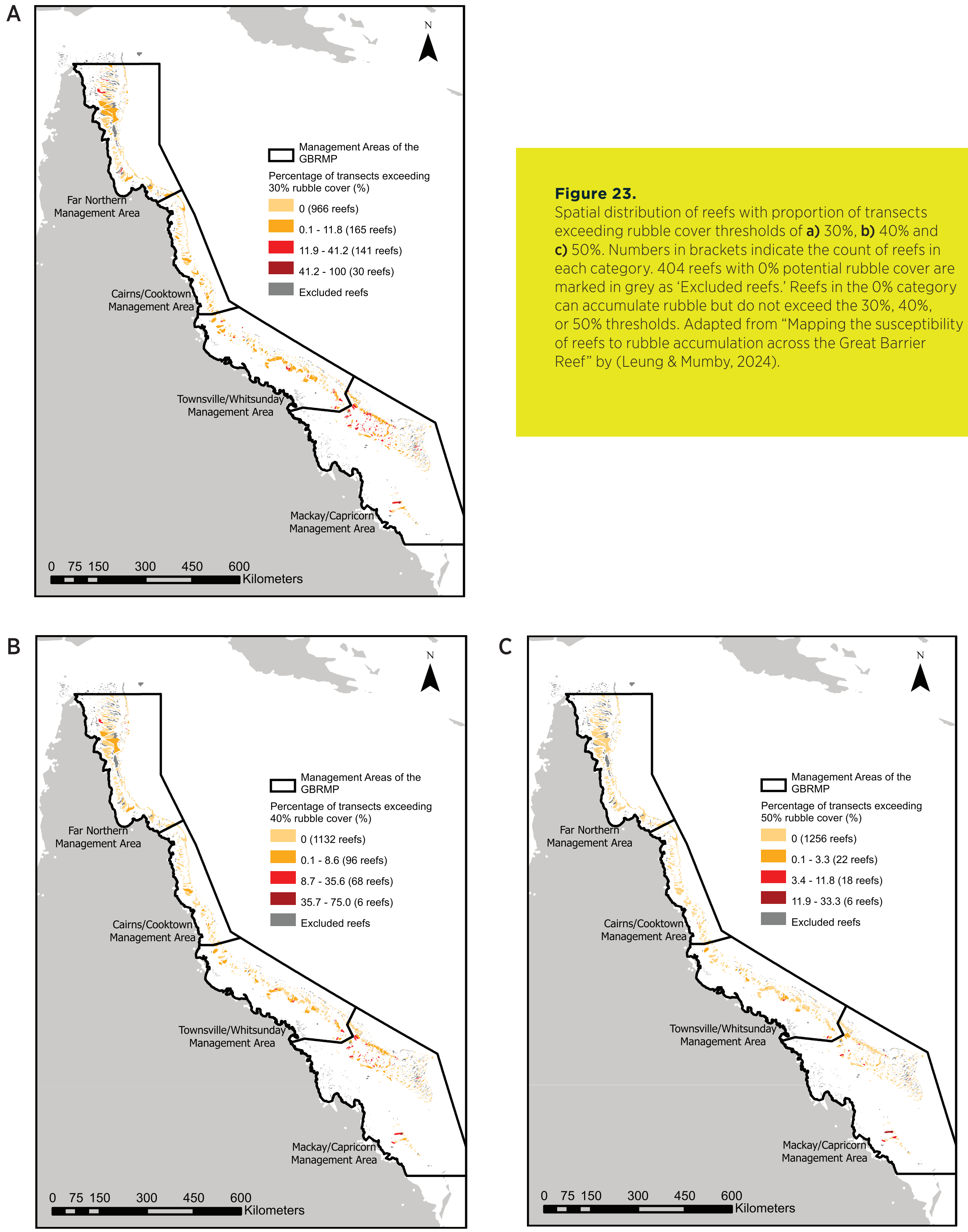


Figure 23.
Spatial distribution of reefs with proportion of transects exceeding rubble cover thresholds of **a)** 30%, **b)** 40% and **c)** 50%. Numbers in brackets indicate the count of reefs in each category. 404 reefs with 0% potential rubble cover are marked in grey as 'Excluded reefs.' Reefs in the 0% category can accumulate rubble but do not exceed the 30%, 40%, or 50% thresholds. Adapted from "Mapping the susceptibility of reefs to rubble accumulation across the Great Barrier Reef" by (Leung & Mumby, 2024).

Understanding rubble stabilisation: mechanisms and implications for reef recovery

Natural rubble bed recovery

It is possible for rubble beds to recover without any intervention. If environmental conditions are favourable and the rubble pieces remain stable or undisturbed over time, they can be bound and eventually cemented by physiochemical or biogeochemical processes (Rasser & Riegl, 2002).

Once rubble is stabilised, by either interlocking, or simply by being in a low-energy environment, organisms like turf algae, sponges, and CCA colonise and bind the rubble. Rubble-binding organisms can colonise in successional stages, starting with fast-growing turf algae and macroalgae, and ending with slower-growing CCA and hard corals themselves (**Figure 24**).

The first colonisers, such as macroalgae, can bind rubble in as little as month (Wulff, 1984), followed by intermediate binders like sponges, within as little as 3 months (Biggs, 2013). Late-stage binders like CCA and corals (e.g., *Agaricia* and *Porites spp.*) can recruit onto sponge-rubble piles and bind rubble within 7 and 10 months respectively (Wulff, 1984). Over longer time periods, fine sediment and cement fill the gaps and crevices between rubble pieces and reef rock, contributing to the stability of the rubble bed. These cementation processes generally occur over long timescales, with cementation rates of 8-25 mm per 100 years on Belizean and Bahamian reefs (Grammer et al., 1993).

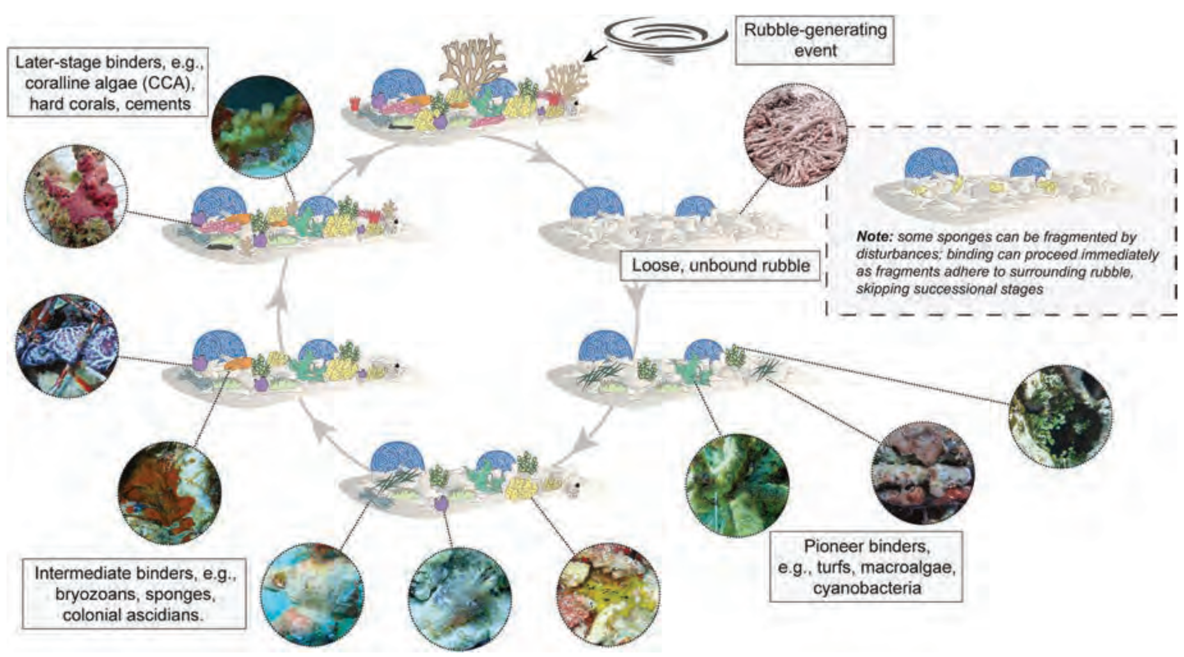


Figure 24. The cycle of rubble binding following rubble generation, highlighting different binding organisms. Note that binding will not invariably proceed in this order—rubble can be rapidly colonised by sponges from sponge fragments (see inset), soft corals, corallimorphs, etc. Furthermore, the cycle may not proceed past a certain stage, for example, if high macroalgal growth due to low herbivory and high nutrients inhibit further colonisation through competition. Adapted from "Coral rubble dynamics in the Anthropocene and implications for reef recovery" by Kenyon et al. (2023a).

Factors affecting rubble mobilisation

The mobility of rubble pieces can be influenced by several factors, including hydrodynamic forcing, the topography of the seafloor, the underlying substrate and rubble bed thickness, the characteristics of the rubble pieces themselves, and biological disturbances (Kenyon et al., 2023a).

These factors interact with each other and have varying degrees of impact on whether rubble is naturally stable or not. By understanding these factors, we can pinpoint potential regions that are vulnerable to the persistence of loose, mobile rubble based on environmental monitoring data and create customised solutions.

Hydrodynamic forcing

Rubble mobility is principally affected by the strength of hydrodynamic forcing from waves, wind-driven currents, and tidal currents (Kenyon et al., 2023a).

Compared to living coral reefs, expansive rubble beds can experience stronger hydrodynamic forcing because they lack the structural complexity and bottom roughness that help dissipate energy across reefs (Guihen et al., 2013; Lowe & Falter, 2015; Lowe et al., 2005). As a result, pieces in rubble beds can be more easily mobilised compared to fragments that are interspersed between live coral colonies. Rubble is not only susceptible to movement during high-energy weather events like storms, cyclones, hurricanes, and typhoons. Even under everyday hydrodynamic conditions, wave energy can be great enough to slide and flip rubble pieces (Viehman et al., 2018). Kenyon et al. (2023b) determined rubble movement and transport thresholds under different environmental conditions, for rubble pieces 4-23 cm in length (**Table 2**). Rubble beds are more likely to remain stable, naturally, in sheltered areas with low hydrodynamic energy under these thresholds. Importantly, if interlocking and imbrication is present in a rubble bed, rubble pieces can also be stable, even under high-energy conditions above these thresholds.

	Near-bed wave orbital velocities (m/s)					
	Chance of moving (%)		Chance of transport (%)		Chance of flipping (%)	
Conditions	50	90	50	90	50	90
Experimental settings (in a wave flume)	0.28	0.28	0.28	0.28	0.28	0.28
Field settings (on Vabbinfaru Reef, North Malé Atoll, Maldives)			0.30	0.75*		

Table 2
Rubble mobilisation thresholds for loose, non-interlocked rubble pieces of size range ~4-23 cm in flume and in the field (Kenyon et al., 2023b). Note that at higher velocities, rubble pieces were less likely to move (rocking motion) and more likely to be transported.

* *The 90% transport threshold in field settings warrants further investigation since it is above the range of velocities measured in the field.*

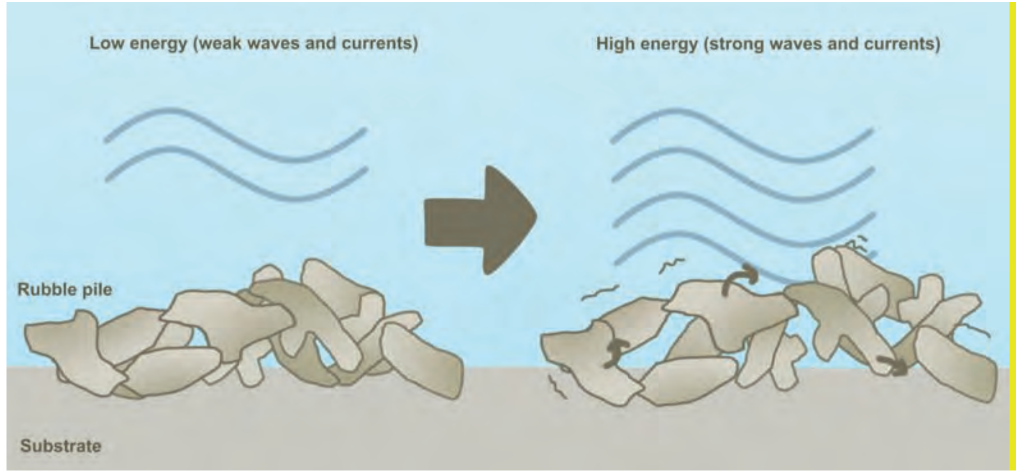


Figure 25.
Rubble pile with little to no interlocking between rubble pieces in a low-energy vs a high-energy environment. Importantly, if interlocking and imbrication is present in a rubble bed, rubble pieces can be stable even under high-energy conditions.
Source: Shu Kiu Leung, The University of Queensland

Topography

The profile and slope angles of the reef are significant predictors of rubble transport and mobility (Harmelin-Vivien & Laboute, 1986; Shannon et al., 2013; Thornborough, 2012). Steeper slopes, especially those exceeding 45°, present a higher risk of "avalanches" triggered by changes in slope dynamics, whereby rubble that becomes initially mobilised can move downslope and offshore under the influence of gravity (Harmelin-Vivien & Laboute, 1986). In steeply sloping areas, stabilisation may not be necessary, but an intervention to prevent the burial and damage of deeper coral colonies downslope could be considered. Likewise, stabilisation interventions might also be ineffective on even moderately steep slopes. Slopes of moderate steepness (15° to 45°), such as those found around Pom Pom Island in Malaysia, for example, experience episodic large-scale downslope movements of rubble and live coral (Philippo, pers. comm.). This semi-continuous movement of rubble, while not as dramatic as on steeper slopes, can lead to prolonged instability and are likely to require a different approach to flat areas.

Compared to areas with moderate to steep slopes, rubble is more likely to accumulate on flat to gently sloping reef slope areas (Leung & Mumby, 2024). Here, rubble may not be so much at risk of downslope movement but can still be moved back and forth with waves and currents. While rubble can also accumulate and cover vast areas on reef flats, it often undergoes erosion in these zones into smaller pieces that are transported shoreward into lagoonal areas (Hughes, 1999; Scoffin, 1993; Shannon et al., 2013; Thornborough & Davies, 2011). Moreover, some reef flats have ecological and environmental conditions that make them unsuitable for binding and recovery, even if the rubble is stable (Kenyon, 2021).

> Overall, we are particularly concerned about reef slopes that are relatively gentle and have low topographical relief because these areas are susceptible to rubble accumulation with persistent mobility.

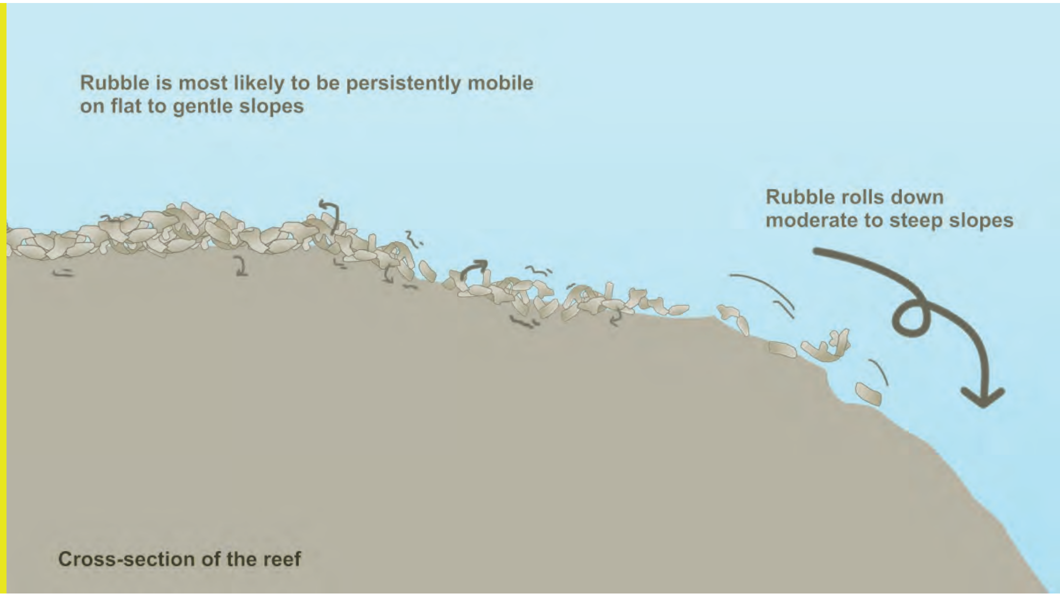


Figure 26.
Rubble mobilisation across different slopes. Source: Shu Kiu Leung, The University of Queensland

Underlying substrate and rubble bed thickness

Rubble pieces tend to be more easily transported on smoother sandy substrates compared to rubble substrates (Kenyon et al., 2023b). When the rubble bed is thin and consists of only a small amount of rubble, rubble pieces are in contact with the underlying substrate, which can be sand or hard carbonate. Since there is less resistance to movement due to the lack of interlocking with underlying rubble layers, rubble pieces move more easily and further compared to in thicker rubble beds. For example, when wave velocities exceeded 0.2 m/s in a laboratory setting, smaller rubble pieces were more likely to move on sand than on rubble (Kenyon et al., 2023b). However, these findings were not replicated in a field setting.

Rubble pieces in thicker rubble beds are more likely to be stable and have more binding. This is because the thicker bed facilitates greater interlocking between pieces (Aronson & Precht, 1997). Kenyon et al. (2024) surveyed rubble beds with thicknesses ranging from 2 to 52 cm across different habitats on the southern GBR. They found that rubble pieces were very unlikely to be stable and/or bound (indicating poorer recovery prospects) in rubble beds found at exposed, deep sites, which were only ~5 cm thick. Of course, rubble bed age must be considered in conjunction with any rubble bed metrics, such as thickness, because low binding prevalence could also be attributed to a short period since disturbance, and not solely the thickness.

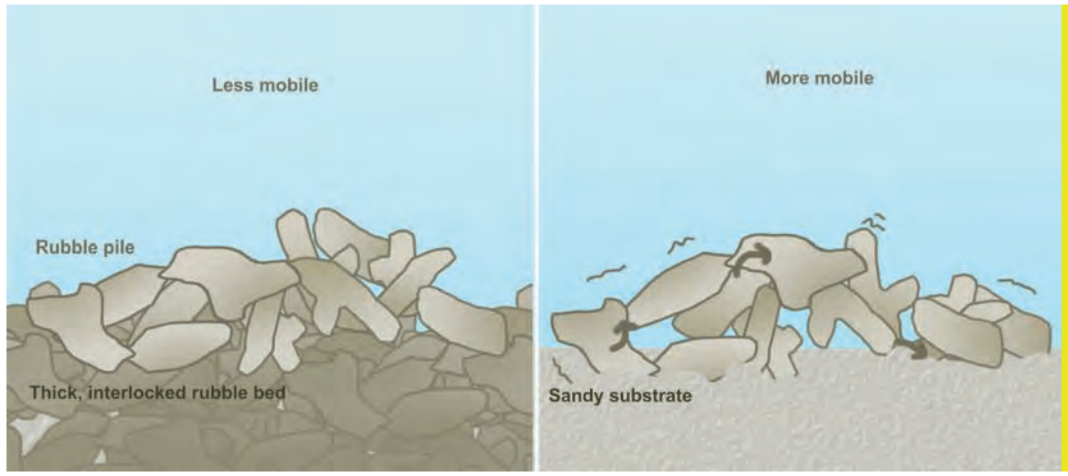


Figure 27.
Rubble pile on a thick rubble bed, where pieces are interlocked with underlying rubble layers vs on a sandy substrate. Source: Shu Kiu Leung, The University of Queensland

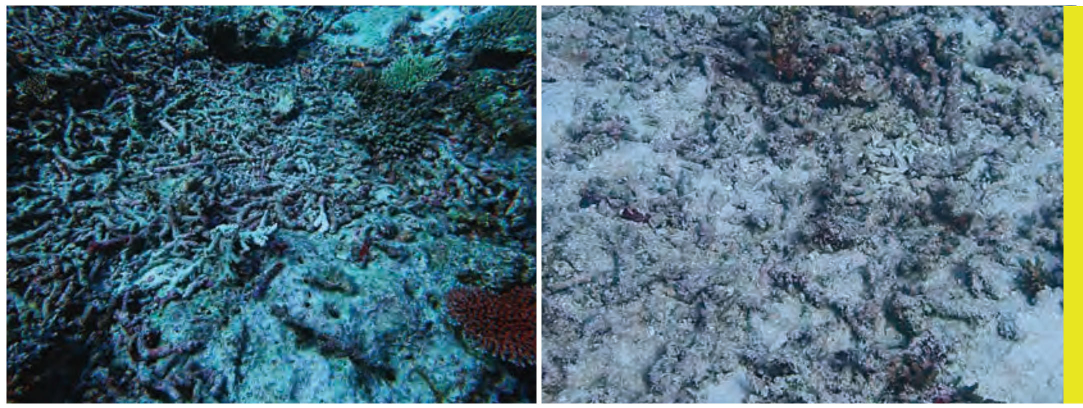


Figure 28.
Rubble on hard carbonate substrate (left) vs on sandy substrate (right). Source: Tania Kenyon, The University of Queensland

Rubble piece characteristics

As well as characteristics of the rubble bed, rubble piece characteristics such as size, shape, and density are significant determinants of rubble mobility and transport (Kenyon et al., 2023a).

Small and unbranched rubble pieces are more susceptible to transport. A study in the Maldives found that smaller rubble pieces on the reef flat moved away from a site more readily than larger ones (Edwards & Clark, 1994). After 3 months of monitoring, 60% of tagged 20 cm rubble pieces were still present at the site, while none of the 5 cm rubble pieces remained. Another study showed that small, unbranched rubble pieces within a size range of 4-8 cm were more likely to be transported at lower velocities, compared to rubble of larger size groups (9-23 cm) (Kenyon et al., 2023b). The rubble beds at offshore, exposed deep sites of the southern GBR, mentioned above, were primarily composed of unbranched rubble pieces with very few branches (only 1 on average per piece) (Kenyon et al., 2024). Rubble pieces in these sites had a very low chance of being stable or bound. Rubble in depositional areas, i.e., undisturbed persistent rubble, also commonly have very few branches, likely contributing to persistent movement (Kenyon et al., 2024; Wolfe et al., 2023).

Rubble pieces that are larger and branched promote interlocking with adjacent fragments, and can more easily lodge in unconsolidated finer sediment substrates. Gischler and Ginsburg (1996) suggested that sites with larger rubble pieces tend to have higher species richness of reef cavity-dwelling organisms.
This is because these larger pieces allow organisms enough time to grow undisturbed as they are less likely to be flipped over by waves. Similarly, Wolfe et al. (2023), found that the branchiness of rubble pieces correlated with an increase in the diversity of sessile, rubble-dwelling organisms on the GBR. Because a subset of these sessile organisms bind rubble, it follows that larger, branched rubble pieces are more likely to support enhanced binding.

Biological disturbances

Fishes and mobile invertebrates can mobilise rubble pieces, though on a smaller scale compared to other physical factors such as hydrodynamic forcing (Kenyon et al., 2023a). Rubble is disturbed by herbivorous fishes while grazing; smaller invertebrates when seeking shelter from waves, predators, and light; and larger invertivores (fish) and reptiles (turtles) when foraging or hunting for prey. While the presence of these organisms may increase the likelihood of rubble mobilisation, the extent to which these disturbances break apart rubble binds and affect reef recovery is yet to be determined.

Considering these factors, interventions may be more necessary if the rubble bed is composed of smaller and less branchy pieces, which is often the case in acute, human-induced disturbances such as blast-fishing and ship groundings (Kenyon et al., 2023a; Kenyon et al., 2023b). This can be the case even when the site's hydrodynamic energy is relatively low, because small, unbranched rubble pieces move at low thresholds and movement is not impeded by interlocking. **Note** that it may be more challenging to stabilise rubble beds with smaller pieces. It is important to consider the factors contributing to the size of rubble.

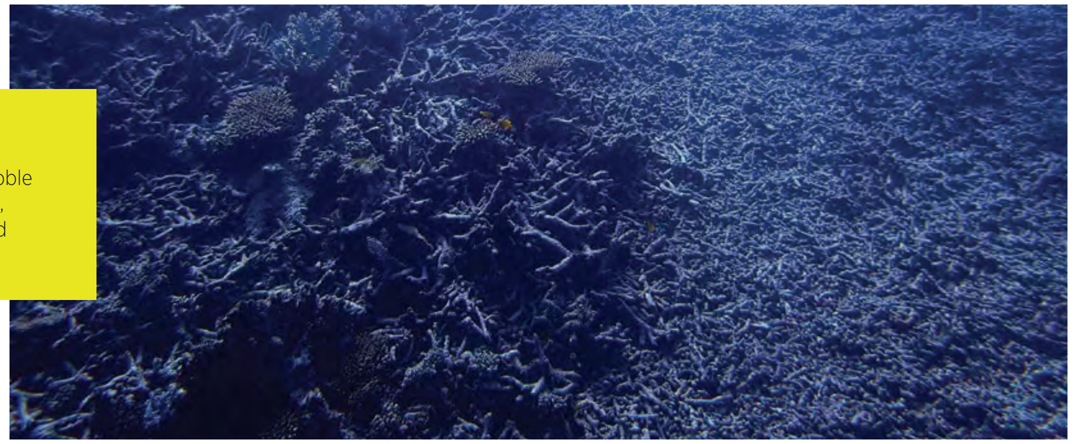


Figure 29.
Interlocked (left) vs loose rubble (right). Source: Tania Kenyon, The University of Queensland

Challenges and opportunities in rubble stabilisation

Despite being an important part of the reef, rubble remains understudied. A recent study emphasizes the importance of filling knowledge gaps in rubble research for predicting reef recovery and planning effective interventions (Kenyon et al., 2023a).

The potential for rubble stabilisation as a promising reef restoration method has been demonstrated in several studies (Ceccarelli et al., 2020; Fox et al., 2019). However, given the paucity of monitoring data on rubble stabilisation methods, especially over long timescales, their effectiveness in a variety of reef environments is uncertain. In Australia, restoration deployments have largely been restricted to local scales, which is unlikely to match the scale and magnitude of reef impacts in the future (McLeod et al., 2020). Therefore, the greatest challenges in managing problematic rubble are a lack of knowledge around:

1) the long-term feasibility of different stabilisation interventions; and
2) the scalability of these methods.

These guidelines aim to fill these knowledge gaps by summarising technical information and facilitating knowledge sharing among stakeholders, including practitioners, managers and researchers. It is important to establish a stronger connection between scientific research and practical efforts, in order to effectively understand rubble dynamics.

Please note that some of the interventions discussed within these guidelines are yet to be systematically tested, and some findings are based on anecdotal evidence. This is because rubble stabilisation research is a relatively new field, and systematic studies are lacking. The information presented is sourced from published research, grey literature, conversations with experts in the field, and discussions held at a rubble stabilisation workshop held in late 2023 (see **Box 3**), funded by RRAP. Readers are encouraged to consider carefully whether the information is applicable to their specific circumstances and reef environment.

Box 3

RRAP Rubble Stabilisation Workshop

The RRAP Rubble Stabilisation workshop was held from 17 to 21 November 2023 at the Coral Triangle Center in Sanur, Bali. This workshop facilitated information gathering on the efficacy of different rubble stabilisation methods. The workshop also expedited knowledge-sharing among researchers, practitioners, managers and representatives from the tourism industry in Australia and other countries including Indonesia, Philippines, Malaysia, Guam, China, and the USA.

Figure 30. Experts participating in the RRAP stabilisation workshop. Source: Peter Mumby.

Rubble stabilisation: From concept to impact

This section provides guidance across all stages of a rubble stabilisation project, from **planning** to **monitoring** and **evaluation.**

In the planning subsection, we discuss **key considerations** and **preparatory steps** that set the foundation for a successful project.

Then, we provide a **detailed synthesis of various rubble stabilisation methods**, including readily accepted techniques and those still under development.

Lastly, to ensure the effectiveness of these methods, we outline **how to establish a robust monitoring and evaluation program.**

Rubble stabilisation projects involve a range of environmental and socio-economic elements at each stage.

The biophysical and ecological context into which an intervention is being deployed, including reef zone, hydrodynamic and topographical regime, water quality and fish biodiversity and abundance are important matters to be considered before undertaking rubble stabilisation. Challenges often arise due to unexpected environmental disturbances or environmental changes throughout the duration of a project that may necessitate maintenance or strategy modifications. Climate change, with its potential to alter temperature, precipitation and storm patterns, adds to these challenges and can significantly impact restoration efforts (Shaver et al., 2020).

Beyond these environmental considerations, it is recommended to systematically consider socio-economic factors to ensure long-term success (Hein et al., 2020). This involves engaging with and establishing strong partnerships with different stakeholders, such as local communities and Traditional Owners, funders, and regulatory or permitting agencies, to accommodate changes in stakeholder attitudes, economic circumstances, and legislation or policy.

An adaptive management framework, such as that shown in Figure 31, can be used to manage challenges across environmental, social and economic landscapes, by incorporating high flexibility and continuous adaptation to changes (Anthony et al., 2015).

Figure 31. A cyclical, adaptive management framework for a rubble stabilisation project, consisting of 4 critical stages: Planning, Implementation, Monitoring, and Evaluation.

Source: Shu Kiu Leung, The University of Queensland

Planning a rubble stabilisation project

Setting project goals

Setting appropriate project goals should be the first crucial step in planning. Goals need to be specific, measurable, achievable, realistic, and time-bound (SMART) (Boström-Einarsson et al., 2020b).

The implementation of rubble stabilisation methods might meet multiple goals simultaneously and yield various benefits. These goals can range from remediating reef damage and improving ecosystem health, building partnerships with local communities, to boosting local eco-tourism revenue. The choice of goals is largely influenced by environmental, social and economic challenges and management capacity (Hein et al., 2020).

To stabilise, or not to stabilise?

Before starting a project, rubble stabilisation should be considered not as a silver bullet, but a part of a larger resilience-based management approach.

Such an approach should prioritise management actions that boost resilience based on factors that influence ecosystem function (Hein et al., 2021; McLeod et al., 2019a). It is advisable to mitigate environmental stressors such as high turbidity and nutrient levels, or high macroalgal cover, prior to implementing a rubble stabilisation project. If the stressors are not addressed beforehand, the project could fail regardless of the method used (Gann et al., 2019).

Read more: There are many guidelines and documents available offering comprehensive guidance on managing coral restoration projects. These resources provide detailed instructions on selecting suitable goals, establishing timelines, and prioritising tasks. For further information, we recommend referring to:

- **Coral Reef Restoration as A guide to coral restoration method** (Hein et al., 2020),
- **A Manager's Guide to Coral Reef Restoration Planning and Design** (Shaver et al., 2020); and
- **Reef Rehabilitation Manual** (Edwards, 2010).

Ideally, the following key aspects should be evaluated at the beginning of the planning process (Ceccarelli et al., 2020; Hein et al., 2021):

1. The historical condition of the area (i.e., has the area always been dominated by rubble, or did it once have corals that were damaged and turned into a rubble bed? And if the latter, is it showing signs of recovery or not?)
   a. Is this an area where rubble is persistently deposited and never had significant coral cover (undisturbed persistent rubble bed), or is it instead an area that was previously living reef (disturbed rubble bed)?
   b. If it was previously reef, do you see corals re-colonising and surviving beyond one or two years (indicating a disturbed transient rubble bed headed toward recovery) or not (indicating a disturbed persistent bed)?
2. The reasons behind coral decline (i.e., what type and intensity of disturbance(s) led to the formation of the rubble bed and when did it/they occur?)
3. The obstacles to natural recovery (i.e., if the rubble bed is not recovering, what factors are preventing it from recovering to its pre-disturbance state or reference level? Factors may include rubble mobility, wave action and tidal currents, low coral larval supply, competition with macroalgae or soft corals, high coral predation, poor water quality and high sediment loads.)

Consideration of these aspects can identify:

1. whether intervention is suitable and appropriate,
2. whether rubble stabilisation is likely to be effective;
3. whether other reef restoration interventions or management actions are needed in addition to or instead of; and
4. what steps need to be taken before proceeding with the chosen intervention (also see Figure 32). A cost benefit analysis, including for social, cultural, economic and environmental values may further assist in evaluating the positives and negatives of implementing a rubble stabilisation project.

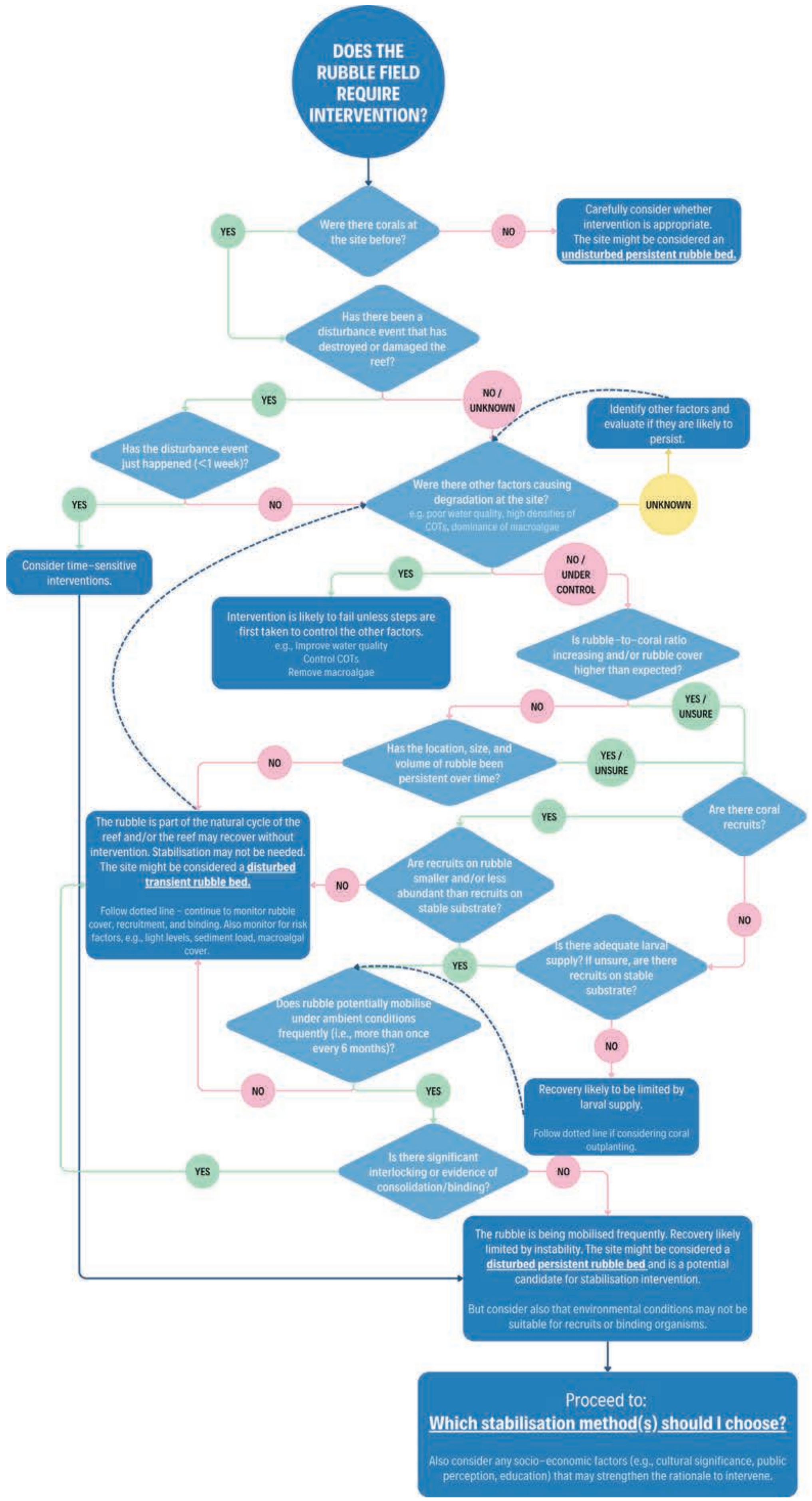


Figure 32. Decision tree for determining the need for intervention in a rubble field (Ceccarelli et al., 2020; Dodgen, in prep.; Edwards, 2010; Kenyon et al., 2023a). Refer to section **Types of rubble beds** for the definition of undisturbed persistent, disturbed transient, and disturbed persistent rubble beds. Source: Shu Kiu Leung, The University of Queensland

Choosing suitable rubble stabilisation method(s)

If rubble stabilisation is considered suitable for the site, and appropriate funding is available or considered realistic to obtain, the next logical step is to select the appropriate method(s).

However, it is important to understand that no single method is universally superior. The best choice depends on various factors such as project goals, site environmental conditions, and socio-economic considerations. In some cases, a combination of methods may be necessary.

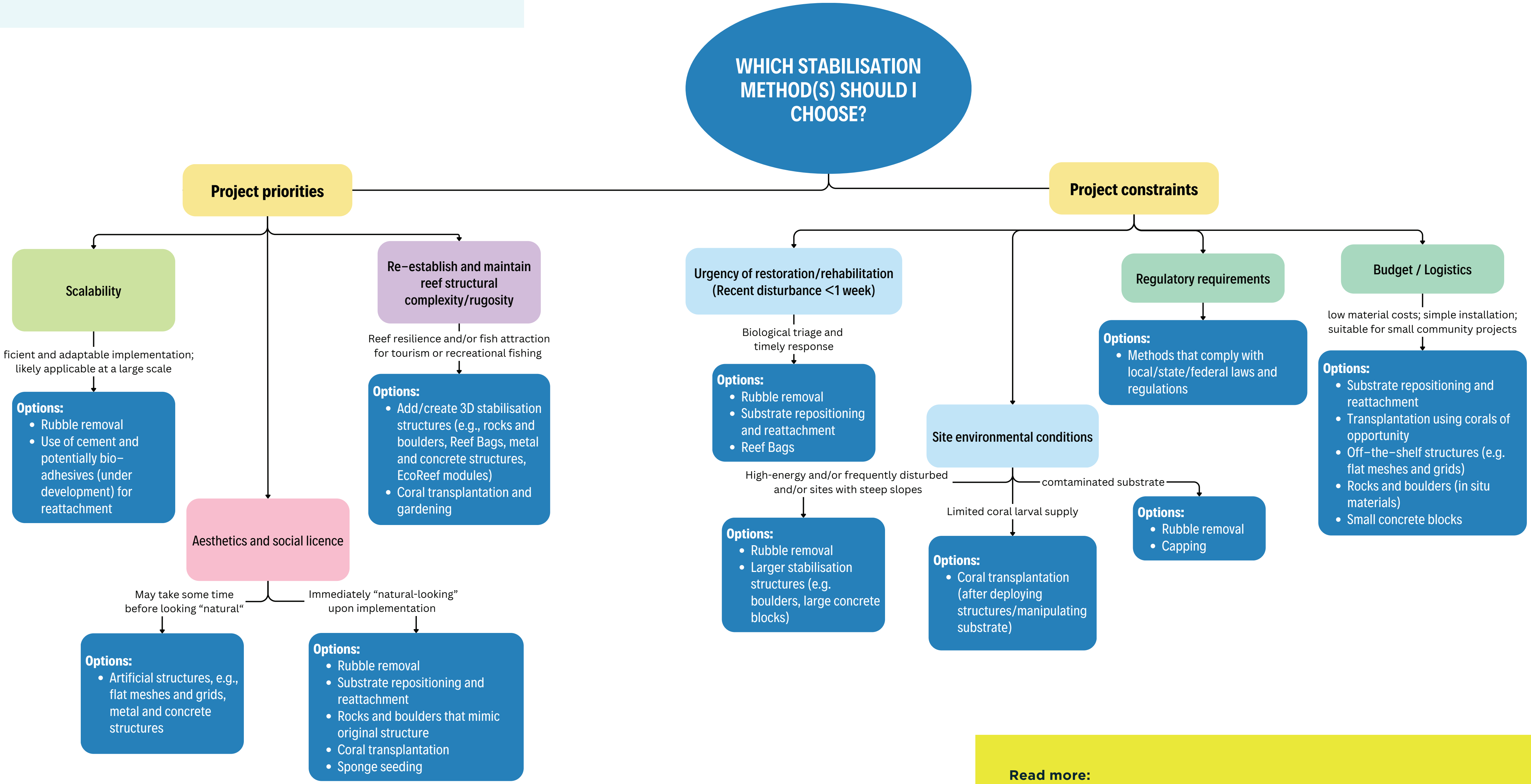
When choosing methods and planning the project design, it is recommended to consider the following factors (Table 3):

Table 3. Considerations for method selection and project design

Category	Factor	Method selection / design considerations
Ecological / environmental	**Hydrodynamic forces**	In low-energy environments, a wider variety of methods can be applied. Attachments should still be made secure to restrict movement under high-energy events such as storms (see Disturbance Regime below). For MARS Reef Stars, for example, this means placing many stars together with the legs interlocked and anchored to the substrate, even in a low-energy environment. In high-energy environments, multiple strategies can be considered: • It is recommended to use larger and more durable structures, such as boulders or concrete blocks, which are less likely to move or be dislodged. Anchors or adhesives could also be added for extra stability. For example, cement can be used to bind rocks together into a more stable pile. • Alternatively, rubble can be removed and transported to an area where it cannot cause harm (Jaap, 2000).
	Slope and bathymetry	While most methods are suitable for flat areas, their effectiveness can diminish on steeper slopes. This is particularly true for methods involving small, flat or short (low to ground) structures, as they are more susceptible to burial or damage by rolling rubble. In such cases, it might be necessary to adjust the orientation or configuration of the structures, or to use methods specifically designed for steeper slopes. The effectiveness of the method can also be influenced by the local underwater landscape. For instance, when rigid meshes are placed on rugged terrain with bumps and pits, they might not fully cover the surface. This leaves gaps, particularly in the pits, where the mesh doesn't make contact. As a result, loose rubble in these areas can remain unstable, reducing the mesh's overall effectiveness.
	Disturbance regime	Certain methods may not remain in place in regions frequently affected by severe storms. Some rubble stabilisation methods will require maintenance post-disturbance. Therefore, it is advisable to consider potential disturbances and the frequency of expected maintenance during the planning phase. If minimal maintenance can be conducted due to financial and logistical constraints, a method should be chosen that is unlikely to sustain damage during high-energy weather events, such as very large concrete structures or rock piles. Tropical cyclones tend to occur less frequently near the equator (within 5° N/S), meaning that regions such as the Maldives, Indonesia, and Kenya, rubble stabilisation efforts are more likely to remain intact over longer periods with less maintenance, if installed properly. On the other hand, regions where cyclones are more common (latitude 5°-30° N/S) may require additional efforts for similar methods.
	Time since last disturbance	Sites that have recently suffered damage, or those where the damage is at a large scale, may require immediate, time-sensitive interventions. These could include efforts such as rubble removal or substrate repositioning and reattachment.
	Rubble bed condition	In the case of ship groundings, rubble may be contaminated by substances like paint and antifouling. These contaminants can be bio-available in the marine environment many years after the grounding. Appropriate methods in this case might include capping the contaminated rubble or removing the rubble and the accompanying water to appropriate disposal facilities. Despite being expensive, other stabilisation methods may not adequately protect the reef environment from the contaminants.
	Larval Supply	In sites where coral recruitment levels are expected to be low due to limited larval supply, consider a combination of coral transplantation and gardening with stabilisation methods (Edwards, 2010). Stabilisation methods can be supplemented with biological restoration techniques to jumpstart coral community recovery and add fecund individuals to the naturally recruiting population. This also helps to immediately enhance rugosity, structural complexity and increase the abundance of invertebrates and fish.
Socio-economic	**Budget**	Costs of transportation, specialised equipment, materials, labour, and appropriate insurances during implementation, monitoring, and maintenance, need to be carefully considered before the project commences. The choice of transportation and materials (particularly for deploying structures) and the decision to use organisms like coral and sponges can significantly increase costs. However, stakeholder support and volunteer involvement can help offset labour costs, especially during project implementation and monitoring (Bruckner, 2006). The growing trend of volunteer participation through eco-tourism ventures and citizen science is enhancing the feasibility, effectiveness, and reach of restoration projects, which were previously reliant on traditional funding and paid staff (Bruckner, 2006). However, careful management is required to avoid exploitation of volunteers and to maintain the scientific integrity of projects.
	Logistics	It is critical to consider resource availability and staff capacity because logistic requirements vary between methods. Certain tasks, such as handling boulders or reattaching large bommies, may require heavy machinery and the involvement of contractors.
	Workplace safety	Many methods typically require scuba divers, with some requiring direct contact with the substrate and/or marine organisms. This can include tasks such as manually removing, repositioning, and reattaching substrates, coral transplantation, and sponge seeding. It is important to ensure that divers are adequately trained, certified and equipped with protective gear for their safety. Gloves are imperative, for example, when handling coral rubble.
	Regulatory requirements	Understanding the relevant regulatory and approval processes is essential to ensure compliance with legislative requirements. Permissions may be required for specific activities in marine environments, such as scuba diving, deployment of structures, using machinery and handling live organisms and substrate (e.g., coral transplantation, removal of rubble, macroalgae, and/or predators etc.). Identify and contact local, provincial, state, and federal government agencies early in the project planning phase to determine the required permissions, streamline the application process, and prevent delays or unexpected hurdles. For example, the permission and approval processes in Australia can be complex, especially in World Heritage listed marine protected areas like the Great Barrier Reef Marine Park (GBRMP). Any activities proposed within the Great Barrier Reef Marine Park may require approval under State and Commonwealth legislation. Please contact the Reef Authority on (07) 4750 0860 or assessments@gbrmpa.gov.au for further advice. Alternately, review information on the Reef Authority website on how to apply for a permit (**Permits | gbrmpa**).
	Aesthetics	Aesthetics, though often overlooked, are a critical consideration, especially for projects involving volunteers or tourism-dependent sites. Aesthetics are usually subjective, but studies suggest that visitor enjoyment is largely dependent on the "naturalness" of the environment (Shafer et al., 1998; Tallman, 2006). Given that visitors value natural-looking, diverse, and non-repetitive landscapes, methods that aim to recreate the appearance of undisturbed reefs may be preferred. Transplanting corals, particularly familiar species like *Acropora* also contributes to people's perception of the ecosystem as healthy and attractive (Tallman, 2006). If aesthetics is a priority, structures that appear natural immediately upon deployment may be preferred. Otherwise, it may take time for natural coral recruits and/or coral outplants to grow over structures, leaving them visually unappealing in the short term.
	Social licence / stakeholder attitude	Stakeholders including project proponents, management agencies, local communities, Traditional Owners, environmental organisations, and the scientific community may have conflicting opinions about the use of different methods (Sutton & Bushnell, 2007). Understanding the perspectives and values of various stakeholders is crucial for a successful project management strategy, particularly for stakeholders directly impacted by the intervention.

Figure 33.
Decision diagram for selecting suitable stabilisation method(s) for rehabilitating and/or restoring a rubble bed (Ceccarelli et al., 2020). Source: Shu Kiu Leung, The University of Queensland

The decision diagram below encapsulates all considerations discussed above and serves as a primary guide for method selection. We strongly advise seeking expert opinion prior to implementation. For further advice, please refer to the stabilisation methods sections and the decision-making tool in Chapter 3, **RRAP Rubble Stabilisation Intervention Toolbox**.



Read more:
We also recommend readers to consult the resources listed below for more information regarding how to choose an appropriate rubble stabilisation method:

- **Reef Restoration Concepts & Guidelines: Making sensible management choices in the face of uncertainty** (Edwards & Gomez, 2007)
- **Reef Rehabilitation Manual** (Edwards, 2010)
- **Substrate stabilisation and small structures in coral restoration: State of knowledge, and considerations for management and implementation** (Ceccarelli et al., 2020)
- **KulBul Decision Tree Manual** (Singleton et al., 2023) and their **website** for more information

Source: Peter Mumby

A global overview of current efforts in rubble stabilisation

Active restoration is an increasingly important tool for coral reef conservation, alongside traditional passive restoration approaches such as habitat protection through the establishment of marine protected areas (Boström-Einarsson et al., 2020a). Oftentimes, the goal of active restoration is to provide a temporary solution until passive methods enable natural recovery.

While coral reef restoration projects are becoming more common, their scale remains notably limited. Most active reef restoration efforts to date are focused on biological methods like coral transplantation and gardening, with most projects located in the Caribbean and Southeast Asia (Boström-Einarsson et al., 2020a).

These projects are typically experimental and small-scale, covering tens to hundreds of square metres over short timeframes, due to the patchiness of reef degradation and prohibitive costs at larger scales (Bayraktarov et al., 2019; Boström-Einarsson et al., 2020a; Ceccarelli et al., 2020). Larger projects, covering a few thousand square metres to a few hectares, are usually funded by industry, insurance companies, or governments, aiming to rehabilitate impacted reefs or offset damages (Edwards, 2010). However, the most extensive effort to date covers only 8 hectares of reef, a scale that pales in comparison to restoration efforts for other coastal habitats like mangroves (7,920 hectares), seagrasses (3,600 hectares), and salt marshes (2,750 hectares) (Edwards et al., 2024).

Rubble stabilisation is a relatively recent and developing concept in the field of active coral reef restoration. The approach of stabilising loose rubble beds to aid reef recovery was first used in the Maldives in 1993 for restoring mined reefs, notably later than coral transplantation in 1979 (Boström-Einarsson et al., 2020b). In recent years, significant efforts have been made to develop and refine various rubble stabilisation methods (Ceccarelli et al., 2020).

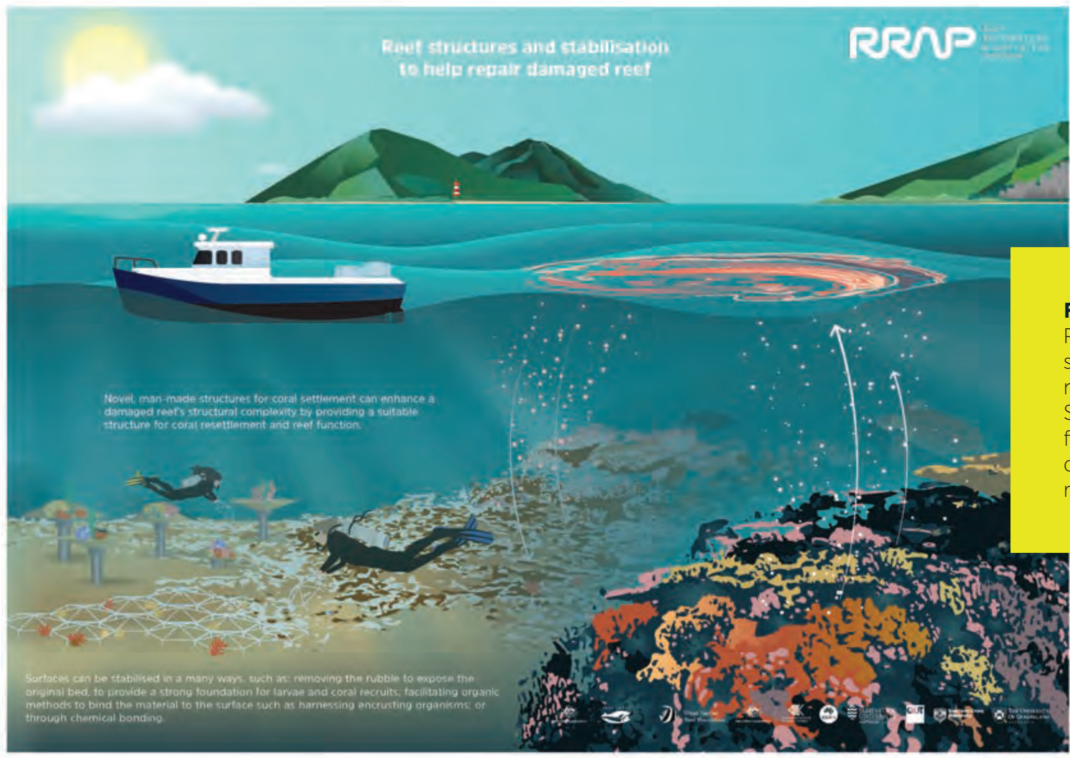


Figure 34.
Reef structures and stabilisation to help repair damaged reef. Source: RRAP, retrieved from https://gbrrestoration.org/rrap-about-us/rrap-resources/

Table 4. Classification of rubble stabilisation methods.

Method category	Purpose and application	Examples
Direct manipulation of the substrate	Removing, rearranging, and/or reattaching substrates to directly restrict rubble movement. Methods in this category are generally considered rapid emergency responses following disturbances such as extreme weather or ship groundings, though they may also be applicable in other scenarios where disturbances occurred some time ago.	• Rubble removal • Substrate repositioning and reattachment • Reef Bags (bagging up rubble into piles) • Bio-adhesives (a novel method being developed as an alternative to other chemical adhesives like cement and epoxy)
Addition of structures to restrict rubble movement	Adding structures designed to restrict rubble movement directly, either by pinning it down, or acting as barriers to prevent downslope avalanches. Structures may also provide stable surfaces for coral recruitment.	• Flat structures (meshes and grids) • Barrier fences
Addition of structures to provide alternative substrate	Adding structures to provide stable and elevated surfaces for coral recruitment. Structures may protrude vertically into the water column, replacing lost rugosity and topographic relief, thus limiting rubble movement indirectly (reduced water flow around vertical protrusions). These structures can be made from a variety of materials, such as limestone, steel, concrete, and ceramic etc.	Basic structures/techniques: • Rocks and boulders • 3D metal frames – Mineral accretion technology on metal structures • Concrete blocks Branded structures designed for specific purposes: • MARRS (Reef Stars) • Reef Balls • EcoReef modules
Propagation of corals and sponges	Transplanting and nursery rearing of corals and sponges, to aid in rubble binding or to increase coral cover. Methods in this category are often combined with the addition of structures, to accelerate reef recovery.	• Coral transplantation and gardening • Sponge seeding

Rubble stabilisation methods can be broadly classified into four categories: 1) direct manipulation of the substrate, the addition of structures to 2) restrict rubble movement, and/or 3) provide alternative substrate, and the 4) propagation of corals and sponges (**Table 4**).

The majority of stabilisation efforts globally have concentrated on rubble removal and the addition of rocks or artificial structures made of concrete (Ceccarelli et al., 2020; Rinkevich, 2005). Branded structures like Reef Stars and Reef Balls are also used in numerous countries.

Rubble stabilisation efforts vary significantly across different regions. In US waters and the Caribbean, common practices for restoring ship grounding scars include rubble removal, reattachment of coral and rubble, and the deployment limestone rocks (Continental Shelf Associates Inc., 2006a; Wever, 2022). In Southeast Asian countries like Indonesia and the Philippines, where rubble is often generated by blast fishing or boat anchoring, there is a focus on using structures that are affordable, easily manufactured, and easy to deploy. These structures are often made from locally available or easily sourced materials, including rocks, meshes, concrete blocks of various sizes, and rebar (Fox et al., 2003; Raymundo et al., 2007; Taylor, 2020; Veenland, 2023). In Australia, stabilisation structures have primarily been used on small scales, in an experimental capacity to test their feasibility and effectiveness. These structures include flat meshes, various metal frames designs (with and without mineral accretion), and Reef Bags (Cook et al., 2023; Rissik et al., 2019). Larger-scale efforts in Australia have involved rubble removal in response to ship grounding events.

The extensive use of artificial structures poses risks to the reef environment, particularly when projects fail and/or are abandoned due to insufficient resources for monitoring and maintenance. There is increasing evidence of failed projects leaving discarded structures on the reefs they aimed to restore (Boström-Einarsson et al., 2018). While some structures might not necessarily cause harm if left unattended, the lack of maintenance could render them ineffective and reduce the aesthetics of the site. Therefore, it is crucial to have a robust project plan in place before deploying any structure and to ensure ongoing monitoring rather than simply deploying and forgetting (see section **Monitoring and evaluating project success**).

Rubble stabilisation methods remain under-studied, despite existing research on the mechanisms and consequences of rubble bed generation and persistence on coral reefs (Kenyon et al., 2020; Kenyon et al., 2023a). Many have not been tested within a scientifically rigorous experimental framework and are labour-intensive and costly to manufacture and/or deploy. Below, we present a comparison matrix of these methods and their suitable environments, focusing on costs, logistics, maintenance requirements, and scalability (**Figure 35**). The comparison matrix, though based on limited data, represents our best understanding at the moment. For details on the expected outcomes and effectiveness of each stabilisation method, refer to the "What realistic outcomes can we expect?" subsections under each method and explore the **RRAP Rubble Stabilisation Intervention Toolbox.**

Figure 35.
Evaluation of various rubble stabilisation method based on four key criteria: overall costs per square metre, logistics requirements, maintenance requirements, and implementation scale. Suitable environments are also listed for each method. The overall costs, which vary widely for some methods, includes material, labour, and installation expenses. Logistics requirements assess the minimum personnel and technical support (e.g. heavy equipment) needed. Maintenance requirements take into account task complexity and frequency. Implementation scale indicates the size of a restoration area. The parameters were first averaged for each method. Then, a score was assigned to each criterion for every method based on the distribution of the values. Scores are given to each criterion at a scale of 1 (lowest/smallest) to 5 (highest/largest). Bio-adhesives and sponge seeding are not included in this evaluation due to the absence of available cost information at the time of writing.

Source: Data from RRAP Rubble Stabilisation Workshop 2023 (**see Box 4**), *Coral transplantation and gardening costs from Bayraktarov et al. (2019)

Source: Peter Mumby

Implementing rubble stabilisation methods

This section discusses four types of rubble stabilisation methods:

1) direct manipulation of the substrate,

the addition of structures to

2) restrict rubble movement and/or

3) provide alternative substrate, and the

4) propagation of marine organisms like corals and sponges.

We discuss the steps for implementation, strengths, weaknesses, expected outcomes, and optimal conditions for each method.

Direct manipulation of the substrate

In this section, we discuss **methods that directly manipulate the substrate** to achieve rubble stability and accelerate subsequent coral recovery.

These methods do not involve adding new or non-biodegradable materials to the rubble bed, but rather focus on limiting the movement of rubble pieces by altering or removing the existing rubble material.

This can be done in several ways, including repositioning or bagging up the loose rubble into more stable piles, capping rubble pieces with cement, or removing the rubble to expose the hard substrate underneath.

We also discuss the use of bio-adhesives, a method currently under development that falls under this category and could be applied for rubble stabilisation.

Rubble Removal

Rubble removal is a common technique for restoring areas impacted by ship grounding within the US territorial waters (Ceccarelli et al., 2020). Yet this method isn't confined to the United States – it has also been applied in multiple instances of ship groundings in Australia.

Notable incidents include the groundings of Bunga Teratai Satu in 2000 on Sudbury Reef and the Doric Chariot in 2002 on Piper Reef (Tilbury, 2003). Another noteworthy case within the Great Barrier Reef Marine Park (GBRMP) is the 2010 grounding of Shen Neng 1 at Douglas Shoal (**see case study 1**), leaving the largest scar to date in the area at over 40 hectares (GBRMPA, 2023). The remediation project for this site continues to date. Moreover, rubble removal has been applied in Southeast Asia, where it was deployed to restore reef areas damaged by a tsunami in 2004 (Ceccarelli et al., 2020).

Rubble removal often acts as the first step of the emergency restoration protocol deployed in response to ship grounding incidents (Challenger, 2006). This vital step prepares the impacted site for subsequent restoration activities, including the **repositioning and reattachment of substrates, coral transplantation, or the addition of structures to provide an alternative substrate and vertical relief**. Given its inherent connection to ship groundings, the financial responsibility for rubble removal and related emergency restoration efforts typically falls on ship owners or is covered by insurance claims (Challenger, 2006).

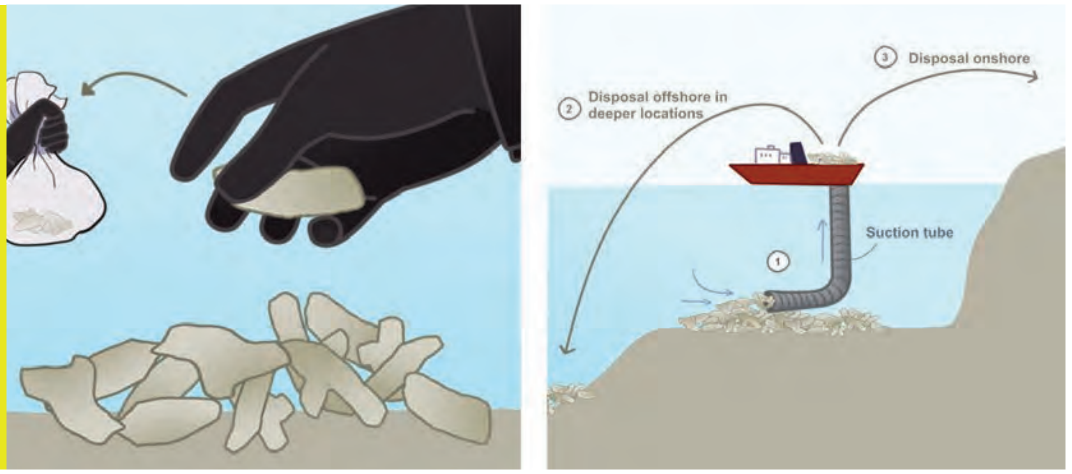


Figure 36.
Rubble removal through manual collection vs suction tube and barge.
Source: Shu Kiu Leung, The University of Queensland

Figure 37.
Locations of rubble removal sites.
Source: Shu Kiu Leung, The University of Queensland

Scale of implementation

The scale of removal operations generally ranges from small-scale efforts covering a few hectares on a single reef to medium-scale projects involving 20 or more reefs (RRAP, 2020). This variability in scale can be attributed to resource availability as well as the location and characteristics of the site. For projects that are larger in scale, it is important to seek expert advice to ensure an optimal and environmentally responsible removal process (Edwards & Gomez, 2007).

How does this method help with recovery?

Reef recovery can be accelerated by removing loose rubble to reveal a hard, stable substrate that is ideal for corals and other sessile organisms to settle on (Ceccarelli et al., 2020).

When and where?

Rubble removal is recommended for timely execution following acute damages, such as ship groundings, when resources are available. When using the method, it is advisable to consider combination with follow-up efforts to enhance structural complexity.

This method can be effective when dealing with relatively thin rubble beds on consolidated reef substrates, especially on sites with flat limestone pavements and low structural complexity (Precht et al., 2001; RRAP, 2020). It is recommended to avoid rubble removal in sites where the substrate underneath is fragile or sandy. Removal in these areas may either leave the substrate unsuitable for coral settlement or risk damaging the underlying reef framework (NOAA, 2017).

Implementation Strategy

The scale of removal further dictates the method employed. Small-scale removal involves manual extraction by divers, with a few kilograms of rubble being collected by hand and placed in bags or bins (Ceccarelli et al., 2020). This method is particularly applicable in cases where rubble may be contaminated by antifouling paint (Tilbury, 2003). On a medium scale, the use of suction tubes and barges enables the removal of hundreds of metric tonnes of rubble (Ceccarelli et al., 2020). For example, The United States National Oceanic and Atmospheric Administration (NOAA) utilises specialised underwater vacuums (**Figure 38**) that extend approximately 10 metres from the boat and bring rubble onto the vessel through connected hoses (NOAA, 2014b). The rubble is then separated from the water and strategically relocated to suitable areas. In this case, rubble is deposited into deeper areas away from the reef, aiming to minimise its environmental impact (Parry, 2013).

Alternatively, rubble can be transported onshore if offshore locations are deemed unsuitable for disposal. The rubble that has been collected can also be used for other purposes, such as constructing artificial reefs. In specific instances, such as the grounding of the Doric Chariot that ran aground on Piper Reef, GBR in 2002, unconventional approaches were tested for the removal of contaminated rubble and sediment. An underwater excavator was initially trialled for this purpose; however, the pressure exerted by the machine inadvertently caused the extrusion of soft clay from the underlying reef matrix, which required significant cleanup efforts (Tilbury, 2003).

Figure 38.
Divers remove rubble using an underwater vacuum in the M/V VogeTrader grounding case, Hawaii. Source: NOAA. Retrieved from https://darrp.noaa.gov/ship-groundings/mv-vogetrader.

Case Study 1:

Douglas Shoal Environmental Remediation Project, Great Barrier Reef, Australia

Background

In April 2010, a bulk carrier Shen Neng 1 grounded on Douglas Shoal (GBRMPA, 2023) (**Figure 39**). The significant damage it caused included contamination from the antifouling paint, generation of substantial amounts of rubble, and compaction of sediment. In response to the grounding scar spanning approximately 42 hectares, the Reef Authority obtained a A$35 million settlement from the ship's owners and insurers to fund remediation efforts.

Douglas shoal is a large non-biogenic, submerged shoal-reef located in the southern GBR, approximately 90 km east of Yeppoon (Costen et al., 2017; GBRMPA, 2011). Its depth ranges from about 11 m below the surface to a seafloor depth of 25-30 m and features a diverse benthic ecosystem. About 10% of benthic cover is composed of hard coral colonies, with *Acropora* being the visually dominant species, thriving on a substrate primarily consisting of hard limestone pavement (85%).

The rubble generated by the impact differed from naturally occurring sediments in terms of coarseness, angularity, and the absence of encrusting organisms (Neale & Boylson, 2019). The 2019 site assessment report indicated that this unconsolidated rubble, shifted over time in a westerly direction, altering habitats beyond the grounding footprint by filling natural depressions and disrupting the shoal's habitat complexity. Nearly a decade post-impact, there is limited evidence of recovery at the grounding site (**Figure 40**). Moreover, the antifouling paints scaped off the grounded vessel's hull contain tributyltin (TBT), which is particularly harmful to marine organisms and has been banned under both international and Australian regulations (GBRMPA, 2011).

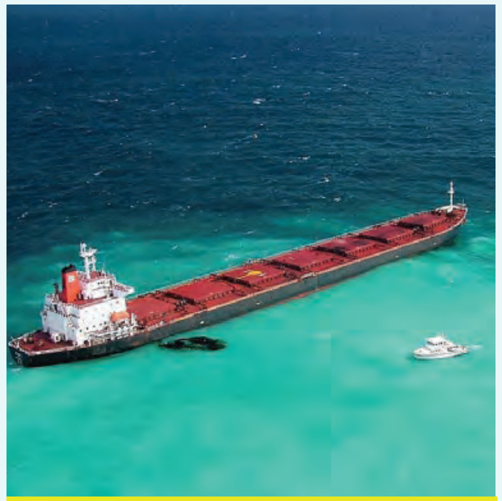


Figure 39.
Shen Neng 1 grounded at Douglas Shoal. Source: © Great Barrier Reef Marine Park Authority

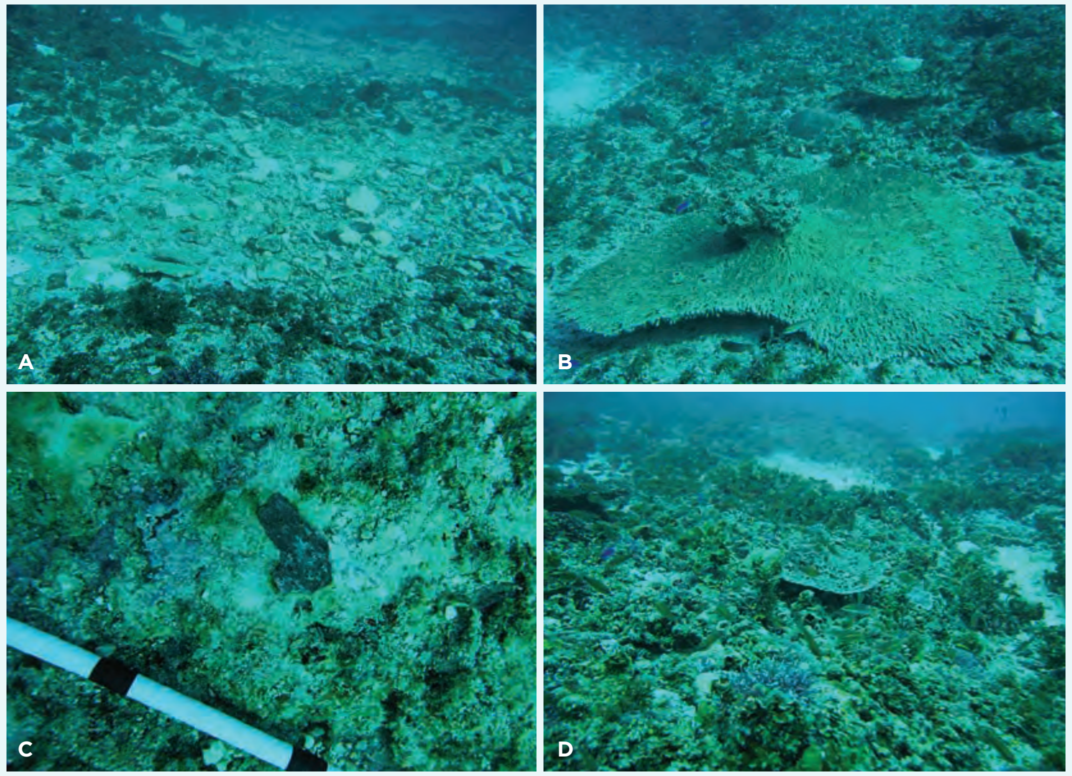


Figure 40.
Photos of substrate taken in Douglas Shoal post-grounding. **(a)** Broken corals and rubble on substrate, and **(b)** overturned *Acropora* Plate coral close to initial grounding location of Shen Neng 1. **(c)** Antifouling paint and metal fragments in the final resting location, and **(d)** undamaged reef substrate adjacent to the final resting location. Source: © Commonwealth of Australia (Reef Authority) 2012 Photographer: P. Marshall

Design and deployment

Considering the severity of the impact and the complexity of the remediation task, the Reef Authority adopted a structured approach with three major work streams: 1) planning and management, 2) remediation, and 3) environmental monitoring.

1) In the planning and management stream, 9.8 hectares of high- and medium-priority areas were identified based on grounding-induced habitat changes (Neale & Boylson, 2019), with bulk rubble removal selected as the optimal option for treatment (Advisian, 2020). Different remediation options were ranked based on their alignment with project objectives, including natural recovery within 10 years, minimising socioeconomic impacts, and meeting regulatory approvals within a specified schedule.

The project emphasized remediation (removing impediments to natural recovery) rather than restoration, which aims to return the area to its historical ecosystem function.

The options analysis report compared various approaches to target rubble, including doing nothing, cement capping, netting, consolidation using **Reef Bags**, and different removal techniques (**Figure 41**). In general, removal methods outperformed non-removal options in terms of consideration of cost, duration, and safety (Advisian, 2020). Surprisingly, doing nothing was not the least favourable choice. Bulk removal via suction hopper with onshore disposal outranked offshore disposal and diver-assisted small-scale targeted removal. The removal strategy also gained support from Traditional Owners with there being no introduction of foreign materials into the marine environment.

2) The on-ground remediation activities were executed in September 2023 using the Trailer Suction Hopper Dredge "Gateway" to remove rubble and water at priority areas (GBRMPA, 2023) (**Figure 42**). The dredge vessel travelled back and forth to Gladstone where materials and water were transported onshore through installed pipelines. Rubble and water were transferred into specially constructed ponds in Gladstone for subsequent treatment and management (**Figure 43**).

The project removed approximately 3,300 m^3 of solid materials created by the original grounding on Douglas Shoal. Onshore management and treatment of water and material removed from Douglas Shoal was ongoing at time of finalisation of these Guidelines (Darren Cameron, Reef Authority, pers. comm.).

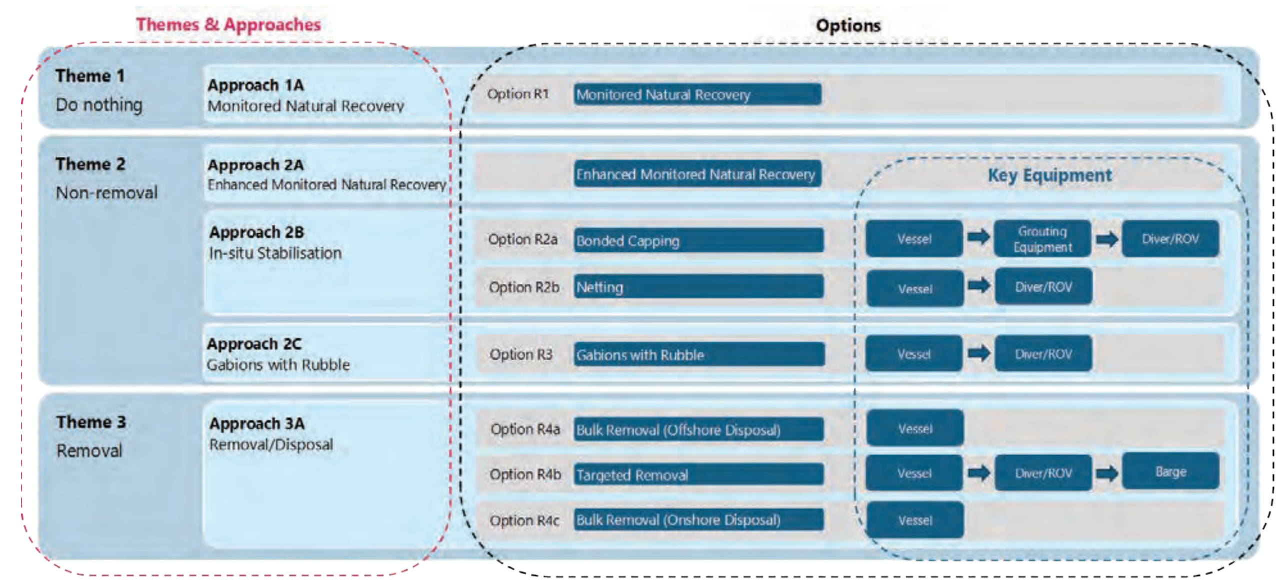


Figure 41. Remediation options for rubble stabilisation evaluated in the options analysis report. Adapted from "Douglas Shoal Remediation Project: options analysis executive summary" by Advisian (2020).

Left: Figure 42. Trailer Suction Hopper Dredge – "Gateway" Source: © Great Barrier Reef Marine Park Authority
Right: Figure 43. Floating pipeline transporting dredged materials from the dredger to onshore ponds in Gladstone. Source: © Great Barrier Reef Marine Park Authority

Results/findings

Environmental monitoring included extensive baseline surveys and monitoring reports, aiming to assess the environment before, during, and after the remediation works (GBRMPA, 2023). Post-remediation environmental monitoring of Douglas Shoal indicates that remediation of the shoal has: removed ship-grounding generated rubble from across the shoal (**Figure 44**), produced consolidated substrate in an early colonisation state, caused little collateral damage to the shoal and reduced the intensity of anti-fouling paint in the sediment (though it is still prevalent at the initial ship-grounding impact site) (Cameron, pers. comm.).

Lessons learned:

- It is advisable to consider the scale and workplace, health and safety matters (diver-assisted vs suction tube and barge vs large offshore vessels) and disposal methods (offshore vs onshore) when dealing with rubble removal.
- Rubble stabilisation projects require extensive planning, sometimes with preparation being more time-consuming than the actual remediation.

Read more about the case at the Douglas Shoal Environmental RemediationProject:

www2.gbrmpa.gov.au/our-work/programs-and-projects/douglas-shoal-environmental-remediation-project

Figure 44. Part of remediation site before (top) and after (bottom) rubble removal. Source: © Great Barrier Reef Marine Park Authority

What realistic outcomes can we expect?

Rubble removal may promote coral recruitment and settlement by exposing hard substrate, and in turn, increase the rate of reef recovery (Ceccarelli et al., 2020), yet its contribution to restoring the original reef structure can be limited.

Although rubble removal can function as a standalone stabilisation method, it is often viewed as a precursor to other emergency restoration efforts. There is limited scientific literature or reports examining the isolated effects of rubble removal as a stabilisation method. For example, in emergency restoration efforts in US territorial waters, removal is often immediately followed by **coral reattachment** or **transplantation** (Parry, 2014), and results typically report a combination of different methods. This makes it challenging to present a general trend of recovery outcomes for rubble removal.

Some studies suggested that rubble removal has minimal effect on increasing structural complexity in the short term, which may explain the limited increase in fish abundance and diversity at restored sites (Challenger, 2006; Ebersole, 2001). While coral growth over time may eventually enhance structural complexity, other methods that add structures can provide these benefits more quickly. In the Florida Keys marine sanctuary, studies found similar fish abundance and assemblages at remediated grounding sites compared to untreated sites (Ebersole, 2001).

Given the importance of herbivory in reef resilience, the benefits of rubble removal on larval settlement may be limited without the necessary habitat structure to support fish assemblages.

The significance of structural complexity becomes clearer when we look at evidence suggesting that initially high-relief areas, such as spur and groove systems that were flattened by groundings, may not fully recover and transition to an alternate community structure after remediation through rubble removal (Precht et al., 2001). On the flip side, sites originally with limited structural complexity that were restored using rubble removal and subsequent substrate reattachment can return to a healthy state similar to nearby natural sites within 10 years.

Costs and maintenance

Manual removal of rubble is typically the least costly option but limited in restoration area it can cover. For larger-scale rubble removal projects involving barges and heavy machinery, costs typically range from US\$133-323/m^2 (~A\$200-489/m^2) (**Figure 35**), depending on factors such as location, personnel, and procedures (e.g., barge use and rubble disposal methods). Many projects associated with ship groundings and are funded by the responsible parties. For example, a recent large-scale project in the GBR, Australia, involved a A\$35 million settlement for the removal of contaminated rubble from a ship grounding (see **case study 1**). Maintenance requirements for such projects are generally minimal or none.

Pros	Cons
• Encourage coral settlement by revealing the hard substrate. • Immediate stabilisation of the substrate. • Potential for beneficial reuse of collected rubble. For example, rubble can be organised into piles as **Reef Bags.** • Requires little to no ongoing maintenance.	• Rubble disposed offshore (if applicable) may have negative impacts on marine ecosystem. • May lead to the death or displacement of organisms such as algae, sponges, and small crustaceans that inhabit or rely on rubble. Disruption to these communities may adversely impact various ecosystem functions. • The method does not significantly increase three-dimensional structural complexity until significant coral growth occurs.

Table 5. Pros and cons of rubble removal (Cameron, pers. comm.; Ceccarelli et al., 2020).

Substrate repositioning and reattachment

Similar to rubble removal, substrate repositioning and reattachment are essential components of post-impact emergency responses. The tasks involved in these efforts are often referred to as **biological triage** (**Box 7**).

Scale of implementation

The scale of implementation can vary widely depending on the approach. Small-scale community projects in Fiji, Indonesia, and the Middle East (**David Lennon**, The Australian Institute of Marine Science, pers. comm.), along with larger initiatives in Australia (McLeod et al., 2019b), have repositioned dislodged corals and rubble in response to extreme weather events as well as human impact. On the other hand, larger-scale reattachment efforts, particularly in response to ship groundings, are more common in the United States.

Box 7

Biological triage

(Continental Shelf Associates Inc., 2006a; Edwards & Gomez, 2007)

The concept of "biological triage", just like first aid, aims to address acute damage, enhance survival rates of displaced organisms, and prevent further deterioration of the habitat.

Tasks can include repairing reef framework, as well as repositioning and/or reattaching displaced corals, loose rubble, and other sessile reef organisms, or in some cases, mobile organisms such as urchins and sea cucumbers.

When determining the order of priority for each reef component, factors such as size, age, placement difficulty, conservation status of the organism, contribution to favourable gene pool, and contribution to topographic diversity might be worth considering.

Special attention may be given to dislodged corals that are particularly vulnerable to abrasion from rubble movement and sedimentation. For example, it is recommended to focus on shorter, single-branch fragments with live tissue in contact with the substrate to avoid further damage. When done right, emergency triage can significantly aid short-term reef recovery efforts.

How does this method help with recovery?

Repositioning and reattaching corals and rubble promotes natural recruitment by stabilising the substrate and restoring the original habitat structure (Ceccarelli et al., 2020). The stabilised rubble becomes a more suitable substrate for coral recruitment, while the increased structural complexity supports diverse organisms.

When and where?

Timing is key to minimise tissue loss and enhance survivorship (Continental Shelf Associates Inc., 2006b; McLeod et al., 2019b). Ideally, both repositioning and reattachment would be undertaken as soon as possible after the initial impact, provided there are sufficient resources.

For repositioning, it is worth noting that smaller pieces of rubble (<10 cm) may not hold well without cement (Lennon, pers. comm.). This method may not be suitable for areas with fine rubble. Reflecting on the case of the Whitsunday Islands (**case study 2**), repositioning could be more applicable to very large rubble, which would typically only be moved during exceptionally rare events.

Using cement for attachment requires careful consideration of the substrate's suitability. In some cases, porous substrates may not retain cement and remain unstable (Florida Keys National Marine Sanctuary, 2015). A thorough, expert-led initial site assessment is recommended to determine the suitability of the substrate for cement use.

While reattachment may offer more stability compared to repositioning alone, both methods may struggle in sites prone to frequent, intense disturbances. Follow-up maintenance, especially after storms or cyclones, can significantly increase costs and may not be cost-effective in the long run. Therefore, it's advisable to opt for areas with calmer waters and at most occasional disturbances. It is important to recognise that repositioning and reattachment may serve better as temporary measures, and it might be a good idea to combine them with other methods.

Figure 45. Locations of substrate repositioning and reattachment sites. Source: Shu Kiu Leung, The University of Queensland

What realistic outcomes can we expect?

Both repositioning and reattachment may yield positive short (<1 year) to medium-term (1-5 years) results, including increased coral recruitment, settlement, recruit survival, as well as fish abundance and diversity. These outcomes indicate a positive effect on reef recovery, though the long-term (>5 years) stability of repositioned/reattachment substrate remains uncertain.

For repositioning, there is limited data on coral recovery outcomes, and long-term monitoring is particularly lacking. This makes it challenging to describe a general recovery trajectory when relying on primarily anecdotal evidence. Observations in the short to medium term generally suggest an increase in coral settlement, fish abundance, and fish diversity. For example, in Whitsunday Islands, successful settlement of recruits from 10 genera onto bommies was observed 16 months post-restoration (McLeod et al., 2019b). Additionally, 20 species of reef fish were observed utilizing the habitat, effectively controlling algal growth through herbivory. Small-scale community trials in Bali and Fiji also demonstrated immediate increases in fish abundance within minutes of repositioning (**Lennon**, pers. comm.).

However, without proper anchorage to secure the repositioned structure, it risks being disturbed by periodic events like storms or cyclones. Therefore, repositioning loose rubble may not suffice as a standalone permanent solution in some locations.

There are more data available on reattachment efforts conducted in US waters. In Puerto Rico, reattachment of rubble and fragmented corals after ship-groundings and hurricanes has led to higher recruitment rates and higher survival of recruits. For example, at the 2006 T/V Margara grounding site (**see Box 5**), hard coral recruitment survival rates in restored areas reached 40-42% from 2008 to 2012 (NOAA, 2015). Although these rates have not yet matched those in reference areas, they significantly outperform the 0% survival observed in unrestored areas.
Similarly, following the grounding of LNG/C Matthew in 2009, significantly higher recruitment rates were observed in restored areas compared to unrestored and reference areas by 2015, along with a higher cover of CCA (18.6% compared to 0% in unrestored sites), which is favourable for coral recruitment (Flynn et al., 2015).

However, like repositioning, it can be difficult to keep rubble and corals attached and/or stable over time as they can remobilised in disturbance events (Flynn et al., 2015; Gilliam & Moulding, 2012; Olsen Associates Inc., 2016). In the LNG/C Matthew case, 10% of hard corals were found missing in 2015, most likely due to detachment, overgrowth of benthic organisms, imprecise mapping, and time constraints during monitoring (Flynn et al., 2015). *Acropora cervicornis* colonies were particularly susceptible to detachment from storms and wave actions. Moreover, in the grounding cases of Spar Orion and Clipper Lasco, both occurred in 2006 in Florida, USA, the presence of scattered and loose rubble, as well as isolated boulder piles, continued to pose significant challenges to recovery, even years following the reattachment efforts (Olsen Associates Inc., 2016).

Table 6. Pros and cons of substrate repositioning and reattachment (Ceccarelli et al., 2020; Lennon, pers. comm.; McLeod et al., 2019b; Sean Griffin, pers. comm.).

Pros	Cons
• Replicates the natural habitat and preserves the original structure. • Uses the existing coral assemblage – no introduction of foreign species. • Provides instant structural complexity and rugosity. • Minimal material costs, potentially none if only repositioning is involved.	• Potential lack of long-term stability – May require multiple maintenance visits if stability is compromised. • The use of Portland cement during reattachment may lead to a high carbon footprint. • Labour-intensive

Limited recovery in terms of low coral cover (0.03-0.1% in restored sites compared to 2.43% in reference sites), low rugosity index, and overgrowth of macroalgae was also observed during monitoring trips 3 and 4 years after emergency restoration at these sites (Gilliam & Moulding, 2012).

When hurricanes hit, the cemented substrate can flake off in large sheets if not secured properly (Shane Wever, NSU Florida, pers. comm.). These cases highlight the significant concern of maintaining long-term stability in repositioned and reattached substrates, a factor that largely contributes to the observed limited recovery.

Box 5

T/V Margara and T/V Sperchios grounding cases

The grounding incidents of T/V Sperchios and T/V Margara occurred in proximity in 2006 in Puerto Rico. The Sperchios grounding site, unlike the Margara, had a hard-bottom substrate with no loose rubble. This presents an interesting contrast in recovery patterns between a rubble field (Margara) and a stable surface (Sperchios).

The number of coral recruits observed at the Margara injury site (no treatment) has remained low over time, whereas the Sperchios injury site has seen a steady increase (**Figure 46**). Furthermore, a comparison of the Margara injury and restoration sites shows that the number of coral recruits in the restored areas has increased over time unlike the rubble sites, highlighting the effectiveness of the reattachment efforts.

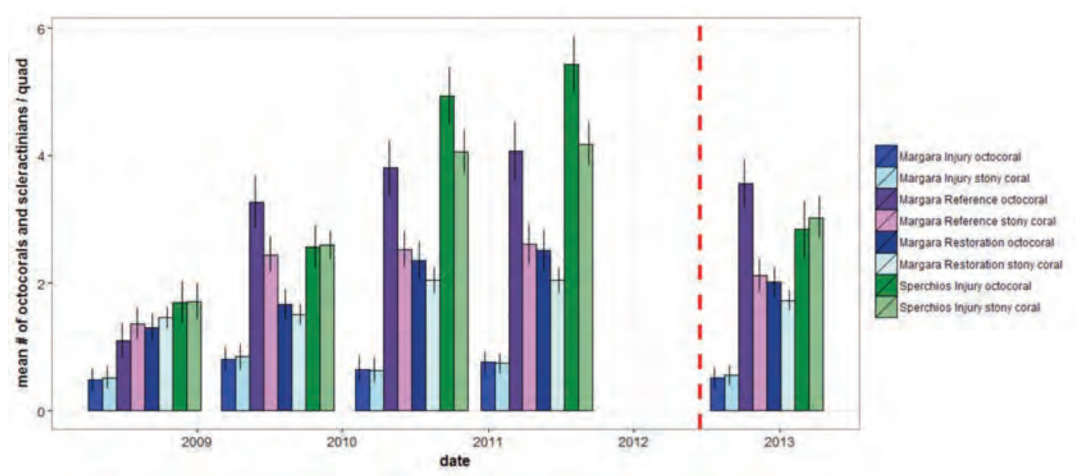


Figure 46. Number of recruits of stony coral and octocorals over time at the T/V Margara and T/V Sperchios grounding sites. Red dotted line represents Tropical Storms Ernesto and Isaac. Error bars represent standard error of the mean. Adapted from "Final Primary Restoration Plan and Environmental Assessment for the 2006 T/V Margara Grounding Guayanilla, Puerto Rico" by NOAA (2015)

Repositioning

Implementation Strategy

Small-scale projects require minimal equipment and technical knowledge, and implementation via snorkelling may be feasible in shallow waters (Lennon & Walch, 2018).

When rearranging rubble, it is recommended to wiggle pieces back and forth until they interlocked with each other as best as possible to ensure the stability of the pile. Please note safety precautions, including the use of personal protective equipment to prevent puncture wounds or stings are essential during manual handling.

During the transportation of rubble on decks of vessels, it is recommended to place a tarp both underneath and on top to keep the rubble moist and shaded. This practice assists in preserving any live fauna or flora that is attached to the rubble. Any fauna that crawls or drops out of the rubble can be collected in the bottom tarp and returned to the seabed along with the rubble.

Large-scale projects may require heavy machinery such as cranes and barges (see **case study 2**). It is recommended that contractors and experts are consulted before implementation.

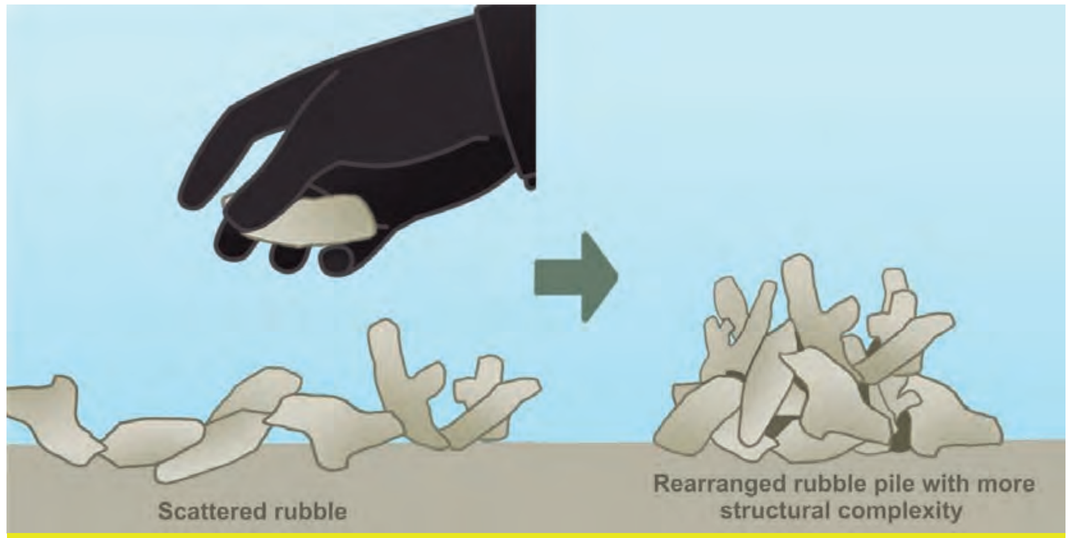


Figure 47.
Rearranging scattered rubble pieces into an interlocking pile with higher stability and structural complexity that increases refuge and opportunities for nature. Source: Shu Kiu Leung, The University of Queensland

Case Study 2:

Repositioning 400 tonnes of bommies after Cyclone Debbie to restore reefs in the Whitsunday Islands

(McLeod et al., 2019b; Neil Mattocks, Reef Authority, pers. comm.)

Background

In March 2017, category 4 tropical cyclone Debbie struck the Whitsunday islands, flattening much of the coral reefs in the area. Manta Ray Bay, located within the Whitsunday Island group, is a popular tourist destination in the region. It is recognised for its abundance reef fish populations due to its complex reef habitat and diverse coral community.

Large *Porites spp.* Bommies, which are key habitat forming species at the location, were dislodged from the reef slope at Manta Ray Bay and left stranded in the intertidal zone (**Figure 48**). This event had devastating effects on both the ecosystem and tourism appeal of the region.

Design and deployment

Recognising the importance of restoring the damaged reef, local tourism operators requested assistance from the Queensland Parks and Wildlife Service (QPWS) and the Reef Authority to reposition bommies to the subtidal reef flat.

Heavy machinery, including a 30-tonne long-arm excavator and a 4-tonne compact track loader, was employed to roll the bommies over the reef flat and push them onto the reef slope. At an estimated cost of AU$30,000, 400 tonnes of dead coral substrate were repositioned.

Results/findings

A follow-up assessment in August 2017, 16 months post-treatment, found that the repositioned bommies not only provided safe environments for in-water tourism activities but also served as thriving habits for reef fish (**Figure 49**). The majority (73%) retained some live coral tissue, with some (36%) even hosting a diverse range of coral recruits across 10 genera.

Figure 48.
Bommies washed onto the shore. Source: Sascha Taylor, Queensland Government

Lesson learned:

- Timely repositioning of corals to their original orientation may accelerate reef recovery through increased coral recruitment as well as reef fish abundance and diversity.
- Replaced 3D structures provided an elevated substrate for recruits, keeping them away from the sediment caused by cyclones lower in the water column.
- Repositioning bommies improved visitor experience.
- The use of *in situ* materials may simplify permitting processes (without needing approval under the Commonwealth Sea Dumping Act) and allow for quicker action.
- Despite promising results, relocated bommies are likely less stable than pre-cyclone conditions and may be mobilised in future storms. A potential shift in coral community structure from long-lived, slow-growing, and stress-tolerant species to more vulnerable species that are short-lived, fast-growing, and stress-susceptible may also occur as a result. It is important to consider long-term stability in project design.

Figure 49.
Relocated bommie after 6 years (natural coral recruitment only). Source: Maya Srinivasan TropWATER JCU

Size and configuration

When selecting rubble for repositioning, it might be beneficial to prioritise stability and increased structural complexity (Lennon & Walch, 2018).

Having various sizes and orientations of rubble helps to keep the habitat diverse in structure while maintaining its stability against water flow (Lennon & Walch, 2018). Smaller rubble piles may be more susceptible to mobilisation due to their higher exposure to flow along their edges. Larger rubble pieces of about 30 to 40 cm can be used to create protective "walls" surrounding smaller piles that can provide respite from currents for organisms, reduce movement of smaller rubble pieces, and create current eddies that hold plankton in the vicinity longer for planktivorous fishes (**Lennon**, pers. comm.). Furthermore, rubble can also be arranged to create cryptic protective spaces for fishes and marine invertebrates.

Arranged rubble piles can be oriented to mimic the natural environment, though piles parallel to the current have been observed to trap plankton and nutrients more readily for sessile filter feeders. It is recommended to trial a range of orientations to help increase diversity and explore whether different orientations cater to different species or are more effective.

It is also recommended that rubble piles are placed close to each other and no further than the diameter of the pile, similar to the strategy employed in positioning artificial reefs (**Lennon**, pers. comm.) (**Figure 50**). This could enhance connectivity between the piles and increase protective spaces for fish and other cryptic organisms. For example, in a lagoon restoration project in Fiji, larger rubble pieces (>10 cm) with live corals were rearranged into more stable piles. However, the initial spacing of 3-10 m between the rubble piles did not attract as many fish as anticipated. After reducing the spacing to between 0.5 and 1 m, there was a rapid increase in the abundance and diversity of fishes (**Lennon**, pers. comm.).

While branching fragments are more likely to interlock and stabilise (Rasser & Riegl, 2002), heavy, unbranched rubble may also be used for repositioning (**Lennon**, pers. comm.).

Costs and maintenance

Repositioning rubble incurs minimal to no material costs; however, maintenance can be challenging. There is no guarantee of long-term stability of the repositioned rubble, thus they may easily shift again during physical disturbance events such as storms, requiring significant efforts to maintain the restoration site.

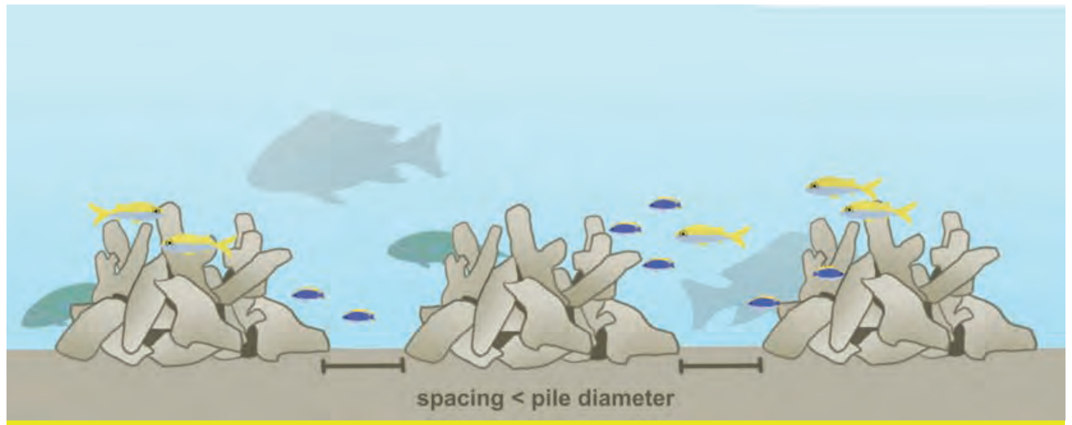


Figure 50.
Placing rubble piles close enough to create protective space for organisms. Source: Shu Kiu Leung, The University of Queensland

Figure 51.
Before (left) and after (right) rearrangement of a rubble bed in Bali, Indonesia creating more vertical relief and protective spaces for fish. Source: David Lennon

Expert tips

"Rearranging rubble, or what you might call reef landscaping, is a low-tech, low-cost first level action in attempt to improve the ecological functioning of a rubble field. We can arrange loose rubble in ways that support more life than just leaving it flat and buried. It is like taking care of a farm but underwater. Just like farms may need repairs after storms, some rubble landscaping might require some upkeep.

I also view it as similar to town planning, where we think about design principles to benefit the ecosystem as a whole. We think about various creatures like fish, shrimp, crabs, and corals. This means considering connectivity between habitats, different levels of structural complexity, and always aiming to provide protective space for the animals."

David Lennon

David Lennon
is a seasoned professional with over 30 years of experience in marine consulting, design and construction of artificial reefs, coral relocations, and development of environmental products/programs such as Reef CPR for recreational divers. He currently works as a Project Manager for Reef Monitoring and Recovery projects at the Australian Institute of Marine Science (AIMS).

Reattachment

In sites with strong currents or wave exposure where repositioning may not provide adequate stability, additional structural support may be necessary.

Reattachment of corals is a common practice in US waters for repairing reefs physically damaged by hurricanes and ship groundings (Ceccarelli et al., 2020). This often involves adding cement to attach the displaced corals, loose rubble, as well as other injured organisms (NOAA, 2014b). As an example, restoration efforts in Puerto Rico and the United States Virgin Islands reattached over 16,000 corals after Hurricanes Maria and Irma impacted in the islands in 2017 (Viehman et al., 2020).

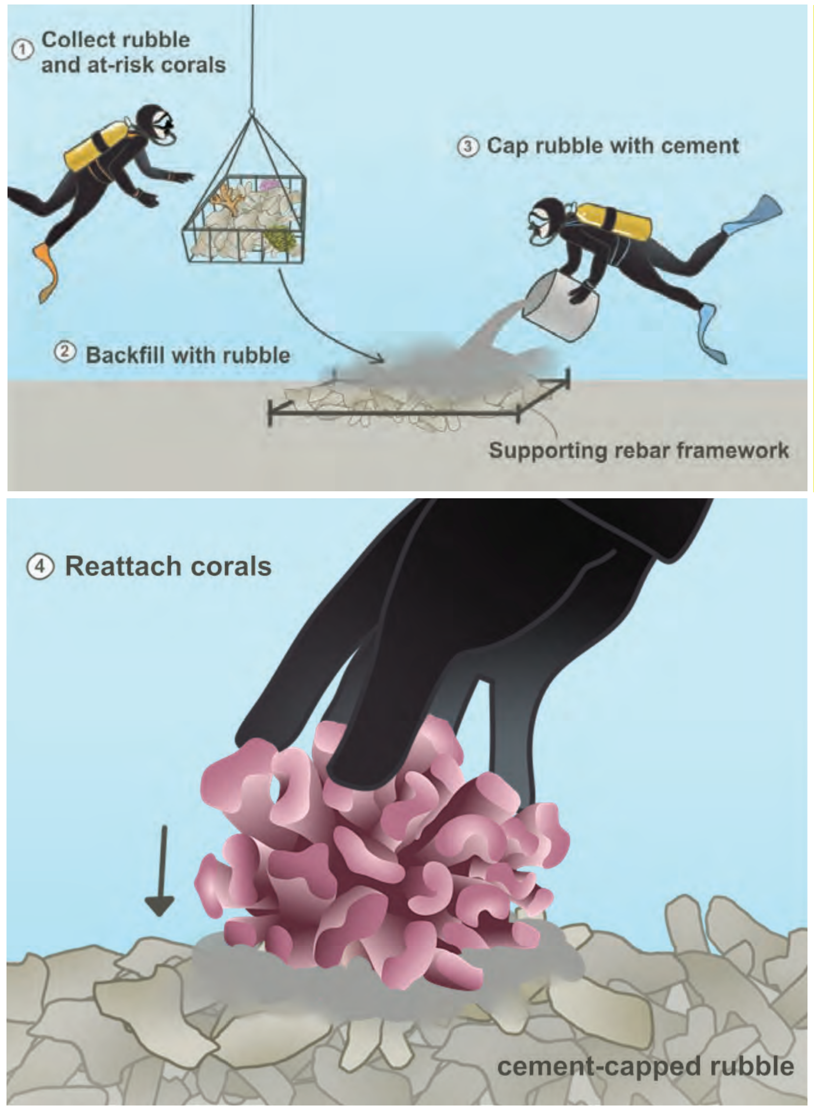


Figure 52.
Process of reattaching rubble and coral fragments to stabilise the substrate.
Source: Shu Kiu Leung, The University of Queensland, adapted from Joanna Woerner, Integration and Application Network

Implementation Strategy

The reattachment process generally involves the following steps (Continental Shelf Associates Inc., 2006a; NOAA, 2014b, 2014c):

1. **Carefully collect dislodged corals and rubble** and stored in a secure location.
2. **Deploy a metal or fibreglass framework** onto the underlying substrate to provide structural support (Continental Shelf Associates Inc., 2006a; Florida Keys National Marine Sanctuary, 2015) (**Figure 53**).
3. **Backfilled collected rubble into the metal framework**, creating a stable base.
4. **Pour cement mixture onto the rubble to hold everything in place.** It is recommended that effort be made to incorporate rugosity in the 'slab', and to create varying ledges and caves (**Figure 54**).
5. **Attach corals by firmly pressing them into the cement mixture** and ensuring they are held in position until securely stable (**Figure 55**).

Figure 53. Divers inserting rebar stakes into the substrate to build the supporting framework. Source: Sea Ventures MRU

Figure 54. Diver applying cement onto prepared substrate. Source: Sea Ventures MRU

Figure 55. Site after reattaching dislodged corals and loose rubble with cement. Source: Sea Ventures MRU

Materials

The choice of cement mix is an important consideration in reattachment projects. The ideal cement is a thick, low-slump mixture that stays where it is applied (Continental Shelf Associates Inc., 2006a). This is especially relevant when the underlying substrate has an uneven surface with numerous bumps and dips. Cement can spread out when applied on uneven surfaces and potentially affect nearby marine life. A good example of an ideal cement mixture specialised for underwater applications consists of Portland type II cement, marble sand, and water, which can minimise dispersion in water (Sean Griffin, pers. comm.). The specialised mixture is prepared on a boat and sent down to divers via lift lines in buckets for direct application onto the prepared substrate. In some cases, a mixture of equal parts Portland cement and silica sand, such as the one used for the 2006 T/V Margara grounding site close to the Bahia de Tallaboa in Puerto Rico, is used and mixed using a commercial mixer (Continental Shelf Associates Inc., 2006a). After reattachment, it is essential to inspect for and clean any leftover cement residue that may have settled on nearby marine life, as the cement usually sets within a few hours (NOAA, 2014b).

Size and configuration

The principle of structural complexity applies to both repositioning and reattachment. Larger pieces of rubble (up to sizes of boulders) can be cemented directly onto the underlying substrate, whereas smaller fragments can be used as backfill and dressing stones to make the site more "natural-looking" (Continental Shelf Associates Inc., 2006b; Polaris Applied Sciences Inc., 2007). Attached corals and rubble can also be spatially distributed to closely replicate natural conditions and restore the area's original rugosity (Continental Shelf Associates Inc., 2006a; Gilliam & Moulding, 2012). Depending on the project goals, it can be helpful to observe and mimic the most productive seascape in the area. This is particularly relevant if the goal is to increase the abundance of certain target species that have specific habitat preferences.

Costs and maintenance

Once reattachment is completed, maintenance is often minimal or unnecessary, although the initial costs can be significant with total costs reaching US\$1,600/m^2 (~A\$2,500/m^2) (**Griffin**, pers. comm.). However, these costs are largely attributed to labour expenses as material costs remain relatively low with the use of *in situ* materials. The investment is often justified by the number of corals rescued and the reduction in expenses associated with growing new corals from scratch (NOAA, 2018).

Expert tips

"When using *in situ* materials to stabilise coral rubble, it is important to secure the structures to withstand any future movement from waves or storms. Structures can be anchored by rebar and cement into solid substrate and/or large enough to prevent mobilisation.

We then use cement to attach corals to the structures to assist recovery especially in areas like the Caribbean where recruitment is low. Corals are sourced from within the impacted areas, outplanted from coral nurseries, and/or transplant at-risk corals from the adjacent reef or other locations with similar environmental profiles. When attaching smaller corals (10-20 cm diameter), it is good to create a 10-20 cm high concrete pedestal to stick them in. Not only does this improve circulation, but the cement also gives them a clean substrate that they can quickly fuse to and not have to compete with algae or other organisms.

Finally, we use orthomosaics to monitor structural stability, changes in rugosity, coral growth and survival, changes in benthic composition and coral recruitment."

Sean Griffin

Sean Griffin
is a coral restoration specialist. His work focuses on coral propagation techniques and mitigating damage from ship groundings and severe weather to reefs in Puerto Rico and the U.S. Virgin Islands. He has extensive experience in various rubble stabilisation techniques, including the use of limestone boulders, metal frames, flat meshes, and cement capping.

Reef Bags

"Reef Bags" are a novel rubble stabilisation method aimed at boosting coral and fish abundance and restoring degraded reefs by collecting rubble into mesh bags to form 'bommie-like' stable mounds (Rissik et al., 2019).

The method was initially proposed by BMT Australia, a technical consulting firm, and developed as part of the Advance Queensland Small Business Innovation Research Challenge for "Boosting Coral Abundance on the Great Barrier Reef" in 2018. The project secured funding from both the Queensland state and federal governments to conduct field trials to assess the method's efficacy.

Scale of implementation

Small-scale trials have been conducted at two reefs on the GBR. These trials aim to demonstrate proof of concept and assess the feasibility of scaling up the method.

Two Reef Bag trials were conducted, Trial 1 in 2019, followed by Trial 2 in 2021, representing a joint initiative between The University of Queensland, BMT Australia, and the Reef Joint Field Management Program (a partnership between Queensland Parks and Wildlife Service and the Great Barrier Reef Marine Park Authority). Trial 1 Reef Bags were deployed in two locations, Bait Reef and Pinnacle Bay (**Box 6**), while Trial 2 Reef Bags were deployed solely at Bait Reef. These sites were chosen for the Reef Bag trials due to the presence of extensive, persistent rubble beds caused by category 4 Cyclone Debbie in 2017, as well as their proximity to sensitive habitats, and the suitability of the bathymetry for placing Reef Bags (Rissik et al., 2019).

Figure 56. Reef Bag Trial 2 deployment at Bait Reef. Source: Conor Jones, BMT

Box 6

Bait Reef and Pinnacle Bay

Bait Reef, located 65 kilometres east of the Whitsunday Island group in Australia, is highly exposed to weather conditions due to its remote offshore location. Winds and swell are predominantly south-easterly and easterly, respectively, and there are moderate currents at the site from tidal flows. Extensive rubble beds are located on the southwestern side of Bait Reef, in a protected, lagoonal area with depths ranging from 2 to 9 m. Rubble beds at Bait Reef generally have a flat to gentle downward slope toward the west.

The reef's predominant benthic cover is rubble, soft coral and some turf algae- and CCA-covered rock.

Pinnacle Bay is a largely sheltered bay on the north-eastern tip of Hook Island and has a fringing reef with low to moderate exposure and minimal current due to headland protection. Pinnacle Bay's depth ranges from 4 to 6 m, and the rubble bed is interspersed with sand patches and large rock pinnacles. The slope of the rubble bed is flat to gentle. The bay's predominant benthic cover is rubble, rock with turf algae, sand, and silt.

Figure 57. Locations of sites where Reef Bags were deployed. Source: Karen Eigeland; Shu Kiu Leung, The University of Queensland

How does this method help with recovery?

Coconut coir mesh bags are used to stabilise coral rubble for long enough to allow natural reef recovery processes of binding and coral recruitment to take place, creating structurally complex 'coral bommies'. As the coconut coir bags degrade, rubble remains in a mound/pile in a bommie formation, providing a rugose habitat for reef fauna, as well as vertical relief for coral recruitment. Microhabitats are also created by the gaps between interlocked rubble pieces, providing hiding holes for small fish in a similar manner to branching coral colonies.

When and where?

The Reef Bag method is best applied in situations where a disturbance has recently come through and created a lot of loose rubble, requiring a rapid emergency response. For example, Reef Bags could be deployed as an emergency disaster response immediately following cyclone events, paired with the transplantation of damaged coral fragments onto the Bags to facilitate rapid coral growth (Rissik et al., 2019).

A prompt response following a disturbance may significantly increase survival of displaced reef fish and invertebrates and, if completed prior to the next coral spawning season, allow for rapid colonisation by hard coral species (**Mattocks**, pers. comm.). Such an operation might involve sending small groups of divers with coir nets and staplers to create rubble mounds, rapidly providing structure for fish while also removing rubble to expose hard substrate (site-dependent) for recruitment on the benthos at the same time.

When choosing sites for deploying Reef Bags, it might be helpful to consider factors such as depth, disturbance regimes, and sedimentation. Trial 1 showed that the piles tend to slump more in a shallower, high-energy environment, and thus they are not recommended for very shallow areas unless the rubble pieces used in the bags are very large. It might be best to steer clear of extremely shallow areas in regions prone to cyclones or high-intensity everyday conditions, due to the risk of pile disturbance. Moreover, it is advisable for the deployment of Reef Bags to occur at a depth that does not present a navigation hazard (Rissik et al., 2019).

In environments where rubble piles do not slump after the degradation of the bag, such as in areas with low hydrodynamic energy and a flat slope angle, it may be suitable to use only rubble mounds without a bag. In these low-energy cases, increasing the rubble mound size might still be a good idea to future-proof the mound in terms of its stability.

Since the bags have only been tested in a location with very high sediment levels and intense competition with organisms like soft corals, further research is needed to assess the method's potential in clearer waters. Bags at sandy, deeper depths in Trial 1, for example, had much slower growth and recruitment, while the bag that was placed at a depth of 5 m on the patch reef slope showed signs of binding by CCA and Halimeda algae, likely due to better access to light and water flow (i.e., less sedimentation). Furthermore, the number of corals on rubble piles in Trial 2 was higher than control rubble about 2.5 years post-deployment, demonstrating the potential of the method. The 'donuts' deployed during Trial 2 also showed promise, with greater levels of stability and binding than the smaller reef bag piles, likely owing to the greater quantity of material in the donuts (Figure 65).

More trials with various net materials and treatments, including larger piles, should be conducted in locations with clearer water to gauge their effectiveness in varying environments.

Implementation Strategy

Trial 1 Reef Bags were deployed in January 2019. The initial plan was to use a barge and an airlift pump or suction dredge system to suction rubble into the bags on a vessel deck. Filled Bags would then be suspended and lowered into the water. Reef Bags could also be filled underwater using a specialised airlift that transports rubble through a flexible pipe directly into the bags, which have been placed on the benthos (Rissik et al., 2019). Due to the variation in rubble size and shape, the suction pump diameter proved too small, requiring commercial divers to fill the bags manually underwater (Figure 58). When moving the rubble, divers tried to minimise the generation of sediment plumes. After filling the Reef Bags, the divers closed them at the top with a hessian rope. Manual filling, while effective, is not the preferred method for scaling up the deployment of Reef Bags, as it is comparatively time-consuming and costly. Further refinement of the airlift pump, which allows filling on deck, would facilitate the formation of multiple bags across a vast rubble bed, in the case of a large disturbance such as a cyclone.

Expert tips

"Ecological factors must be considered when selecting a suitable site for Reef Bag deployment., The prevalence of rubble stabilisers in the environment, such as CCA, sponges, and corals, is essential for initiating the binding process and subsequent cementation. This aspect can be influenced by various local environmental factors including the depth of the site, water clarity, nutrient loads, and distance from shore/islands. Before project implementation, a thorough investigation becomes incredibly important given these considerations.

Also, consider carefully what the project's objectives are. If for example, it is important to provide immediate habitat and refuge for fish species, the inclusion of larger rubble pieces and even objects such as ceramic pipe within the bag/mound matrix may be beneficial for creating microhabitats."

Neil Mattocks

Neil Mattocks
is the coordinator of Reef Conservation Actions for the Reef Joint Field Management Program with the Reef Authority, a joint initiative of the Queensland and Commonwealth Governments. The program manages the day-to-day activities within the Marine Park, such as deploying rangers for wildlife monitoring, maintaining public contact, and ensuring zoning compliance. It also conducts trials of different rubble stabilisation methods, such as Reef Stars and Reef Bags.

Reef Bags were deployed at various depths and monitored over various timescales depending on the trial. Trial 1 consisted of five bags deployed at Bait Reef over a range of depths (3 on a deeper sandy substrate at 8 m, 1 bag at 5 m on the patch reef slope, and 1 bag at 2 m behind the patch reef crest) and 4 bags at Pinnacle Bay in the 4-6 m depth range (Figure 59). The bags in Trial 1 were double-layered coconut coir net. Trial 2 Reef Bags were deployed in October 2021 in a more orthogonal design (Figure 60). They were placed in a randomised treatment grid pattern, within a large rubble bed (200 m x 70 m) at a depth of 6-9 m.

The treatments consisted of:

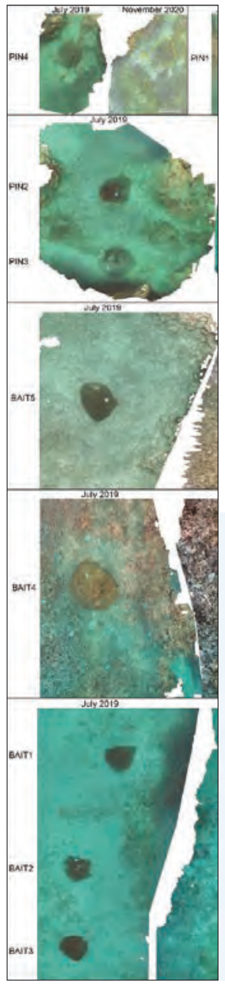
(i) **single-layered** Reef Bags filled with rubble (8 replicates);

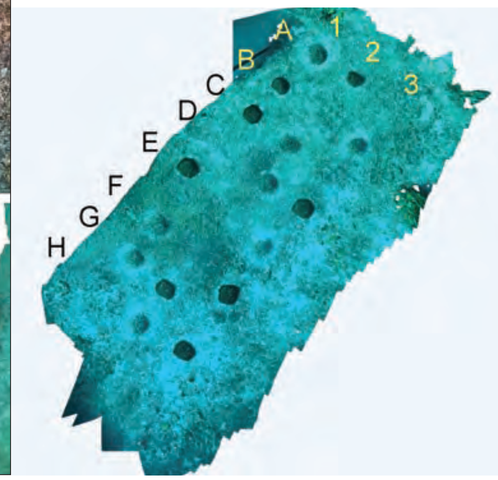
(ii) rubble mounds of a similar size to the Reef Bags but not contained within a bag (8 replicates); and

(iii) flat areas of disturbed rubble as controls (8 replicates).

Flat areas were disturbed through actions of collecting and filling to ensure that the rubble in these areas had been treated similarly to the rubble in piles and Bags.

Figure 58. Divers filling Reef Bags manually where air lift was inadequate. Adapted from "Feasibility Report: Stabilising Reefs for Coral Establishment after Physical Disturbance" by Rissik et al. (2019).





Far left:
Figure 59. Photogrammetry reconstruction showing the positioning of Trial 1 Reef Bags at Pinnacle Bay and Bait reef.

Left:
Figure 60. Photogrammetry reconstruction of deployment grid pattern of the Trial 2 Reef Bags on Bait Reef.

Source: Conor Jones, BMT

As well as the change to the number of layers of coir net, an industrial stapler - instead of hessian rope – was used to close the Trial 2 Reef Bags, to speed the closing of the bags. The metal staples were very tiny and degraded easily over time. In addition to the reef bag and mound treatments, extra rubble material was arranged into two 'donuts' as part of Trial 2. These were roughly 5 m in diameter and 1 m high, compared to the piles and reefs bags which were approximately 1 m^3 in both trials.

Routine monitoring has been conducted on Trial 1 and Trial 2 Reef Bags, to assess the efficacy of the method over time. Monitoring efforts consider: the degradation rate of the bag, fish abundance and diversity above the Reef Bags and mounds, coral abundance on the Reef Bags and mounds, and how stable and bound rubble pieces are, using methods described in (Kenyon, 2021).

What realistic outcomes can we expect?

Reef bags can promote increased fish abundance, rubble binding and coral density in a short (<1 year) to medium-term (1-5 years) period, potentially assisting in reef recovery. However, as these bags degrade and slump over time, they may lose effectiveness in stabilising rubble, warranting further investigations using bags of different fibres and/or increasing the bag/mound size.

As this method has only been trialled at Bait Reef and Pinnacle Bay in the Whitsundays, outcomes could be vastly different at different sites. The results presented here could also evolve with future monitoring at Bait Reef.

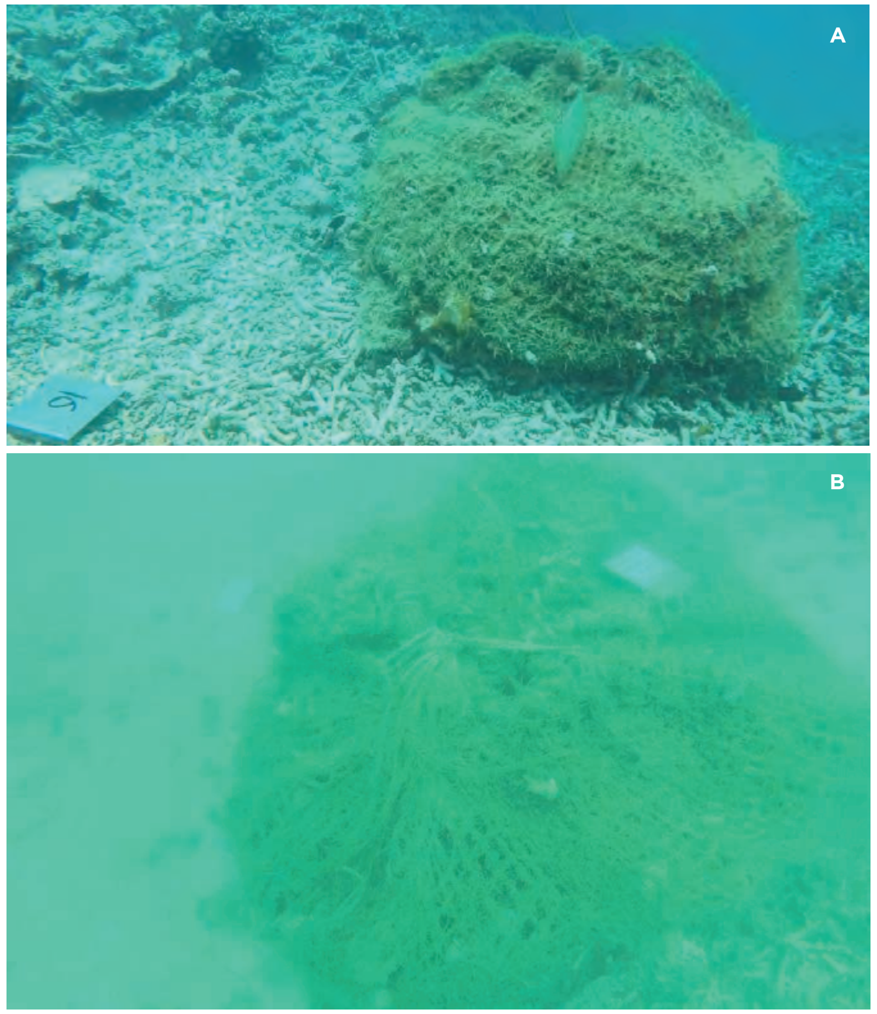


Figure 61.
(a) Trial 1 Bag at Bait Reef one month following deployment. Note minor algal growth at this location.
(b) Trial 1 Bag at Pinnacle Bay. Note the difference in water clarity here caused by silt from a rainfall event. Adapted from "Feasibility Report: Stabilising Reefs for Coral Establishment after Physical Disturbance" by Rissik et al. (2019).

Monitoring conducted one month after deployment of Trial 1 Reef Bags revealed that the bags had not moved from their deployed location, and there was evidence of silt and algal growth on the Bags at Pinnacle Bay following heavy rains (Rissik et al., 2019). Fish were observed swimming around the Reef Bags as early as the installation day (Dave Rissik, pers. comm.).

The double-layered coconut coir net used on the Trial 1 Bags remained completely intact during the first 12 months and degraded completely after 2 years, with shallower bags degrading earlier than deeper bags (Kenyon et al., 2025). Bags in shallower locations and on steeper sections of reef (the bags at 2 and 5 m) showed slumping of the pile and loss of some rubble pieces downslope after the bag had degraded.

Monitoring at 2 years showed that fish abundance was higher over the Reef Bags (which were just mounds now that the bag had degraded) than the surrounding flat rubble areas (controls) at both Pinnacle Bay and Bait Reef (**Figure 62**), showing the bags were successful in providing habitat for fish. The degree of rubble binding in Reef Bags at both locations also increased 2 to 3 years post-deployment, while the degree of rubble binding remained constant in control rubble over this period (**Figure 63**). However, binding did not translate to significantly higher coral recruitment on the bags compared to the control rubble 3- and 4-years post-deployment, despite a trend towards more corals on the bags in year 4 (**Figure 62**).

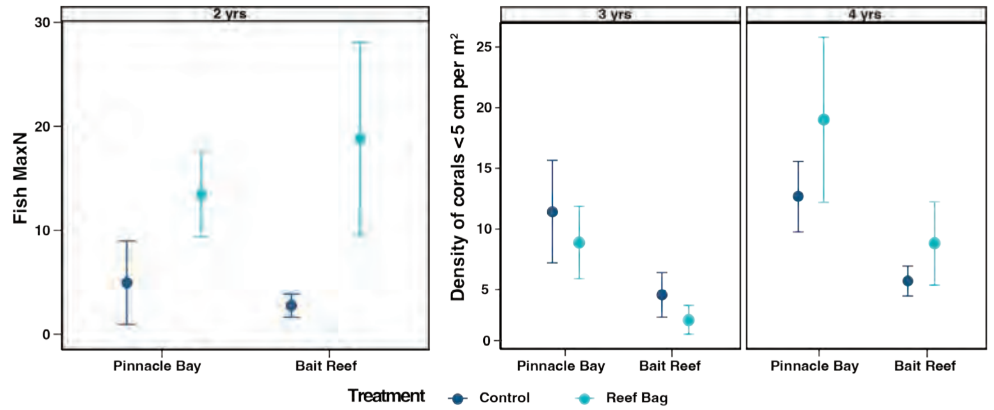


Figure 62.
Mean (± standard error) count of fish (MaxN) on Reef Bags and surrounding control rubble at Pinnacle Bay and Bait Reef after 2 years (November 2020) (left), and the density of coral recruits <5 cm at Pinnacle Bay and Bay Reef 3 years (May 2022) and 4 years (May 2023) post-deployment (right).

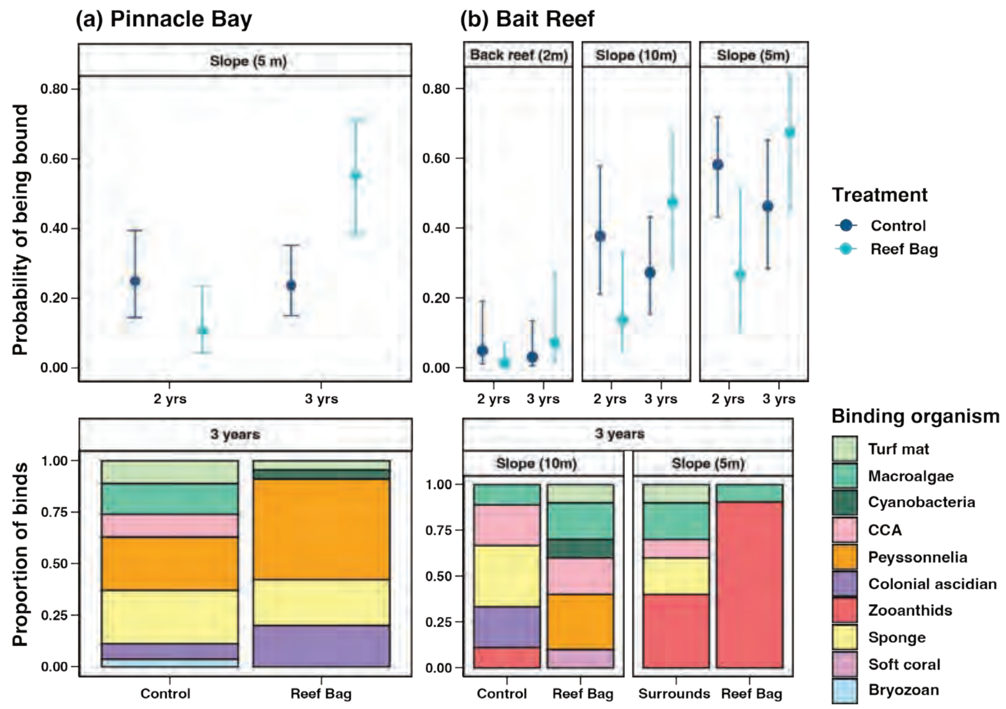


Figure 63.
Mean likelihood (± standard error) of binding in control rubble and Reef Bags after 2 years (November 2020) and 3 years (May 2022) (top row) and the proportional composition of binding organisms observed in control rubble and Reef Bags after 3 years (bottom row) at (a) Pinnacle Bay and (b) Bait Reef.

Figures 62 & 63 adapted from "Bio-degradable 'reef bags' used for rubble stabilisation and their impact on rubble stability, binding, coral recruitment and fish occupancy." by Kenyon et al. (2025)

The single-layered Trial 2 Reef Bags biodegraded more quickly than the double-layered Trial 1 bags. Much of the Trial 2 bags had biodegraded within 6 months (May 2022) and had completely biodegraded within 12 months (December 2022). There was some slumping of the rubble piles, particularly of those that were not piled into a bag upon deployment. Rubble stability was measured by picking up a rubble piece and noting whether it was 'stable' (i.e., there was some resistance from interlocking or part burial) or not. After over 2.5 years (June 2024), rubble pieces in flat, disturbed control areas were ~25% less likely to be stable on pick-up compared to rubble pieces in Reef Bags (i.e., the mounds left after the bag had degraded), and ~30% less likely to be stable compared to 'donuts', i.e., large piles (Figure 64a). Rubble binding likelihoods, however, were similar between controls, 'pile only' (i.e., mounds that were never enclosed in a bag) and Reef Bags, with between 21 and 26% of rubble pieces having at least one bind. In the donuts, however, rubble pieces had a higher likelihood of binding, at 66% (Figure 64b). The average number of corals was ~1.5 times higher on piles compared to control rubble (Figure 64c). The variability in the number of corals for reef bags and donuts meant that no significant difference was detected between these treatments and the control. There may be a lag for reef bag treatments while the coir breaks down over the first year and makes the rubble more available to colonisation by hard corals. Thus, we expect that the number of corals on reef bags may also be higher than controls over time. (Figure 64).

While the Trial 2 Reef Bags show promise, we observed that the greater amount of material comprising the donuts led to a more stable structure which experienced less slumping over time (Kenyon, pers. comm.). While the number of corals was not higher on donuts compared to reef bags or piles, we propose that creating larger mounds of rubble in this manner provides greater opportunity for successful recovery in future, due to enhanced stability and thus, maintenance of the structure at a certain height above the substrate over a longer period. If the piles are large enough that they are stable, a bag is less likely to be needed, which also removes the 'lag effect' on coral recruitment while the bag degrades.

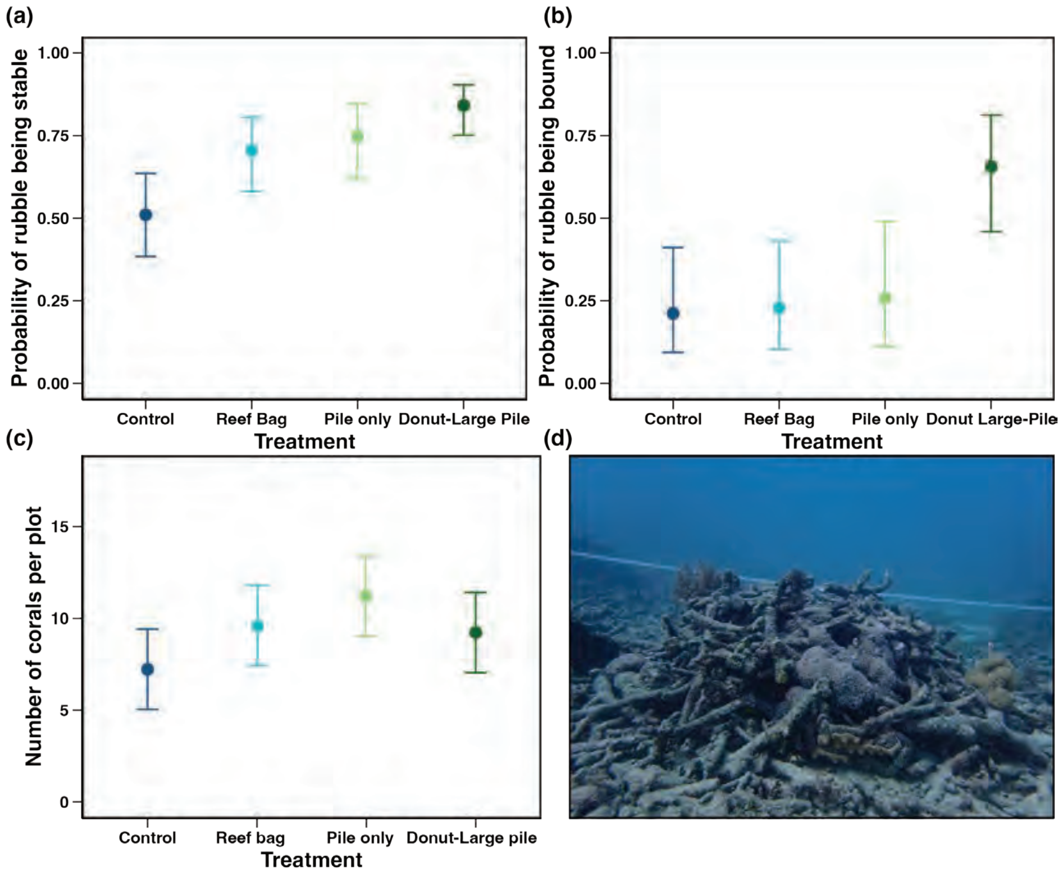


Figure 64. The **(a)** probability of stability, **(b)** probability of binding, **(c)** average number of corals per plot, and **(d)** one of the reef bag treatments, G2, (after the coir mesh has degraded leaving the rubble mound) that have hard corals recruiting onto it, photographed in June 2024. Source: Tania Kenyon, The University of Queensland

Table 7. Pros and cons of Reef Bags (Kenyon et al., 2025; Mattocks, pers. comm.; Rissik et al., 2019)

Pros	Cons
• Kills two birds with one stone – removing unwanted rubble from some areas while providing structural complexity and rugosity. • Provides a stable settlement surface raised above the substrate level, potentially reducing the impacts of sedimentation and competition on coral recruitment. • Provides habitat, including crevice spaces, for fish and invertebrates. • If manual filling: – Relatively easy and cheap to install on a small scale due to type of material, design and weight (few divers needed for manual filling). – Could be implemented very quickly following a disturbance owing to the few materials needed. • Coconut coir netting is a natural and biodegradable material, leaving no trace of foreign material on the reef. • Approval process is potentially more straightforward compared to other rehabilitation techniques that add foreign, non-biodegradable materials. • Requires minimal materials with most resources already onsite (i.e., rubble).	• Can only be deployed where there is a large amount of rubble available to fill the bags. • Depending on the number of layers, the bag may degrade sooner than binding organisms and corals are able to colonise. This may not be a problem if the rubble mound does not slump after the bag is gone (this is where a larger quantity of rubble can help, e.g., size of the 'donuts'). • Due to the use of divers, scaling up (to 100s of reefs) would be expensive and require a lot of manpower. If, however, this method could be carried out with the use of a barge vessel and suction pump as per the original design, larger areas could be covered with an ever-decreasing cost per bag. • By making rubble mounds, the chemistry of water between rubble pieces is likely to differ from that between rubble pieces in a flat rubble bed (increased flow and more mixing in a mound). This could affect the chances of long-term processes like cementation from occurring. • Due to the arrangement into a mound/pile, rather than lying flat, the gap size between rubble pieces might also be too wide for strong binders such as coralline algae to span, meaning that binding processes may not be accelerated if rubble pieces are very large (although coral recruitment can still be successful in the absence of binding).

Materials

Reef Bags were inspired by the commercially available, UV-treated Kyowa Rock Filter Bags that are made of 100% polyester and designed for environmentally conscious coastal engineering projects (Rissik et al., 2019). However, these polyester bags proved unsuitable for in-water filling due to coral rubble catching on the mesh. In addition, to explore natural alternatives and address concerns about plastic pollution, researchers constructed the bags from coconut coir netting, which offers both durability and biodegradability. These bags can remain in place indefinitely, eventually biodegrading and leaving no trace.

The bag design was modified from the Kyowa Rock Filter Bags following load capacity testing. In Trial 1, the bags were double layered to ensure they could be suspended using a crane for deployments from a boat. However, the double-layered design appeared to restrict light and flow reaching the surface of the contained rubble, which was thought to impact the settlement and growth of corals and binding organisms (Kenyon et al., 2025). Thus, the coir netting was used as a single layer only in Trial 2. These bags were filled in-water, and thus did not need to withstand suspension. This single-layered bag biodegraded more quickly, which leaves the rubble pile vulnerable to slumping before corals or binder can sufficiently recruit. As such, there appears to be trade-off between the strength of the bag and ease of deployment, and the speed at which is biodegrades.

It may be necessary to explore alternative materials and designs. For example, there is an interest in testing galvanised mesh made into approximately 2-metre diameter circles with a height of 50-75 cm, filled with rubble to create a stable 3D habitat (**Mattocks**, pers. comm.). These structures would be similar to oyster gabions, used in oyster reef restoration (Grizzle et al., 2024). Alternatively, a coir net product from another supplier, or even a polyester product (if microplastics can be avoided) that offers greater durability, could be considered (Kenyon et al., 2025; Rissik et al., 2019). The other factor that could be modified to improve stability of the piles, without changing the material, is size of the piles, as observed in the donut trial (**Figure 65**).

Size and configuration

Reef Bags were filled to a volume of approximately 1 m^3 and weighed around 1000 kg. Hydrodynamic modelling showed that bags of these dimensions would remain intact under load suspension if being craned from a vessel deck into the water and remain stable under typical storm and cyclonic wave conditions (Kenyon et al., 2025). The size was also determined by factors including deployment logistics and equipment, which are contingent upon site conditions and permitting allowances.

In Trial 2, Reef Bags were arranged in a grid pattern for experimental design purposes, without the consideration of ecological outcomes. In a non-trial deployment, the configuration of Reef Bags would mirror the pre-disturbance landscape in terms of structural complexity (Rissik et al., 2019).

Their ideal configuration would also promote rugosity and provide microhabitats. The value of Reef Bags for fish and invertebrate diversity and abundance could be enhanced by incorporating additional structures, such as ceramic hollowed cylinders, into the piles (**Mattocks**, pers. comm.). As mentioned previously, if the piles are being created underwater, and not suspended on a vessel, a larger pile size could provide more stability, as observed in the donut trial. These were approximately 5 m in diameter and 1 m high. Further investigation is warranted into this option (see section **Expert tips: Tania Kenyon**).

Costs and maintenance

The two trials showed limited cost-effectiveness due to their small-scale nature with only up to 8 Reef Bags installed each day (during the second trial). Based on the trial findings, it was projected that a team of five could deploy up to 200 Reef Bags in a week at an approximate cost of A$39,000 (Rissik et al., 2019). Aside from monitoring costs, the cost per bag (material and installation) would be reduced as the operation is scaled up, with in-kind assistance potentially further reducing overall expenses. Methods for upscaling the Reef Bags, such as testing a bucket dredge to collect rubble and assemble bags on a vessel are under exploration (**Mattocks**, pers. comm.). Maintenance of the bags is not required because the bags are designed to break down.

Figure 65. One of the larger piles – the 'donuts' - being surveyed in June 2024. Source: Craig Heatherington

Expert tips

"Making the bags out of non-degradable material would take away the 'natural materials' advantage, but would keep the rubble piles very stable, and the net would eventually be overgrown. This might be preferable to the natural fibre bag, which may not stay together long enough for solid binding to take place. Alternatively, the size of the pile might be altered to improve the stability.

Major insights about optimal materials and size could be gained by deploying Reef Bags with:

(i) natural fibre netting, and

(ii) synthetic fibre netting (to see if this improves long-term stability and recruitment), together with

(iii) rubble piles only (no bags), and

(iv) flat, disturbed, control rubble areas, all at about 5 m, in exposed (high current) vs sheltered (low current) areas of sites in regions such as Bali or Raja Ampat.

These regions have good water quality and coral recruitment is high, meaning that the issues of sedimentation and low larval supply would be absent. Then, to investigate pile size, double the replication by running the above experimental design with both:

(a) Reef Bags/mounds of 1 m^3, and

(b) Reef Bags/mounds of 5 x 5 x 1 m (in line with the size of the donuts).

Such an experiment would provide valuable insights into whether coir netting is most suitable or whether a more durable material might be beneficial in some cases, depending on the pile size, and on the current speeds at the site and the slumping risk.

Also, due to the surface area to volume ratio of the bags, there are many inner surfaces – of rubble pieces in the inside of the pile – that are likely to remain unbound while the outer surface might bind. These bags might be combined with 'sponge seeding', in which sponges are sprinkled in the inner layers of the bags, in the hope that they stabilise the rubble more rapidly than waiting for settlement and recruitment processes to proceed (and all before the bag degrades). Although, this should be considered very carefully as you do not want to introduce a new, unknown species into an environment."

Tania Kenyon

Dr Tania Kenyon
University of Queensland researcher Dr Tania Kenyon is a specialist in rubble dynamics. She has researched rubble movement, rubble binding and rubble stabilisation and recovery on reefs in the Maldives, Indonesia and on the Great Barrier Reef (under the RRAP Rubble Stabilisation sub-program) since 2016.

Tania has experience in the determination of hydrodynamic thresholds for rubble mobilisation, contributing to our fundamental understanding of rubble movement on reefs. She has also investigated rates at which rubble is bound together by binding organisms, across different environments. Specific to rubble stabilisation, Tania has tested the effectiveness of various methods such as meshes, metal frames and Reef Bags.

Bio-adhesives

A challenge when addressing rapid environmental degradation is to have sustainable approaches especially for rubble stabilisation. Much of the materials used in current restoration efforts can contribute to a negative environmental footprint.

To solve this problem, a rapidly expanding area of research and development is in underwater, bio-adhesives (Choi et al., 2024; Moghaddama et al., 2022; Zych et al., 2024).This approach utilises biological or biomimetic adhesives based on adhesive proteins from mussel, coral and other sessile benthic fauna which naturally work underwater, in saltwater conditions, and on different substrates. Bio-adhesives can be an alternative for both direct rubble stabilisation interventions and integration into existing restoration practices.

Important properties of bio-adhesives for use in rubble stabilisation and reef restoration more broadly, are that they work in seawater, are negatively buoyant, require little to no surface preparation, have fast rates of adherence, and are non-toxic to marine life. Another potentially important aspect of bio-adhesives under development is that they can be 'tuned' to improve properties such as adhesion, cohesion, biodegradability, and viscosity (Lewis et al., 2024). This allows a bio-adhesive to be designed for a specific restoration need or environment (e.g., high flow currents) and can assist in overcoming limitations of current stabilisation methods (see section **Challenges and opportunities in rubble stabilisation**). Bio-adhesives can also represent a more sustainable alternative to petroleum-based compounds, metals, plastics, and cement regularly used for stabilisation and broader restoration practices.

At present, bio-adhesives are in the developmental stage and are not commercially produced for large-scale marine applications. In laboratory and research settings, the underwater bio-adhesives being trialled in reef restoration (Lewis et al., 2024; Moghaddama et al., 2022) have been shown to be cost-efficient. Larger-scale field trials of rubble stabilisation using bio-adhesives are anticipated to be completed over the next several years.

How does this method help reef recovery?

Bio-adhesives effectively stabilise rubble by binding fragments together, biomimicking the natural processes of initial binders such as algae, sponges, coralline, and ascidians (Ceccarelli et al., 2020; Cui et al., 2019; Pang et al., 2020), but at a significantly faster rate by creating strong binds minutes after application. This approach may accelerate natural stabilisation by providing a stable substrate nucleus where additional binders can develop, and subsequent stabilisation processes such as rigid binding (Rasser & Riegl, 2002), serving as a practical alternative to **sponge seeding**. Importantly, the biodegradable nature of the bio-adhesives means that, whether stabilisation is successful or not, there will be no traces of the material remaining in the reef ecosystem within a few years.

When and where?

Bio-adhesives with simple formulations and commonly available material components are suitable for global use, particularly in remote areas and Small Island Developing States and Least Developed Countries (Lewis et al., 2024). Their adaptable nature allows for deployment anytime and anywhere for various applications, though they may be most effective when integrated with existing methods. It will be best suited for stabilising rubble soon after a disturbance event, but because the bio-adhesive has the potential to be used to bind rubble with well-developed biofilms, it can also be deployed later. An initially low-energy environment for application is preferred for the bio-adhesive to adhere to rubble fragments and improve cohesion.

Bio-adhesives may be best used in combination with other methods, such as **elevated metal structures**, **concrete blocks** and **direct coral fragment reattachment** after disturbance events, when coral fragments are still viable. For example, modular artificial reef structures are often arranged in blocks or islands and positioned adjacent to healthy reefs to maximise three-dimensional connectivity. Bio-adhesives can be used to stabilise the loose rubble between modular islands, enhancing connectivity and providing additional substrate for colonisation by coral recruits.

Implementation Strategy

While still in development, there are two general approaches being considered for the dispensing of the bio-adhesives: automated and manually. Automation would involve underwater robots to directly dispense bio-adhesives to rubble on the substrate. Manual methods are initially more likely and will be more suited for use in Small Island Developing States and Least Developed Countries.

Basic mechanisms of dispensing bio-adhesives can include piping systems, syringes and caulking guns allowing direct targeting of rubble areas (or coral fragments) for glueing and bonding (e.g., Roberts, 2023). Caulking-type guns can also allow injection of the bio-adhesive deeper into the rubble bed. The bio-adhesive can be applied in geometric patterns – such as strips or meshes – by hand-held or automated guns. **Flat meshes and grids** have proven effectiveness for rubble stabilisation and in high-flow flume tank experiments, while applying bio-adhesives in strip patterns have also been shown to be effective in stabilising rubble. Importantly using strips or mesh patterns for bio-adhesive deployment help rubble interlocking and reduce rubble movement without the need for complete covering of the bed in bio-adhesive. Bio-adhesives can also be reapplied as necessary.

Other methods for the implementation of bio-adhesive include producing large balls of bio-adhesive packaged into dissolvable casings or skins (Roberts, 2023). Once deployed on a rubble bed the outer layer would dissolve, releasing bio-adhesives onto the substrate for infiltration and binding of rubble. This method can be less labour intensive.

To increase coral recruitment onto rubble beds stabilised by bio-adhesives, coral larvae can be supplied either during natural spawning events or through artificially assisted larval settlement processes. Coral fragments can also be directly attached to bio-adhesive stabilised patches.

As both the bio-adhesive products and methods for intervention are still being developed, best practices for bio-adhesive application remain in their infancy. Bio-adhesives offer high flexibility and can be tailored to specific environments or rubble systems (Lewis et al., 2024) that can differ in terms of accessibility, rubble extents, hydrodynamic exposure and slope. Consequently, efforts are underway to develop a toolbox of bio-adhesives and deployment mechanisms to complement existing or future restoration techniques such as the addition of stabilisation structures.

What realistic outcomes can we expect?

Bio-adhesives can limit rubble movement and stabilise rubble and surrounding areas for more than a year. These adhesives allow coral recruits to settle in a day or two after application, and coral overgrowth on bio-adhesives can be seen within three months. Both laboratory and field trials found no evidence of toxicity to marine organisms. Larger-scale field trials in the future may provide more insights regarding the outcomes of rubble stabilisation using bio-adhesives.

Bio-adhesives are being tested in laboratories, used in aquaculture for coral fragment attachment (e.g., Seatak), and in small-scale field trials (**Figure 66**). Its use and success may be limited by the amount/area of rubble requiring stabilisation and the volume of adhesive that can be deployed.

Laboratory trials have shown that bio-adhesive stabilised rubble can withstand shear stresses up to 120 N of force and ambient flow velocities tested up to 0.80 m/s. For comparison, current velocities across different water depths and environments at Lizard Island ranged between ~0.1 and 0.8 m/s (Johansen, 2014). Bio-adhesives also showed no evidence of water temperature or pressure dependency, indicating that they can perform similarly in a variety of environments.

It is expected that rubble patches to which bio-adhesive is directly applied can remain stable for over 1 year. Surrounding areas may also have increased stability by interlocking with the glued rubble, by becoming stuck onto exposed bio-adhesive after movement, or where patches of glued rubble become obstacles on the bed hindering movement of rubble along the bed.

Trials conducted at Townsville Aquarium to assess if fish or other marine life are attracted to the bio-adhesive, would attempt to eat it or could passively affect surrounding marine life (i.e., through environmental toxicity and chemical leaching) showed that the bio-adhesive had no effects on the local reef ecology. The deployment of the adhesives did not attract marine fish or invertebrates, nor did it cause any harm on the adjacent reef ecosystem. Moreover, examinations of recovered coral attachment devices after 9 months in natural reef environments showed that coral overgrowth on the bio-adhesive occurred within 3 months. It is expected that rubble stabilised with bio-adhesives will be ready to receive coral larvae within a day or two after application, and coral growth can be observed over time.

In a 9-month field trial on the GBR, bio-adhesives were used to hold small coral larval tiles into ceramic devices. The tiles were successfully held in all devices while allowing coral larvae to grow. The devices and exposed bio-adhesive were biofouled by coralline algae, indicating that the bio-adhesives were non-toxic to organisms.

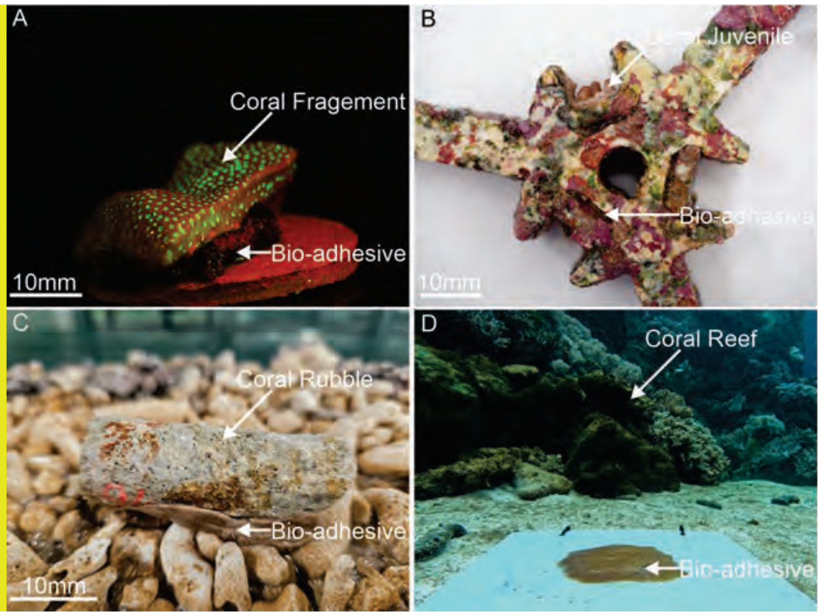


Figure 66.
High-definition digital images illustrating the applications of bio-adhesives in coral restoration. Panel **(a)** shows a coral fragment secured to the substrate with a bio-adhesive after three months. Panel **(b)** features a coral seeding device with 'tabs' bonded by bio-adhesives, deployed on a coral reef for nine months. Panel **(c)** depicts a coral fragment remaining adhered after exposure to wave-induced currents of approximately 0.5 m/s for one hour. Panel **(d)** illustrates bio-adhesive applied in larger quantities within a large enclosed coral reef ecosystem, where its effects on attracting grazers and overall ecosystem health are being assessed.

Source: Brett Lewis, Queensland University of Technology

Table 8.
Pros and cons of bio-adhesives (Bryan, pers. comm.; Lewis, pers. comm.; Lewis et al., 2024; Queensland University of Technology, 2023).

Pros	Cons
• Eco-friendly – bio-adhesives can contain high amounts of natural materials. • Biodegradable, leaving no negative environmental footprint. • Biomimics natural processes and causes minimal changes to the natural habitat, preserving the original structure. • Some bio-adhesives have a relatively simple formulation simplifying production which can be important when needing to stabilise rubble in remote areas • Customisable formulas to create a toolbox of fit-for-purpose bio-adhesives. Non-catechol group bio-adhesives use materials that are cheap and can be sourced locally. • Has scalability potential due to the use of commonly available and cheap materials that permit large-volume production and coupled with the use of automated devices. • Minimal surface or site preparation required. • Rapid binding strength developed within minutes. • Generally non-toxic to marine organisms.	• Many formulations are still in development. • Few bio-adhesives are fully commercialised. • New and unfamiliar product may encounter resistance from the public or local communities. • The logistics related to the production, transport and storage of large quantities is unknown. • Still relatively expensive but becoming cheaper. • Long-term performance (adhesion and coherence) unknown.

In summary, based on the available evidence from laboratory and field trials, bio-adhesives can have an important role to play in stabilising rubble and are non-toxic to marine life and juvenile coral growth (Johansen, 2014; Queensland University of Technology, 2023).

Materials

Two general groups of underwater bio-adhesives have been developed: **1)** catechol-based and **2)** non-catechol-based adhesives. In the first group, catechol-containing polymers or other chemical functionalities, such as phosphate or amine-rich moieties, play an essential role in generating the strong supramolecular forces to various substrates underwater (Cholewinski et al., 2019; Shao & Stewart, 2010). An example of a commercially available product in this category is Seatak (https://www.seatak.com/), which has been used in aquaculture. Although the presence of catechol groups improves the properties of wet adhesives, these groups are susceptible to oxidation, pH, and temperature (Lee et al., 2021). Catechol-based adhesives are also costly to manufacture at any scale. Consequently, researchers have developed numerous non-catecholic based adhesives, such as acid/base carboxyl-based adhesives that can use plant-based materials (Moghaddama et al., 2022).

Increasing awareness of environmentally sustainable technologies is driving a shift in bio-adhesives towards plant-based polymers derived from mill waste such as tannic acid, vegetable oil and lignin (Choi et al., 2024; Zych et al., 2024). Plant-waste-based bio-adhesives offer substantial advantages over traditional adhesives, including cost-effectiveness, global availability, antibacterial properties, biocompatibility, and potential biodegradability (Jain et al., 2017; Pang et al., 2020; Schmidt et al., 2019). Transitioning towards these polymers would align restoration practices with UN environmental sustainability goals (United Nations, 2024), particularly in Small Island Developing States and Least Developed Countries.

Costs and maintenance

As bio-adhesives are still under development, their precise costs are not yet established. The overall expense will be influenced by factors such as the scale of application, the specific bio-adhesive formulation, and the technological requirements for its application. Maintenance requirements may also vary depending on the method of application and the environment in which the bio-adhesives are used.

Addition of structures to restrict rubble movement

This section explores the use of structures specifically designed to **physically restrict rubble movement** and accelerate the stabilisation process.

Methods in this category include flat structures and barrier fences.

Flat structures (meshes and grids)

Flat structures like meshes and grids are widely used for stabilising rubble due to their ease of installation and affordability. This technique has found extensive application in Southeast Asian countries, notably in the Philippines, Indonesia, Malaysia, and to a lesser extent, in Australia's Great Barrier Reef.

Scale of implementation

Restoration projects using flat structures have ranged from small-scale pilot tests of 6 m^2 plots in Nusa Penida (Blue Corner Marine Research, 2020) and experiments of 17.5 m^2 plots in the Calagcalag Marine Protected Area, Philippines (Raymundo et al., 2007), to medium-scale efforts covering 100 m^2 on Pom Pom Island, Sabah, Malaysia (**Philippo**, pers. comm.), and even larger initiatives spreading over thousands of square metres in Raja Ampat, Indonesia (The SEA People, 2024).

How does this method help with recovery?

Flat structures placed directly on rubble can pin rubble pieces down and prevent their movement, thus allowing for subsequent binding and cementation. Once stabilised, the rubble surface becomes a suitable habitat for coral recruits to settle, and more importantly, survive, which are a crucial step in reef recovery. Moreover, deploying flat structures can increase the surface area available for coral settlement. Once the flat structure is stable and covered in a biofilm, corals, sponges, and other consolidating organism can grow over and encapsulate the mesh material, further stabilising the underlying rubble.

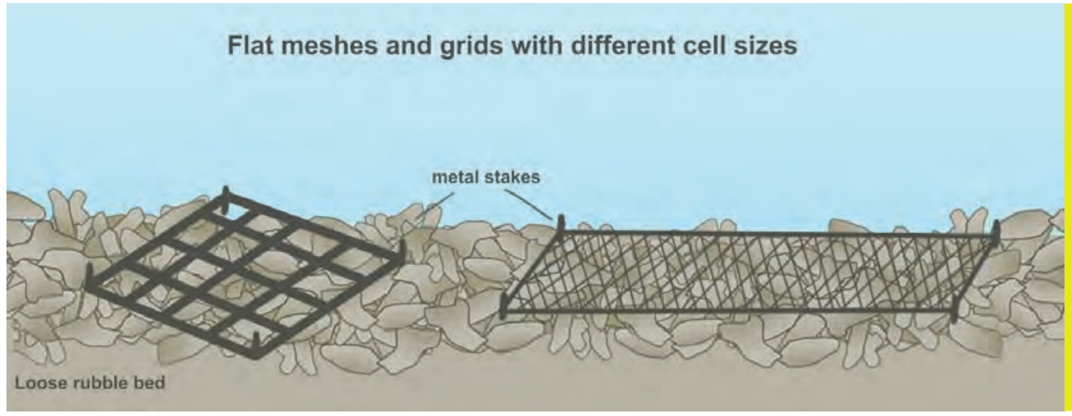


Figure 67. Placing flat meshes and grids directly on top of a loose rubble bed. Source: Shu Kiu Leung, The University of Queensland

Figure 68. Locations of sites treated with flat structures. Source: Shu Kiu Leung, The University of Queensland

When and where?

A good timing of plot deployment facilitates efficient colonisation of recruits due to seasonal variability (Raymundo et al., 2007). It is recommended to synchronise deployment with the broadcast-spawning season to optimise recruitment rates; otherwise, plots may remain largely uncolonized until the subsequent spawning season which would slow down the recovery. As for suitable locations, meshes and grids are more effective on relatively flat and sheltered rubble patches found at depths ranging from 2 m to 10 m (**John Edmondson**, Wavelength Reef Cruises, pers. comm.). They are best suited for locations characterised by flat or gently sloping terrain with low or infrequent high-energy events. An illustrative example is the rubble generated by intermittent cyclones, resulting in shallow beds comprised of small, mobile, non-interlocking rubble pieces, occasionally disturbed by strong winds of 25 to 35 knots, a scenario commonly encountered at Great Barrier Reef tourism sites (**Edmondson**, pers. comm.). The effectiveness of meshes and grids diminishes on irregular surfaces due to challenges in uniformly applying pressure across the entire rubble bed (Davidson Rato Nono, pers. comm.), potentially leaving unstable gaps.

Implementation Strategy

Before installation, it is recommended to measure the length of the slope and adjust the size of structures accordingly, particularly when the structures are flexible (e.g., rolls of thin meshes – **Figure 69**) (**Arnaud Brival**, The SEA People, pers. comm.). This ensures an optimal fit and makes the structures more manageable underwater due to their reduced weight.

During installation, divers usually anchor meshes or grids directly onto rubble beds using metal stakes, with additional weights (e.g., rocks and boulders) often employed for extra stability (Raymundo et al., 2007) (**Figure 70**). Other anchoring options such as U-shaped rebar spikes and cable ties can also be considered (Chen et al., 2018). To accommodate existing coral heads, diver can cut holes into the mesh and fit it around the existing coral, which then serves as supplementary anchors or attachment structures (Raymundo et al., 2007).

Flat structures offer high versatility as they can be used in combination with other structures such as **3D metal frames** and **rocks**, as well as **coral transplantation** (Raymundo et al., 2007; Taylor, 2020). It allows for the transplantation of various forms of corals, including encrusting and plating corals such as *Echinopora, Galaxea,* and *Porites* (**Andrew Taylor**, Blue Corner Marine Research, pers. comm.).

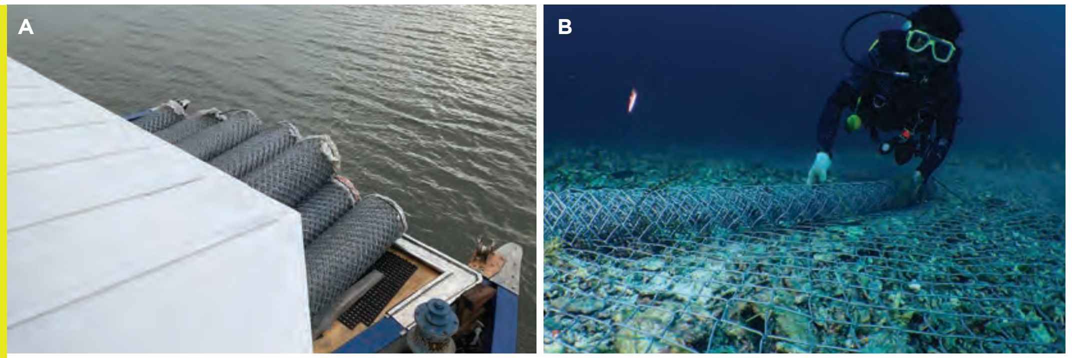


Figure 69.

(a) Mesh rolls are transported to the site using a boat. Then, **(b)** divers unroll the metal wire mesh over the rubble bed, and **(c)** hammer down pegs to stabilise the mesh.

Source: Arnaud Brival, The SEA People

Figure 70. Diver placing plastic meshes and rock piles onto the rubble bed. Source: Laurie Raymundo

Corals of other growth forms can also be “sprinkled” on top of the structures, including *Seriatopora, Hyndopora, Pavona, Pectinia* and *Anacropora spp.* (**Brival**, pers. comm.). In addition, according to Taylor (2020), planting soft corals can enhance the stability of the structure, especially meshes.

While meshes can be used as a base for coral transplants, it is important to immobilise transplants immediately, as any movement will result in abrasion, partial mortality, and failure to accrete onto the substrate. Structures such as cemented rock piles placed on mesh may offer better substrates for transplants due to less movement and abrasion (Raymundo, pers. comm.).

What realistic outcomes can we expect?

Flat meshes and grids may stabilise rubble and promote recruit survival in the short (<1 year) to medium term (1-5 years). Over a longer period, these structures contribute to the increase of coral cover and species diversity, supporting reef recovery. However, flat structures lack vertical relief that supports structural complexity and can become less effective over time due to their susceptibility to burial or damage by rubble or sand moving downslope, and potential dislodgement in high-energy environments. To see how outcomes can differ between flat structures and raised structures with vertical relief, see case study 5, which compared metal structures to a flat grid design on the Great Barrier Reef.

While flat structures are used in multiple regions, most of the available data are anecdotal evidence from practitioners. The findings presented below are primarily based on practitioner observations and a single study by Raymundo et al. (2007) that conducted rigorous surveys and data collection.

On the positive side, Raymundo et al. (2007) demonstrated higher survival rates of coral recruits on meshes (63.4%) compared to the control rubble site (6%) at 10 months, with significant growth over time. Remarkably, recruits reached 15-18 cm in diameter and established a diverse community with 17 genera of reef-building corals 5 years after deployment (Edwards, 2010). At 3 years post-treatment, hard coral cover had increased to 18%, while remaining at 8% within the rubble field. This trend continued over time, with significant increases in cover, coral species diversity, and colony size observed 8 years after deployment (Raymundo, pers. comm.) (**Figure 71**).

There was also some seasonal variability with coral recruitment, with differing numbers of recruits observed on meshes deployed at different times of the year (Raymundo et al., 2007). The authors also observed that recruits located near the plot edges grew beyond the mesh plot, to stabilize rubble adjacent to the mesh (Raymundo, pers. comm.).

Flat meshes have been found to stabilise rubble, reducing movement down reef slopes and preventing erosion 1 year after deployment (Taylor, 2020). According to Taylor (2020), binding organisms like soft corals and sponges were found under meshes on rubble beds in Nusa Penida, which indicates signs of natural stabilisation taking place.

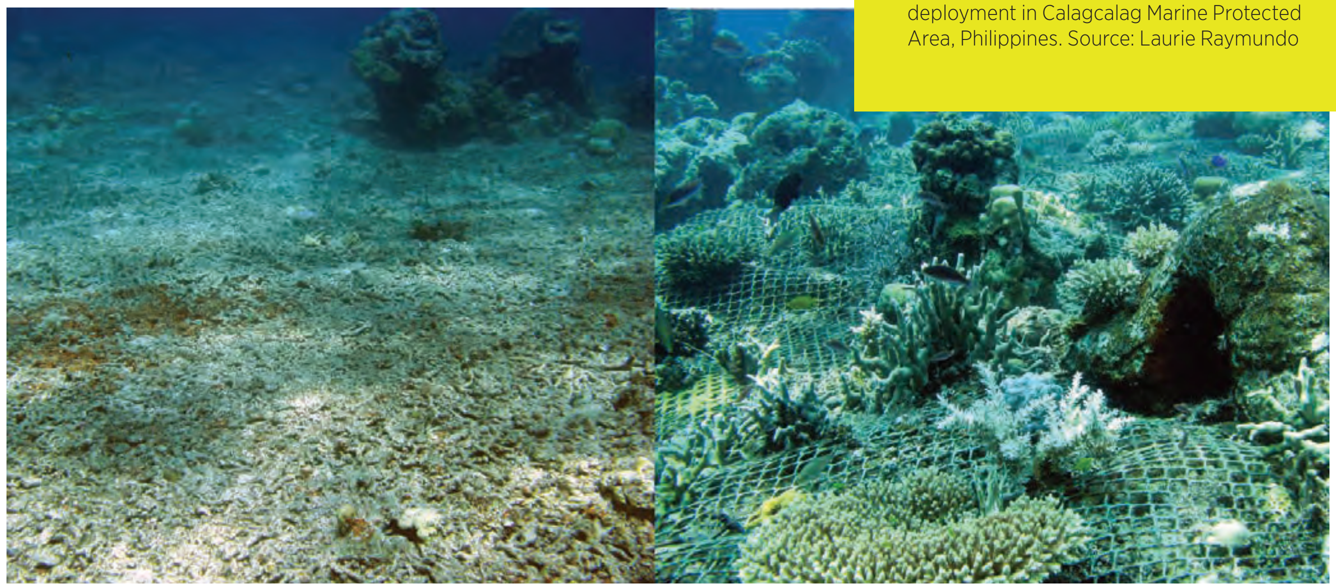


Figure 71.
Control rubble site vs restored site 8 years after deployment in Calagcalag Marine Protected Area, Philippines. Source: Laurie Raymundo

Similarly, a community project in Amed and Pemuteran saw over 20% of rubble become stabilised after 1.5 years (Rato Nono, pers. comm.).

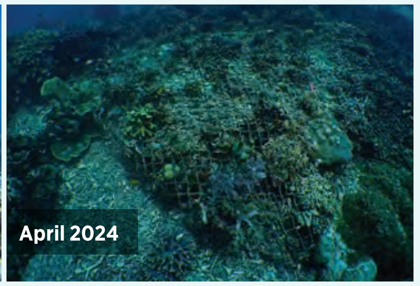
When combined with coral transplantation, the method may lead to an accelerated increase in coral cover compared to simply deploying meshes only (**Brival**, pers. comm.) (**Table 9**).

Although flat structures offer promising benefits for rubble stabilisation and reef recovery, it is important to acknowledge that challenges and limitations also exist. For example, sites in Raja Ampat, Indonesia have shown high variability in benthic cover possibly due to differences in microhabitats (Brival, pers. comm.). Despite receiving the same treatment, these sites can vary greatly, ranging from coral-dominated, to algal-dominated, or even being completely covered by sand (**Figure 72**). A rapid succession of soft coral on flat structures was also observed in some cases, such as on the shallower end of the reefs of Pom Pom Island, Malaysia (**Philippo**, pers. comm.).

While the initial colonisation by soft corals helps stabilise rubble, it eventually outcompetes hard coral fragments outplanted on the structures.

Moreover, the stability of the structure can be compromised if structures are dislodged due to disturbances such as storms or interference by curious marine animals. Despite efforts to secure meshes, they may become detached or fouled during storms, leading to partial coverage or displacement (Raymundo et al., 2007). For example, following Cyclone Jasper in December 2023, mesh panels were transported downslope and transplanted corals were fragmented and overturned (see **case study 3**). Although the panels were returned to the original location, this incident has significantly set back the process of reef recovery.

Table 9.
Restoration sites in Arborek, Raja Ampat, Indonesia. Photos show changes in coral cover over nearly 3 years, comparing sites restored with only meshes to those restored with meshes and coral transplants. Source: Arnaud Brival, The SEA People

Treatment	Before	After
Flat meshes only	 June 2021	 April 2024
Flat meshes combined with coral transplanting	 June 2021	 April 2024

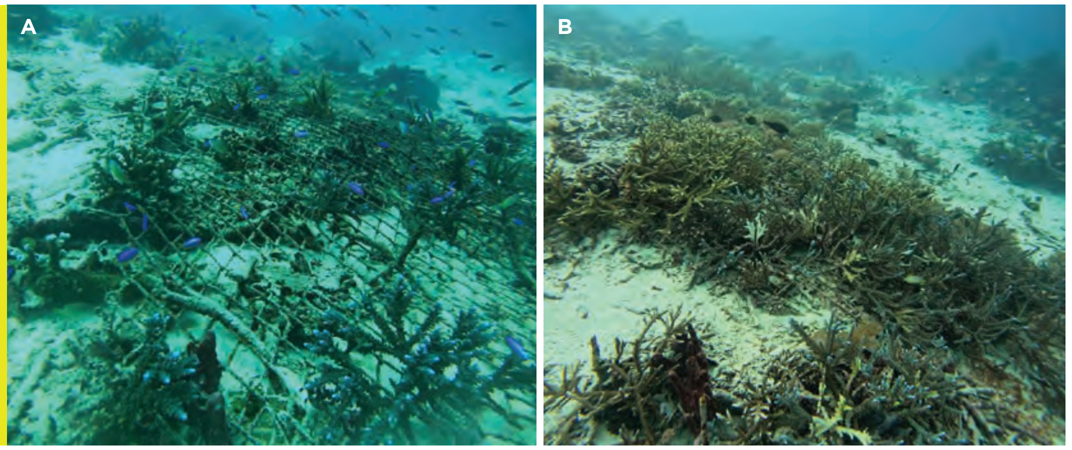


Figure 72.
Meshes deployed in Yenbuba, Raja Ampat, Indonesia. Some parts of the meshes were covered by sand and rubble due to bioturbation by bottom dwellers. (a) photo taken right after installation in April 2021; (b) same plot in May 2023 with some areas covered by sand and rubble. Source: Arnaud Brival, The SEA People

Case Study 3:

Utilising mesh coral nursery panels as temporary rubble stabilisation structures in the GBR

(Edmondson, pers. comm.)

Background

Three closely related pilot trials were conducted at two tourism sites at Opal Reef on the GBR between 2020 and 2024. Mesh panels were positioned on a rubble bed that had shown no recovery since a 2014 cyclone. The rubble bed was located at a depth of 3 to 4 metres, on a gentle slope that had very low sedimentation and good water exchange.

These trials aimed at testing the feasibility of utilising mesh-panel nursery structures to stabilise loose rubble whilst simultaneously supplying corals for outplanting onto the rubble bed as it consolidates. The objectives of using temporary structures include simplifying permitting requirements and minimising longer-term aesthetic risks or maintenance obligations.

Design and deployment

1 x 2 m aluminium mesh panels ("diamond mesh" 60 mm mesh openings) were used as mid-water nurseries in the Coral Nurture Program by nine tourism operators at 12 sites on the GBR. These panels are readily available in Australia and can be used off-the-shelf without further fabrication (US$55 per panel). They are easy to remove or relocate because of their manageable size, lightweighted and non-rusting properties.

In normal use, the nursery panels are suspended mid-water to maintain the same depth for donor corals, nursery and outplanting (**Figure 73**). Good water flow around the meshes could enable fast growth of corals. The subsequent placement of these panels directly onto rubble in the GBR drew inspiration from the "coral carpets" initiative in the Gulf of Eilat, Red Sea (Golomb et al., 2020). Here, the meshes are also deployed directly onto rubble beds for stabilisation.

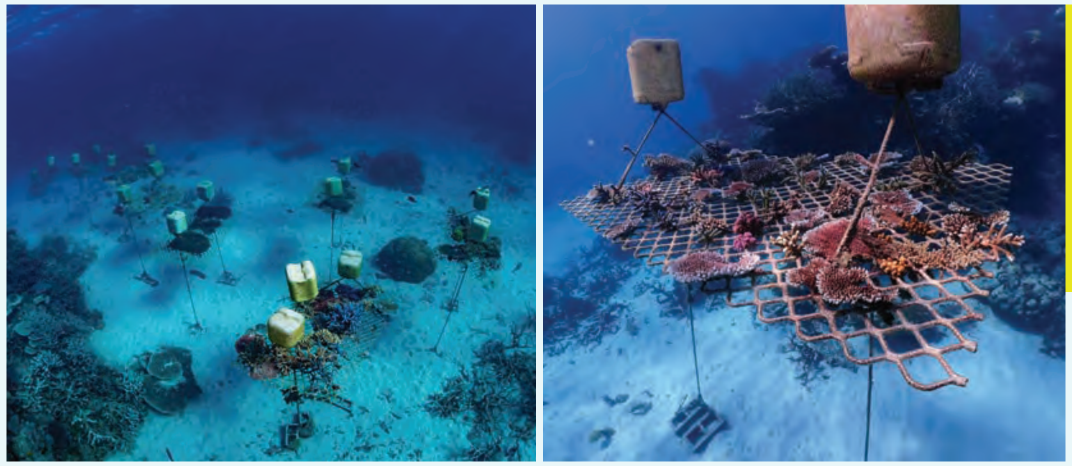


Figure 73.
Mid-water nursery panels deployed on Opal Reef. Source: John Edmondson, Wavelength Reef Cruises

In the first pilot trial (2021), 3 panels with some established coral colonies (mostly *Acropora millepora*) were placed directly on a shallow (2 m) rubble site and anchored in place with rebar stakes (**Figure 74**). Over a period of 18 months, these meshes generally prevented rubble movement, albeit with some erosion at the panel edges.

The second trial began in May 2022. During the trial, 10 panels, stocked with a mix of branching, plate and digitate corals, were relocated from a nursery site within the same reef via towing. The 10-panel cluster was placed in a checkerboard pattern with gaps between the panels. Fragments of corals from the panels, and other nearby **corals of opportunity**, were placed in the gaps between the panels at intervals during the trial (**Figure 75**). The intention was for the structures to reduce rubble movement and allow time for stabilisation. During this period, the fragments placed on rubble remain relatively undisturbed. After 2 years, panels could then be removed, and more fragments could be added to the gaps.

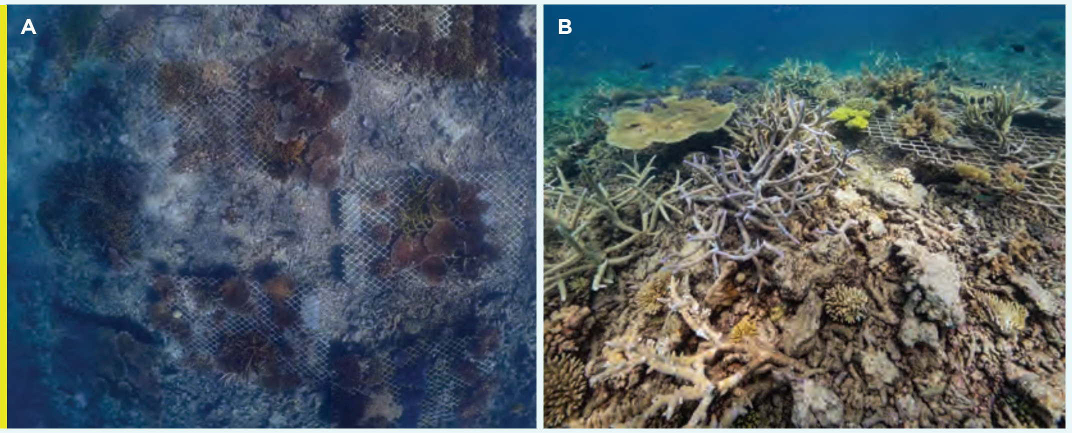
In the third pilot trial, which also started in 2022, two mesh panels were suspended slightly above the rubble substrate (**Figure 76**). These panels were stocked with *Acropora millepora* as part of a separate experiment. Panels were elevated above the rubble with support structures such as concrete blocks, rocks, or rebar pegs. This approach was designed to enhance herbivore access to algae that grows on the rubble surface. The panels may also indirectly limit rubble movement by providing resistance to water flow and reducing energy near the seabed.

Results/findings

Across all pilot trials, results within the first year were encouraging. The corals on the panels suspended above the rubble substrate demonstrated substantial growth and high survival rates. Specifically, coral cover increased from less than 5% to over 35% in two years, and the survival rate was 70%. However, corals on panels placed directly on the rubble showed a lower survival rate of less than 40%. These corals, after being established for over a year, died due to infestation by juvenile *Drupella* snails.

Figure 74.
Pilot trial site before (left) and after (right) initial placement of panels. Source: John Edmondson, Wavelength Reef Cruises

Figure 75.
(a) Nursery mesh panels placed in a checkerboard pattern (May 2022).
(b) Corals transferred to gaps between the panels (November 2023). Source: John Edmondson, Wavelength Reef Cruises



In December 2023, the site was directly hit by a Category 2 cyclone, Cyclone Jasper. This resulted in some coral loss from the 10 panels and a complete loss of corals placed on rubble between them. The cyclone also moved the intact panel assembly about 10 m downslope. However, the rubble bed had been completely scoured and rearranged, tending towards finer pieces. A half-buried rock, about a metre in diameter, was overturned and shifted several metres downslope by the storm. The other two nearby pilot trials were more sheltered by reef structure from prevailing conditions and remain undamaged from the storm. Unfortunately, severe coral bleaching followed in March 2024, causing additional mortality within the 10-panel pilot trial.

Lessons learned:

- The placement of panels with outplants almost instantly improved coral cover. However, long-term survival rates of the outplants were disappointing, likely due to the selection of coral species and high risks of repeated damage with frequent storms.
- Mesh panels effectively prevented rubble movement. However, further research is needed to understand when to optimally remove the temporary panels. Coral recruitment and algal growth occurred under the mesh, but the consolidation was insufficient to resist severe storms.
- A gap under the mesh panels allowed parrotfish to graze, possibly reducing algae growth and influencing the biota on the rubble, which could be important for coral recruitment.

Top left:
Figure 76. Parrotfish were observed grazing on the mesh and the rubble located beneath it, where the mesh was installed 20 cm above the substrate.

Top right:
Figure 77. Close-up view of mesh panels reveals some recruitment, but there are also more algae under the mesh after 3 years. The panels now sit higher than the surrounding eroded rubble that has undercut the edges.

Bottom:
Figure 78.
After Cyclone Jasper, the 10-panel trial was restored to its original location on February 1, 2024, with surviving corals. Some signs of bleaching were observed in March/April 2024.

Source: John Edmondson, Wavelength Reef Cruises

Expert tips

"The pilot trials were primarily motivated by the need for temporary structures on the Great Barrier Reef (GBR), due to permit conditions requiring removal after 3 years. Further investigation is needed for these temporary methods. However, if regulations and attitudes towards permanent installations change, it may be more beneficial to use heavier and more secure structures that elevate corals above the rubble, like Reef Stars, which also have better storm resistance and coral survivorship.

Nevertheless, certain rubble patches that are protected by surrounding rock from regular disturbance have shown good recovery and the same coral species are often seen as the first colonisers. These would be the best candidates for stocking the panels."

John Edmondson

John Edmondson
is a committed marine biologist and the owner of Wavelength Reef Cruises in Port Douglas. With a strong passion for sustainable tourism, he promotes a partnership between ecotourism and scientific research. Through extensive research and conservation efforts, he actively explores various methods for reef restoration, including the use of meshes and coral nurseries.

Table 10.
Pros and cons of flat structures (Edmondson, pers. comm.; Brival, pers. comm.; Raymundo et al., 2007).

Pros	Cons
• Installation process is simple and does not require advanced technical knowledge, making it suitable for engaging local communities and volunteers. • Structures can be deployed quickly due to their simplicity, allowing a large surface area of reef to be covered in a short period. • Materials are cheap and can be sourced locally.	• The method does not significantly increase three-dimensional structural complexity until significant coral growth occurs. • Introduction of foreign materials into the environment can potentially lead to pollution if structures degrade. • There is a risk of damaging benthic organisms during installation.

Materials

These structures can be crafted from different materials, including plastic, metal, and biodegradable coconut coir (**Figure 79**).

Commonly used metals include galvanized steel and aluminium, with plastic-coated wire meshes demonstrating superior durability compared to plain metal counterparts (**Taylor**, pers. comm.). Trials in the GBR demonstrated that aluminium meshes outperformed steel meshes due to their lighter weight and superior resistance to corrosion (**Edmondson**, pers. comm.).

On the other hand, non-coated steel and biodegradable meshes may degrade rapidly and potentially introduce marine debris and pollutants. In addition, corals may fail to attach to corroded metal surfaces and show tissue loss when in direct contact with rusted metal (Raymundo & Burdick, 2022). A project in Malaysia found that non-coated steel mesh rusted after 6 months of deployment, likely due to the choice of material and the thickness of the wire (Chen et al., 2018). Similarly, in Raja Ampat, meshes made of uncoated, ungalvanized metal wire with a thickness of 2 mm showed signs of degradation after one year and a half (**Brival**, pers. comm.).

There are concerns that plastic meshes could become brittle and break apart over time, potentially introducing microplastics into the environment. However, contrary to the concern, Raymundo et al. (2007) found that plastic meshes remained visible and intact, though covered with CCA, for at least 7 years after their deployment, which included a direct hit by a typhoon.

Size and configuration

The size and configuration of flat structures play an important role in stabilisation effectiveness. Rolls or panels of meshes can be cut into appropriate sizes to fit the site. Mesh panels typically measure 1 to 2 square metres and are bundled together for greater stability. Minimizing edges by connecting more structures to cover a larger surface area can improve stabilisation effectiveness by reducing erosion or rubble at the edges. (**Edmondson**, pers. comm.).

Installing meshes parallel to the reef slope is often preferred to mitigate the risk of "avalanches" of rubble and sand down the slope, which can smother the meshes and hinder stabilisation success (**Brival**, pers. comm.). Alternatively, starting the installation of meshes at the upper part of the slope and using **barrier fences** may also mitigate the risk of avalanches and ensure stability (**Figure 80**).

Cell sizes of meshes and grids can vary from 2 to 15 cm in diameter, with smaller cell sizes suitable for finer rubble but can block access of larger herbivores (**Edmondson**, pers. comm.), which may lead to increased algal growth and a change in the biota that colonises the rubble habitat. However, any effects on rubble ecology caused by reduced predator and herbivore access need further study.

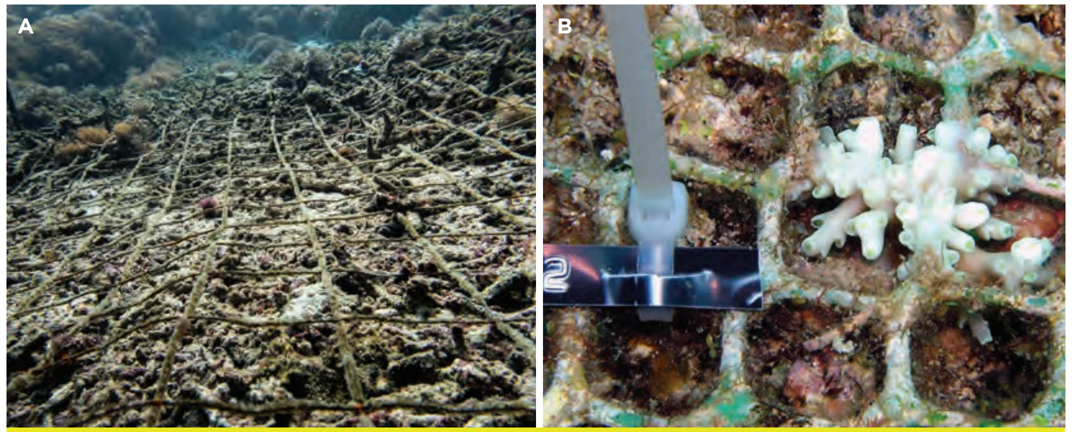


Figure 79. Examples of meshes made with different materials: **a)** Metal wire mesh in Nusa Penida, Indonesia, and **b)** plastic mesh in Calagcalag Marine Protected Area, Philippines.
Source: a) Andrew Taylor, Blue Corner Marine Research; b) Laurie Raymundo

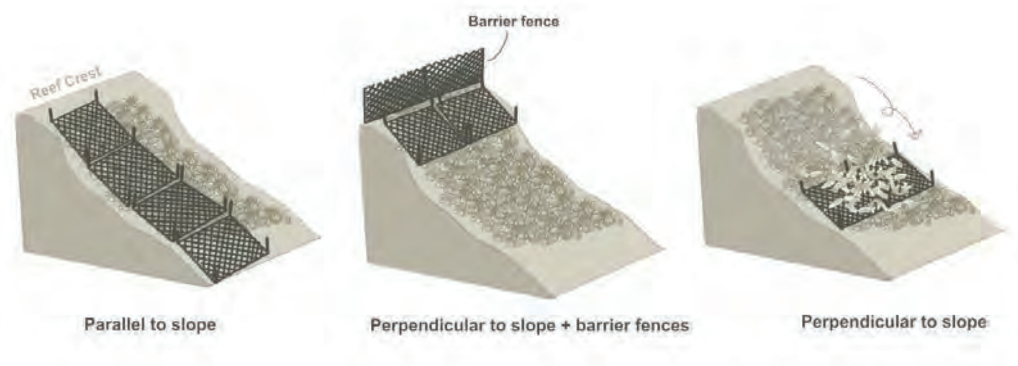


Figure 80.
Configurations of flat meshes and fences on a steep slope.
Source: Shu Kiu Leung, The University of Queensland

The recommended mesh/grid thickness ranges from 3 mm to 7 mm, balancing durability with cost and ease of implementation (**Brival**, pers. comm.; **Edmondson**, pers. comm.). Thinner structures may degrade quickly and become ineffective, while thicker structures offer greater stability but may be more expensive and challenging to handle. Furthermore, thicker structures can provide settlement surfaces for coral recruits, potentially enhancing recovery.

Costs and maintenance

Generally speaking, this method is both cost-efficient and low maintenance.

As reported by Raymundo et al. (2007), the combined cost of materials and labour for mesh deployment in plots was roughly US$4.3/m^2 (~A$5/m^2), inclusive of the rock piles that were locally sourced.

If the deployment were to be scaled up to cover the entire 2,400 m^2 rubble bed, maintaining the current ratio of 5 plots per 500 m^2, the total cost would be approximately US$3300 (~A$4000). This equates to about US$1.4/m^2 (or about A$2/m^2). Note that these costs were based on 2007 figures and are kept low due to volunteer assistance from the fishing community. Meshes can be deployed efficiently due to its simple installation process. In fact, a team of just two divers can cover an area of 100 to 150 square metres using one tank of air (**Brival**, pers. comm.).

There were also minimal to no maintenance requirements for anchorage or cleaning once the meshes were installed, except occasional removal of algae or reattachment of structures if dislodged or buried.

Expert tips

"The goal is to minimize maintenance needs to a one-time task or ideally, none at all, especially in cases where resources are limited. If a method requires regular maintenance, for example, very frequent cleaning of algae or adjustments of rebar pegs, it could suggest that they may not be the right fit for the site, or that the initial implementation was ineffective."

Arnaud Brival

Arnaud Brival
the co-founder of "The SEA People" NGO based in Raja Ampat, is a dedicated marine conservationist. He leads field projects, deploying structures like metal frames, steel meshes, and barrier fences in collaboration with local communities. To date, their collective efforts have successfully covered over 4000 m^2 of reef in the area.

Barrier Fences

Barrier fences can have so far been implemented exclusively in Indonesia (**Brival**, pers. comm; Taylor, 2020). These structures are usually positioned on reef slopes to limit downslope movement of rubble and are coupled with other methods.

Scale of implementation

Barrier fences have only been tested at two locations, Raja Ampat and Nusa Penida, at a local scale.

How does this method helpwith recovery?

This method may help facilitate the natural binding and subsequent cementation of rubble by hindering rubble movement, as well as creating a stable surface for coral recruitment. Recent empirical observations suggest that fences may only delay, not halt, the "avalanche" process of rubble moving downslope, particularly if coral growth does not keep pace with rubble movement (**Brival**, pers. comm.).

When and where?

Given their degradation over time, fences are most effective when used in combination with other techniques such as **flat structures** (see "When and Where?" within the section) and **rock piles**, and on gently sloping areas.

Figure 81. Locations where barrier fences have been deployed. Source: Shu Kiu Leung, The University of Queensland

Implementation Strategy

Divers directly install fence panels onto the rubble bed in an upright position and ensure they are firmly anchored using rebar stakes (Figure 82).

What realistic outcomes can we expect?

Although there is only anecdotal evidence, observations suggest that the piled rubble behind the fence was often colonised with soft corals and potential binding organisms (Taylor, 2020). In Bali, coral recruits of massive and encrusting growth forms have also been observed after deployment. However, fence materials tend to degrade and lose their function after 1 year. Instances of fences being overflooded by rubble or sandy substrate within as little as 2 years have also been reported (Brival, pers. comm.). This could be attributed to factors such as inappropriate placement, disturbance by curious organisms, wrong choice of cell size, or an excessive amount of rubble.

Materials

Similar to flat structures, these fences can be made of plastic or wire.

Size and configuration

Barrier fences typically stand 40 cm tall and are supported by 1 m rebar stakes (Taylor, 2020). The size of the fences can be adjusted based on site environmental condition. For example, larger rubble pieces require taller fences and finer rubble pieces require fences with smaller cell sizes.

These fences are often positioned perpendicularly to the current or reef slope. This strategic configuration allows rubble to accumulate in piles against the barrier, directly limiting its movement and blocking currents that may disturb loose rubble (Brival, pers. comm.; Taylor, 2020). If used in a repeating pattern following a slope contour, this creates a terraced configuration similar to that used in agriculture on mountain slopes (Raymundo, pers. comm.).

Costs and maintenance

The costs are similar to those of flat structures, as the materials and installation processes are alike. Maintenance tasks may involve checking for damage or burial from downslope rubble and sand movement, as well as removal of macroalgae.

Table 11.
Pros and cons of barrier fences (Brival, pers. comm.; Taylor, 2020).

Pros	Cons
• Directly limit downslope movement of rubble, stabilising the rubble bed and preventing potential damage from "avalanches" to areas further down the slope. • May change flow in terms of small-scale turbulence around the structures, reducing proximal rubble movement and also encouraging the settlement of recruits to the area (which rely on turbulence for settlement). • Provides a stable settlement surface above the substrate level. • Installation process is simple and does not require advanced technical knowledge, making it suitable for engaging local communities and volunteers. • Structures can be deployed quickly due to their simplicity, allowing a large surface area of reef to be covered in a short period. • Materials are cheap and can be sourced locally.	• The method does not significantly increase three-dimensional structural complexity until significant coral growth occurs. • Introduction of foreign materials into the environment can potentially lead to pollution if structures degrade. • There is a risk of damaging benthic organisms during installation.

Figure 82. Barrier fences deployed in Nusa Penida – rubble piles can be seen accumulating against the fence. Source: Andrew Taylor, Blue Corner Marine Research

Addition of structures as an alternative substrate

This section explores the **use of various structures**, including small modular structures and large artificial reefs, to stabilise loose rubble on degraded reefs.

Well-designed and properly constructed structures can instantly enhance structural complexity and provide a stable substrate for coral recruitment or transplantation (Ceccarelli et al., 2020; Edwards & Gomez, 2007). They can also limit rubble movement by obstructing water flow and preventing rubble pieces from sliding or overturning.

The evolution of artificial reef structures for restoration has seen a shift from using "materials of opportunity" like sunken ships and tyres, to engineered products and parametric structures designed to meet specific objectives (Edwards & Gomez, 2007; Levy et al., 2022; Tallman, 2006). This change reflects a growing focus on sustainability and functionality. Technological advancements have enabled the design of diverse, complex structures that mimic coral reef habitats, leading to a surge of artificial reef research.

Box 7

Recent developments in artificial reef structures

Advances in technology have expanded the possibilities for creating artificial reef structures. Technologies like 3D printing and artificial intelligence (AI) are now used to design customised, detailed structures for reef restoration. While mainly used for fishery enhancement, 3D-printed artificial reefs hold promise for custom-built structures that assist in rubble stabilisation and reef recovery across different environments (Levy et al., 2022).

Depending on the printer and method used, a variety of materials can be chosen, enabling the creation of diverse, eco-friendly shapes not commonly possible with other methods (Levy et al., 2022; Yoris-Nobile et al., 2023). The use of locally sourced, sustainable materials is especially important when restoring already sensitive reefs. For example, the use of local materials like sand and shells is not only cost-effective, but it also has a lower carbon footprint compared to other materials like concrete (**Lennon**, pers. comm.).

Figure 83. 3D printed reef structure made of local materials – "Reef Arabia" deployed in Bahrain.
Source: David Lennon

Another significant benefit of 3D printing is the ability to customise the shapes and sizes of artificial reefs. Many stabilisation structures currently in use do not adequately replicate the natural reef shape (Levy et al., 2022). Addressing this key issue is crucial to enhancing biodiversity and promoting recovery in degraded areas. 3D printing technology enables the creation of highly accurate structures that closely resemble natural reefs, providing a variety of habitats for marine life. For example, 3D models of an actual reef landscape can be obtained using underwater cameras and complimentary 3D imaging software, which can then be printed to achieve a high degree of precision.

Recent advancements in 3D printing technology have led to the development of innovative artificial reefs designs, such as the MARS2.0 (Modular Artificial Reef System) developed and patented by Reef Design Lab Australia (RDL). Robin Philippo (TRACC Borneo) and Alex Goad (RDL) have revised the original design to better suit sloping reefs, particularly those affected by blast fishing. Unlike traditional methods that involve 3D printing reef structures directly, this approach uses 3D-printed moulds to produce structures on-site by filling them with cement, which significantly reduces logistical challenges for small island communities and projects with limited funds (**Philippo**, pers. comm.). This makes reef restoration more accessible and increases employment opportunities for local communities.

MAR2.0 will be tested on sloping reefs ranging from 15 to 50° on Pom Pom Island, Malaysia. The first structure was placed on a 25° slope in August 2024, and further testing on steeper slopes (up to 50°) is currently underway. The cement structures are designed to incorporate the following features:

- Heavy, wide base with minimal upper weight to enhance stability on steep slopes and avoid toppling
- Large surface area to facilitate coral recruitment
- Large number of anchor points for coral outplanting
- Grooves for easy maintenance
- User-friendly design that allows for simple deployment with limited training

Figure 84.
Photos of MARS2.0 (Reef Design Lab) deployed on a 25° rubble slope on Pom Pom Island with TRACC Borneo. Source: Robin Philippo, TRACC Borneo

TRACC's scientists, dive team, and volunteers are planning to conduct a 5-year research project to test the effectiveness of MAR2.0 on sloping reefs in promoting coral recruitment and supporting reef recovery. Structures will be deployed at 4 sites on Pom Pom Island, with each site containing 3 installations of 16 modules and 13 smaller plates, totalling 192 modules and 156 plates. Each installation at the site will undergo one of three treatment types:

1) structures with outplanting and maintenance,
2) structures with outplanting but no maintenance; and
3) structures with no outplanting and no maintenance. Over the next 3 to 5 years, TRACC and RDL will assess how well these installations perform on sloping reefs and evaluate the cost-effectiveness of the three treatments.

AI-assisted designs are currently being explored to make artificial reef design more accessible and tailored to restoration project goals (**Lennon**, pers. comm.). By tweaking input parameters, such as rubble size, coral growth form, and desired porosity of structures, even those without expert knowledge can generate a preliminary design, visualizing the end product and simplifying the design process. However, it is recommended for experts to validate AI-generated outputs to ensure their effectiveness.

The feasibility of using 3D printing and AI for rubble stabilisation remains a question. It might work for small-scale projects where inexpensive desktop printers are used to print modular units (Levy et al., 2022). However, the high initial costs of professional to industrial machines, which are capable of large-scale production, is a major hurdle. In addition, operating these machines requires technical knowledge. Given the recent introduction of these technologies to coral reef environments, the best practices are still being determined.

Figure 85. Diver transporting an individual MARS2.0 module for assembly at the site. Source: Robin Philippo, TRACC Borneo

Figure 86.
AI-assisted design of an artificial reef. Source: David Lennon

Table 12.
Pros and cons of using different materials for constructing stabilisation structures (Boström-Einarsson et al., 2020a; Ceccarelli et al., 2020; Fabi et al., 2015; Florisson & Tropiano, 2017).

The **material choice** of reef structures may influence coral settlement and benthic community development (Boström-Einarsson et al., 2020a). **Table 12** below compares the common materials used for reef structures:

Material	Pros	Cons
Natural materials (e.g. rock, coconut coir)	• Likely to be perceived as aesthetically pleasing as they blend easily with the environment. • Provide a suitable surface texture for coral settlement. • Unlikely to cause long-term pollution.	• Limited durability if materials are biodegradable.
Plastic	• Offers flexibility in shape and size. • Low-cost • Lightweight and easy to handle	• May not look natural. • Non-biodegradable and poses risks of microplastic pollution. • May degrade under UV radiation.
Metal	• Offers flexibility in shape and size. • Durable and stable.	• May not look natural. • Poses risks of corrosion and thus requires coating. • Limited use in shallow / highly oxygenated water bodies.
Concrete	• Offers flexibility in shape and size. • Durable and stable. • Provides a heavy weight for stabilisation. • Provide a suitable surface texture and large surface areas for settlement.	• May not look natural. • The structures' heavy weight might require the use of machinery. • The use of cement contributes to carbon emission.

Rocks and boulders

Rocks and boulders were deployed in the United States and across Asia to repair coral reefs damaged by various environmental stressors. Within the US territorial waters, particularly in Southeast Florida and Puerto Rico, rocks and large boulders were used to stabilise loose rubble beds after ship grounding accidents (NOAA, 2015; Wever, 2022).

This is usually done following emergency restoration efforts like rubble removal and coral reattachment. In Southeast Asian countries, including Indonesia and the Philippines, rock piles were used to stabilise large rubble fields resulting from extensive blast fishing (Fox et al., 2005; Raymundo et al., 2007), with the additional objective of creating fish habitat. Additionally, in China, rocks were used to restore degraded coral reefs impacted by tourism activities, typhoons, and reservoir floodings (Xia et al., 2020). This method is relatively simple and has low technical requirements, making it a feasible option in developing nations with limited resources and capacity for reef restoration. Building these structures, if cement or other adhesives are necessary, may also be an activity that local communities or citizen scientist groups can undertake (Raymundo et al., 2007).

Scale of implementation

Stabilisation efforts can range from small-scale projects spanning just a few square metres to large-scale restoration across multiple reefs. For example, a large-scale study was conducted in Komodo National Park, Indonesia (see **case study 4**), which involved restoring 4 rubble beds covering an area of over 6000 m^2 (Fox et al., 2019; Fox et al., 2005).

How does this method help reef recovery?

Rocks work by providing a hard, rugose, and stable substrate that is favourable for the settlement of coral recruits (Fox et al., 2019). While keeping the coral recruits elevated from the benthic layer, rocks can minimise the burial and abrasion of coral recruits caused by rubble movement (Fox et al., 2005). Moreover, the rocks' uneven surface and the crevices between them create instant rugosity and structural complexity. This not only increases the settlement area for new organisms but also supports a wide variety of species by providing numerous living spaces (Ceccarelli et al., 2020; Raymundo et al., 2007).

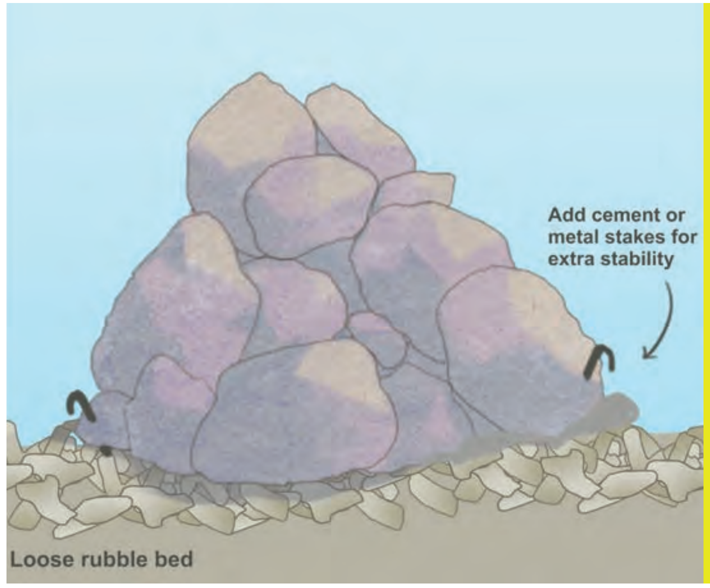


Figure 87.
Placing rocks onto a loose rubble bed. Source: Shu Kiu Leung, The University of Queensland

Figure 88.
Locations of sites where rocks and boulders were deployed. Source: Shu Kiu Leung, The University of Queensland

When and where?

Rock piles tend to generate the best outcomes in sites with adequate coral larval supply and good water quality (Fox et al., 2000).

Moderate currents might be the optimal conditions for rocks and boulders to work. In strong currents, rubble tends to fill in around rock piles and bury them (Fox et al., 2019). In addition, soft corals were favoured over hard corals in these conditions. The study did not find much success in low-current sites as well due to a high sediment load that limited coral growth. The study also recommended avoiding locations with large volumes of coral rubble and very strong tidal currents.

Due to logistical challenges, such as the use of large boats for rock transportation, implementing rock piles can be difficult in shallow areas like reef flats where boats are unable to gain access. This may greatly increase the cost and labour requirements.

Implementation Strategy

Before deployment, it is recommended to thoroughly clean the rocks to minimise the risk of introduction of pollutants, pathogens, external sediments, or foreign species (Olsen Associates Inc., 2016). Prepared rocks can be transported to the restoration sites by cargo boats or barges (Fox et al., 2000; NOAA, 2015). After the boat anchors over the restoration site that is marked with a temporary buoy, rocks can be deployed manually by scuba divers or by machinery.

In Komodo National Park, rocks were thrown overboard and then arranged into piles by scuba divers (Fox et al., 2000). For this approach, extra care must be taken to minimise accidental damage to fauna or the underlying hard substrate. For larger boulders, cranes may be used to unload the rocks from the barge into a specific location and configuration (Olsen Associates Inc., 2016).

Cement and metal stakes can be added to ensure rocks remain stable in environments with strong wave action, currents, and/or slopes (Olsen Associates Inc., 2016; Raymundo et al., 2007). Cement can be applied around the outer parts of the rock piles, leaving the inner part untouched to maintain sufficient interstitial spaces (Olsen Associates Inc., 2016). Additionally, containment features can be used to prevent cement from overflowing from the boundaries of the piles, and the surface of the poured cement can incorporate "dressing stones" or rubble to create a more natural-looking surface and increase rugosity. It is crucial to consider the effect of water pressure on cement – this includes finding the right tools and mixture that is suitable for underwater application (Wever, pers. comm.). Read more about using cement to attach rubble in the section **Substrate positioning and reattachment - Materials.**

Rock piles can also be combined with other methods, such as **flat structures** and **coral transplantation** depending on the needs of the site. Raymundo et al. (2007) demonstrated the use of plastic mesh and rock piles together to stabilise a 2400 m^2 rubble field in the central Philippines. In this case, rocks were utilised to provide weight and stability to the mesh, simultaneously increasing the availability of microhabitats and surface area for coral and fish recruitment. In the M/V Clipper Lasco grounding incident, large limestone boulders were used to stabilise the rubble. This was followed by biological restoration through the transplantation of 334 stony corals of 17 species, 10-50 cm in diameter, were transplanted to the site, aiding in community recovery (Wever, pers. comm.). A significant increase in adult stony corals (>5 cm) was observed at the 5-year monitoring mark, with this upward trend persisting through the 9-year period.

Case Study 4:

Long-term study of rock piles in Komodo National Park, Indonesia

Background

Located in eastern Indonesia between the major islands of Sumbawa and Flores, Komodo National Park (KNP) has a rich diversity of coral and fish. However, around 50% of coral reefs within KNP had suffered damage from chronic fish blasting activities from 1950 to the mid-1990s.

Although blast fishing has decreased by 80-100% as the authorities initiated a patrolling program with support from The Nature Conservancy, sites that had been heavily blasted remained as large rubble fields (Fox et al., 2003). These rubble fields have seen minimal natural recovery despite good water quality and high recruitment rates.

Design and deployment

In the effort to find a cost-effective way to stabilise the rubble and restore the sites, a pilot study began in 1998 to test the performance of 3 stabilisation methods in 1 m^2 square plots in increasing hard coral cover, namely netting, cement slabs, and rock piles (**Figure 89**) (Fox et al., 2005). While all methods initially saw coral recruitment, over time, nets were scoured and buried by rubble, and cement slabs were occasionally overturned by currents. Rock piles were not immune to these challenges but showed the most potential and could be built above the rubble.

The rock piles study was then scaled up in 2000 in 100 m^2 plots in 9 rubble field sites in KNP. The results were promising – rocks were quickly colonised by CCA and encrusting organisms, demonstrating high recruitment rates of 10-20 recruits/m^2 at some sites after only 6 months (Fox et al., 2005).

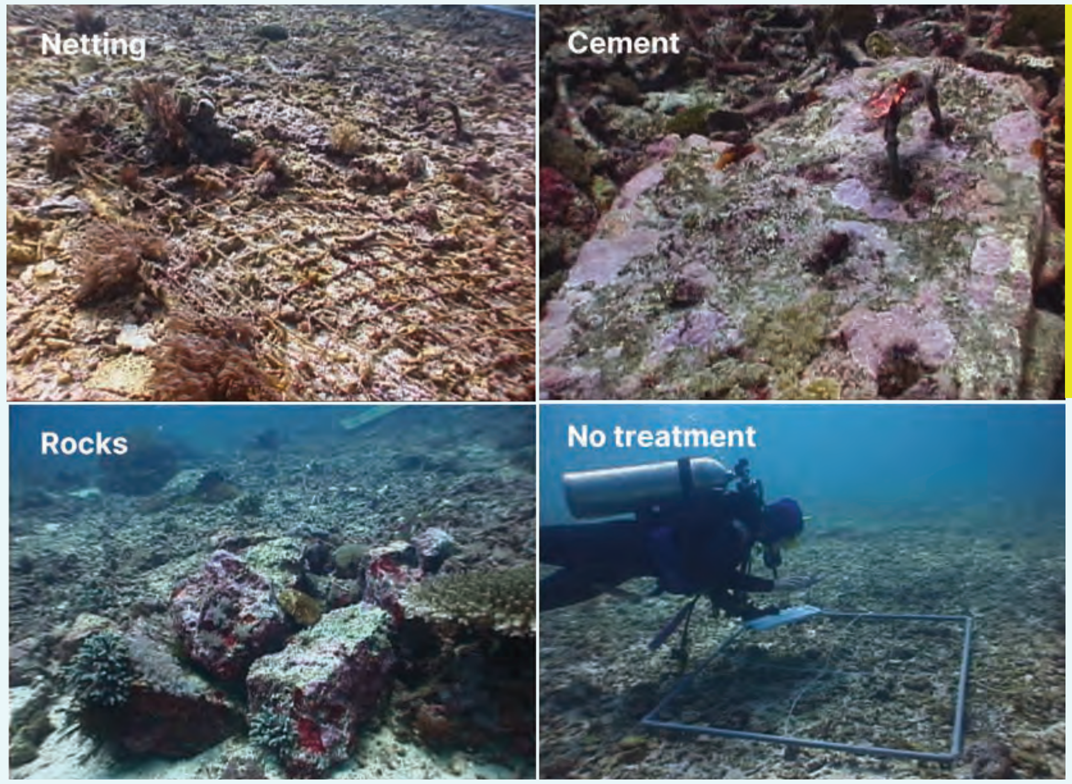


Figure 89.
Setup of the 3 stabilisation methods and control plot tested in the pilot study. Source: Helen Fox

Based on the encouraging results from the baseline surveys and pilot studies over the years, a large-scale study covering approximately 6430 m^2 across 4 sites in KNP was conducted in 2002 to further test the effectiveness of rock piles arranged in different configurations (**Figure 91**) (Fox et al., 2005).

Results/findings

On average, the plots from the large-scale study show increased coral recruitment, growth, and cover over 16 years (**Figure 90**) (Fox et al., 2019). In some of the best-case scenarios, rock piles facilitated the recovery of coral cover up to 82% in 14 years, translating to an annual increase of 6% (but the least successful site only had 3.2% cover at that time).

The long-term study presented the use of locally available materials as a low-cost low-tech way to stabilise rubble. However, when compared to enforcement, protection proved to be far more cost-effective than restoration, with the net total cost of law enforcement being around 250 times less than that of rock piles (Haisfield et al., 2010). A seven-year model of cost-effectiveness showed that the implementation of rock piles (US$52.92, or ~A$80) costs more than 5 times per square metre of increase in coral cover than enforcement (US$9.64, or ~A$15).

Lessons learned:

- Rock piles offer a low-cost, low-tech option for restoring rubble beds, with demonstrated long-term success that is seldom documented in other methods.
- Rock piles are adaptable to different scales. It is recommended to gradually upscale restoration projects, starting from a pilot study to test feasibility and then slowly expanding.
- Prevention over cure – restoration cannot replace the mitigation of disturbance. Enforcement is required to ensure no ongoing stressors are causing continued reef degradation for the method to work

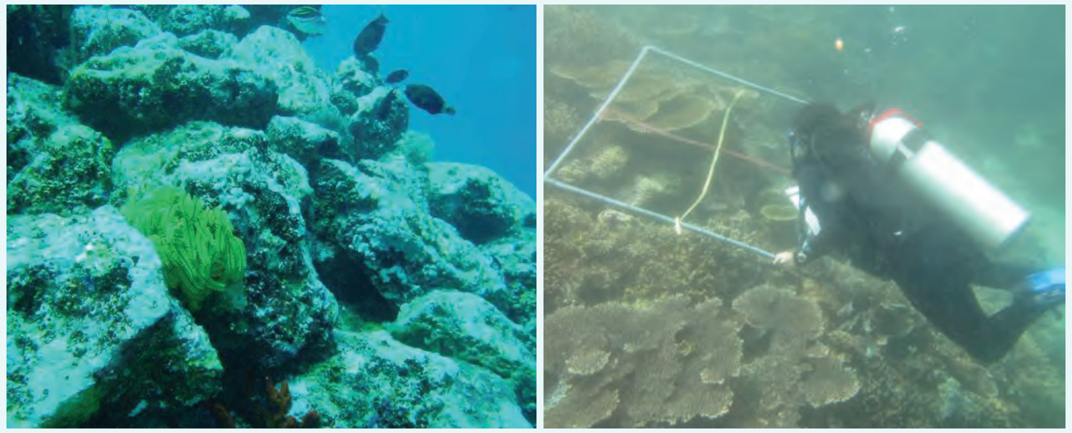


Figure 90.
Restoration site in 2004 (left) vs 2016 (right). Rock piles deployed in 2002. Source: Helen Fox

What realistic outcomes can we expect?

> In the short (<1 year) to medium term (1-5 years), rocks and boulders may promote coral recruitment and benefit fish communities by increasing fish abundance, diversity, and causing positive shifts in the fish community. Over time, they could contribute to an increase in the cover and density of hard corals. However, the success of rocks and boulders may vary greatly depending on the environment.

The effectiveness of rocks and boulders in stabilising rubble beds is well-documented. Multiple scientific studies have demonstrated the short- and long-term recovery outcomes of this method (Fox et al., 2019; Raymundo et al., 2007; Viehman et al., 2018; Wever, 2022; Xia et al., 2020).

Fox et al. (2019) reported a significant increase in hard coral cover from 0% to an average of 44.5% on average over 16 years in areas treated with rock piles, while nearby untreated rubble fields remained at 3%. There was also considerable coral recruitment of 12.46 recruits/m^2 after 2 years of treatment (Fox et al., 2005).

In the T/V Margara case in Puerto Rico, Viehman et al. (2018) used limestone boulders and observed similar patterns of hard coral density (~10 corals/m^2) between the restoration area and the reference site after 7 years, both significantly higher than the untreated rubble site. Similarly, Wever (2022) documented a 700% increase in coral density 7 years after deploying boulders in Florida.

The response in fish parameters was observed to be quite rapid. Raymundo et al. (2007) found shifts in the fish community within 3 years, transitioning from community characteristics typical of rubble fields to those resembling adjacent healthy reefs, with an increase in both biomass and average size. Moreover, Xia et al. (2020) noted an increase in fish diversity and density in 2 years, with 23 species and 1.2 fishes per m^2, compared to the control rubble site which had only 7 species and 0.5 fishes per m^2.

However, there is high variability in the success of the method in different sites depending on the environmental factors. For example, in the study conducted by Fox et al. (2019), the most successful site achieved 82.5% hard coral cover, while the least successful site only had 3.2% cover. The authors noted that the success of the method may be variable depending on multiple factors like current strength and soft coral dominance.

Pros	Cons
• Provides habitat, including crevice spaces, for fish and invertebrates. • Provides instant structural complexity and rugosity. • Provides a stable settlement surface area raised above the substrate level, potentially reducing the impacts of sedimentation and competition on coral recruitment. • May help provide coastal protection by wave attenuation depending on its size and arrangement relative to the shore. • Use of natural materials avoids the introduction of plastic or metal that may affect the environment. • Ocean chemistry, pressure and time can consolidate limestone back into the carbonate platform. • Relatively low-cost if *in situ* material is available.	• May introduce pollutants, pathogens, or unwanted species if the rocks are not cleaned properly before deployment. • There is a risk of damaging benthic organisms during installation. • In the case of large limestone boulders, the site may appear man-made rather than natural for extended periods of time. • The cost is largely dependent on material availability and logistics – May require extensive and complicated logistical considerations involving barges and machinery, which could significantly increase installation costs.

Table 13.
Pros and cons of rocks and boulders (Fox et al., 2019; Fox et al., 2005; Griffin, pers. comm.)

In Florida, Wever (2022) also highlighted that despite the increase in coral density, the presence of adult key reef-building species was notably absent in boulder sites, likely due to their slow growth. This indicates that it may take several more years for the method to fully realise its potential.

Materials

Typically, limestone or other types of locally sourced rocks are used. Limestone, in particular, is preferred because it is a sedimentary rock composed principally of calcium carbonate (CaCO3), which is similar to the composition of natural reef-forming coral skeletons. For example, Fox et al. (2005) used limestone and lithic sandstone quarried from nearby resources in western Flores for their rubble stabilisation project. It is recommended that other suitable rock materials exhibit high density, stability, and durability to endure the hydrodynamic conditions at the site (Olsen Associates Inc., 2016). Provided there are sufficient resources, it is recommended to carefully inspect these rocks, selecting those free of cracks or flaws that could compromise their durability on-site or during handling and placement, as proposed by Olsen Associates Inc. (2016) at the damaged reefs off Ft. Lauderdale, Florida. Ideally, rocks would have high rugosity and a coarse-grained texture to provide ample settlement surfaces and attract recruits. A study conducted in Hainan Province, China, used locally available basalt rocks, noted for their electrically charged surface that may attract coral settlement (Xia et al., 2020).

Size and configuration

Rocks of various sizes are selected based on their availability, stability, and similarity to natural pre-disturbance landscape. These can range from small 20 cm rocks to large boulders over 1 m. Using rocks of different sizes can promote structural complexity at the site and create diverse microhabitats for fish and invertebrates.

It is advisable to pile rocks up to a height such that they will not be buried by loose rubble. Moreover, it is recommended that the sizes and shapes of the rocks reflect the local features to preserve the natural appearance of the site, which can be important for areas with high traffic from recreation and ecotourism. For example, in the grounding cases of M/V Spar Orion and M/V Clipper Lasco in Florida, rocks with a flatter profile were chosen to resemble the low-relief reef structures of the site (Olsen Associates Inc., 2016).

The configuration can be based on the site environment and the goals of the project. For example, rocks can be stacked closer to each other in high-energy environments to ensure stability. If increasing fish abundance and diversity is the goal, then rock piles can be arranged in clusters to create cryptic spaces of various sizes for bigger fishes to use (Raymundo, pers. comm.).

Fox et al. (2005) tested four different configurations of rocks, including:

1) complete coverage;
2) rock piles of 1-2 m^3 spaced 2-3 m apart;
3) rows of rocks aligned perpendicular to the prevailing current; and
4) rows of rocks aligned parallel to the prevailing current (Figure 91).

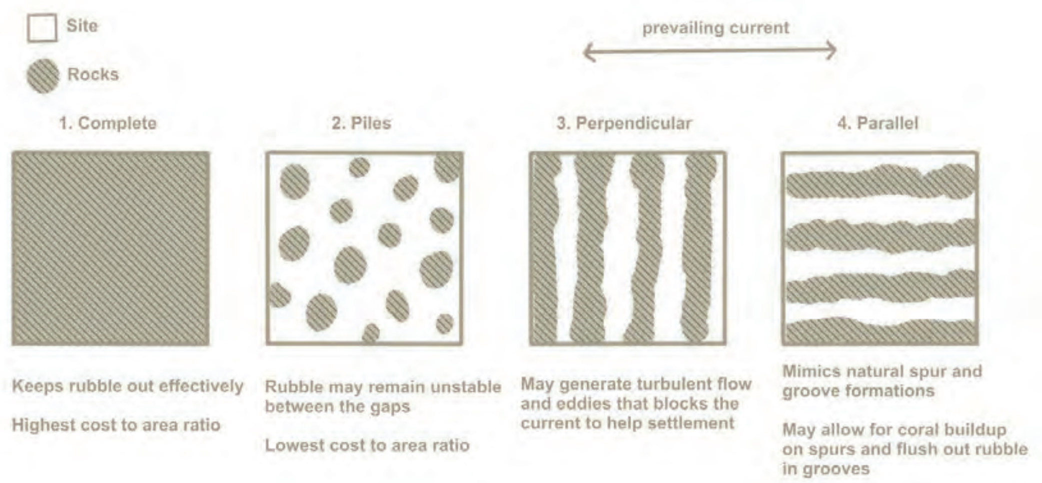


Figure 91.
4 configurations of rocks tested in **case study 4** (Edwards, 2010; Fox et al., 2019; Fox et al., 2005). Source: Shu Kiu Leung, The University of Queensland

However, all configurations showed similar results in terms of coral recovery. In terms of cost-effectiveness, rock piles had the lowest total cost at US\$2.84/m^2 (~ A\$4.5/m^2), because they covered the largest area per volume of material.

Costs and maintenance

When rocks are sourced locally from *in situ* materials found within or adjacent to the restoration sites, the costs for restoration projects range from US\$4.8 to US\$10/m^2 (~A\$7-15/m^2), depending on the scale of implementation (Haisfield & Fox, 2010). However, in Florida, the cost can escalate to between US\$150-1500/m^2 (~A\$230-2300/m^2) when large boulders were brought in to restore grounding damage and bow scars left by ships like M/V Spar Orion and M/V Clipper Lasco. The higher cost is attributed to the complex logistical support required for these operations involving skilled labour, barges and/or larger vessels for deployment. Higher labour and material costs in the US add to the financial burden, along with monitoring costs and other expenses related to rubble repositioning and reattachment (Olsen Associates Inc., 2016).

If *in situ* material is not available, the costs can skyrocket. For example, in Puerto Rico, the cost of using limestone sourced from other areas can be more than 3 times higher (US\$6,000, or ~A\$9200/m^2) compared to reattaching *in situ* materials (US\$1,600, or ~A\$2500/m^2) (Griffin, pers. comm.). But in many cases, *in situ* material is not readily available for restoration and/or there is not enough material to meet the restoration goals.

It is important to note that while minimal maintenance is generally expected, the need for maintenance can vary based on local conditions. For example, seasonal algal blooms may require additional work such as removing algae in cases of fouling and low herbivory or adding cement if the structure shifts or settles and becomes unstable. These maintenance requirements can contribute to the overall costs of the project, potentially impacting the financial feasibility of the project.

Metal structures

Metal is a widely used material for constructing rubble stabilisation structures, due to its versatility in terms of shape and size. This section explores variations of metal frames, highlighting examples including Reef Stars by Mars Inc., as well as mineral accretion technology, which utilizes electricity for enhancing coral growth on metal structures.

3D metal frames

Metal frames, with their many variations in shape and size, are a versatile tool in coral reef restoration. In this field, they are predominantly used as **coral nurseries or structures for outplanting.** However, although metal frames were not historically considered in the context of rubble stabilisation, they can also play a significant role in this capacity.

Rubble stabilisation efforts using metal frames have been used across Australia and Southeast Asia. In Australia, Reef Stars have been deployed at various sites across the GBR (see section **Reef Stars**) and peaked metal frame designs have been placed in Bait Reef under RRAP (**Kenyon**, pers. comm.). In Asia, countries including Indonesia (e.g., the Nusa Islands and Raja Ampat) (Taylor, 2020; The SEA People, 2024), Malaysia (e.g., Tioman, Sibu, and Pom Pom Island) (Abdul Adzis, pers. comm.; **Philippo**, pers. comm.), and China (Liu et al., 2024) have also initiated similar efforts.

Figure 92.
Examples of different metal frame designs placed on a loose rubble bed.
Source: Shu Kiu Leung, The University of Queensland

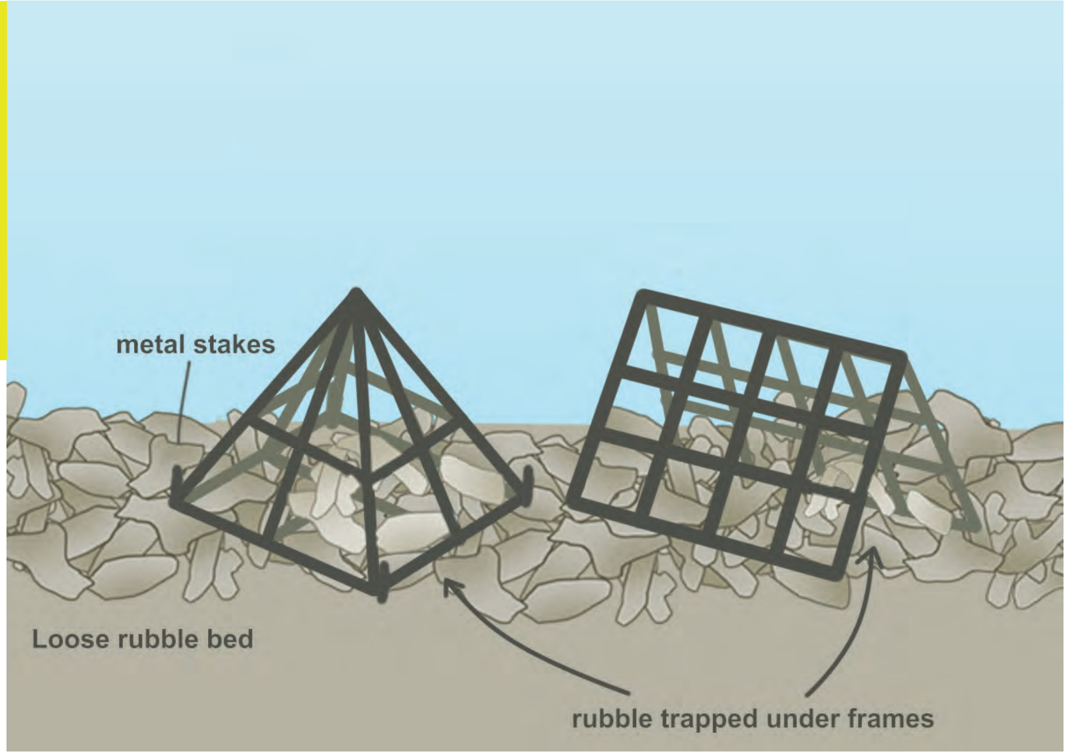


Figure 93.
Locations of sites where metal frames were deployed.
Source: Shu Kiu Leung, The University of Queensland

Scale of implementation

The use of metal frames in coral reef restoration is typically seen on a small to medium scale, often covering a few hectares of a single reef (RRAP, 2024). These efforts are usually research-driven, serving as pilot studies, or are part of local community projects.

How does this method help with recovery?

Metal frames serve multiple purposes in reef restoration. They stabilise rubble, which can facilitate the natural succession of binders onto the rubble, leading to consolidation of the rubble into a stable substrate for coral recruitment. Frames also create a barrier for rubble to be trapped and limit its movement. In addition, this vertical relief provides a substrate for coral recruits and/or coral transplants, held up above the loose, mobile rubble and sediment.

When and where?

Due to the design and installation requirements, metal frames work best in rubble beds or sand. They need a substrate into which the legs can be driven and anchored. With appropriate anchorage, metal frames can be deployed in high-energy areas.

Metal frames can be deployed in a wide range of depths, from very shallow to deep. However, very shallow areas that frequently experience cyclones or intense everyday conditions should be avoided due to the risk of dislodgement. In areas of high hydrodynamic energy, frames could be deployed close together, as per Reef Stars, to afford greater protection and reduce dislodgement risk. In calmer areas, they could be spaced further apart, as per the A frames at Nusa Penida (see **case study 7**).

Peaked structures such as the A-frame, appear suitable for moderate slopes, as they can trap rubble moving downslope, while not becoming buried due to their elevation from the substrate (**Figure 94**). For example, A-frames can be deployed on slopes as steep as 50 degrees (**Taylor**, pers. comm.). On the other hand, **flat structures**, including the flat grid design utilised in the Whitsundays (**case study 5**), are likely to be appropriate only on reef flats, gentle slopes, or the upper portion of the reef slope (see section **Flat structures**). When placed further down the reef slope or on steep areas, downslope rubble movement could easily bury flat meshes. Nonetheless, peaked metal frames can still be buried depending on the amount of rubble and slope angle (e.g., very steep slopes). Once frames are buried, they lose functionality and only serve to create rubble mounds, which alters rubble movement paths but does not halt it.

Metal frame designs that offer high elevation and a large surface area for natural recruits, may be necessary in areas where coral larval supply is low or has high deposited sediment loads, and high cover of coral competitors including macroalgae and soft corals (**Kenyon**, pers. comm.). Metal frames can also be used in conjunction with coral transplantation in these areas. With the help of outplants, metal frames can disappear into the background and become aesthetically pleasing relatively quickly, which may be important in tourism areas. If predation is high, natural recruits and outplants may need to be protected.

Implementation Strategy

Divers can install metal frames either by directly inserting their legs into the substrate or by securing them in place with metal or basalt rebar stakes hammered into the rubble at each corner. Additional support may be provided by fastening the stakes to the frames with cable ties. Proper anchorage is crucial to prevent the frames from being lost or flipping over during storms.

Metal frames are frequently used alongside other artificial structures such as **flat structures** and **concrete structures**. They are also combined with **coral outplanting** because they provide multiple suitable anchor points for attaching coral fragments. Coral transplants of a variety of genera can be easily attached using cable ties to the elevated portion of the structures to accelerate recovery. Frames are particularly well-suited for the attachment of branching coral species along the bars (**Taylor**, pers. comm.). It is possible to transplant other morphologies, though they can have lower success rates or require modifications (e.g., attaching encrusting or plating corals at crossbars, or onto a mesh strung between frame bars) (Phanor et al., 2021). Regardless, attaching a diversity of corals is desirable. By attaching plating corals, for example, a large surface area for future recruitment is provided above and beyond that provided by the frame bars only. As inevitably some of the plates will die in the future, new corals can recruit onto their surfaces (**Kenyon**, pers. comm.). As they grow, the coral fragments encrust the metal structures and expand vertically and horizontally beyond them. Once the coral has gained significant mass and anchorage of its own, the structure becomes superfluous and is gradually filled in over time through coral breakage events.

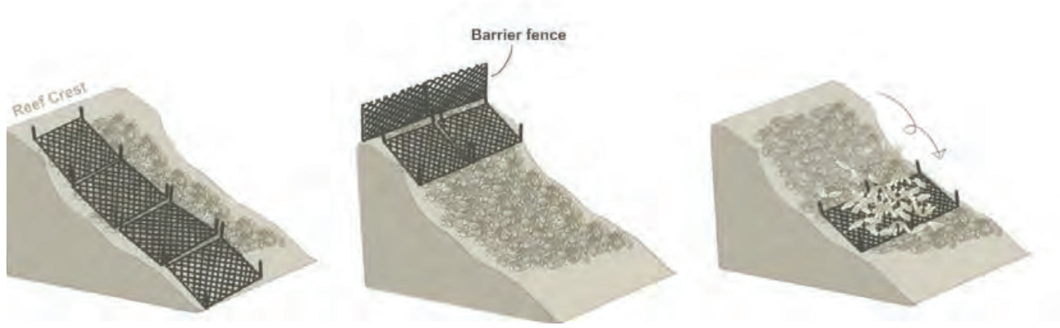


Figure 94.
Flat grid (see section **Flat structures**) vs elevated metal structure (peaked frame) on different slope angles (**case study 5**). Source: Shu Kiu Leung, The University of Queensland

What realistic outcomes can we expect?

Metal frames may reduce rubble movement and increase rubble binding and density of coral recruits in the short (<1 year) to medium term (1-5 years). Nevertheless, coral recovery outcomes are expected to vary depending on the physical and environmental characteristics of the site. Long-term outcomes are uncertain.

There is limited long-term data on the coral recovery outcomes of metal frames, particularly in relation to natural recruitment onto the frames and/or the proximal rubble beneath and surrounding frames. There are also few studies on the impact of metal frames on rubble movement. Outcomes in general are commonly observational or anecdotal and rarely quantified.

Generally, the use of metal structures is expected to reduce rubble movement beneath the frames, and potentially in their vicinity (if frames are placed close enough together), as compared to control plots that are not stabilised (see **case studies 5 and 7**). Binding by organisms such as sponges and CCA might also proceed more rapidly on the rubble beneath the structures, and coral recruit settlement and survival could increase if rubble movement was hindering coral recruitment (see **case study 5**). However, at sites where rubble movement is not the cause, or not the sole cause of low coral recruitment, the addition of metal structures alone may not be enough to boost recovery.

Table 14.
Pros and cons of 3D metal frames (Eckman, 1990; Eigeland, pers.comm.; Gross et al., 1992; Kenyon, pers. comm., Taylor, pers. comm.)

Pros	Cons
• The lightweight, modular design allows for deployment flexibility, with as many or as few structures used as needed, or arranged in different formations, depending on the size of the site, site layout and restoration goals. • The modular design also allows usage in scenarios where budgets are low but there are ample human resources, which is common in many reef restoration projects powered by volunteers. • Provides a stable settlement surface above the substrate level, potentially reducing the impacts of high sedimentation and competition. • Provides habitat and protected spaces for fish and mobile invertebrates. • Relatively easy to install due to design (rebar) and weight (few divers/no barge needed). • Frames sitting above the level of the substrate may change flow in terms of small-scale turbulence around the structures, reducing proximal rubble movement and also encouraging the settlement of recruits to the area (which rely on turbulence for settlement).	• As they are held up above the substrate, and the surface area of bars is small, it may take much longer for corals to grow out onto surrounding areas, compared to a method like rock piles where corals have more space. • Coating, when conducted manually on a small-scale, is a time-consuming process. • Limited scalability – deploying frames over very large areas (100s of reefs) would be expensive and require a lot of manpower. This is largely because the frames need to be attached to the substrate by divers, they cannot be deployed from a boat. • Without a healthy population of herbivores to keep the frames clean, they will require maintenance by divers at most sites, particularly in the very early stages post-deployment. • Introduction of foreign materials into the environment can potentially lead to pollution if frames degrade. • There is a risk of damaging benthic organisms during installation

Materials

Rebar or steel typically ranging from 6-12 mm in diameter is frequently used to construct frames, which are commonly coated with marine-grade epoxy followed by a layer of carbonate sand. This coating serves a dual purpose:

1) protecting the metal from corrosion and leaching for an extended period; and
2) providing a carbonate base to promote coral recruitment and attachment of coral transplants.

However, in instances where CCA colonisation is rapid and coral recruitment rates are high, the coating may not be necessary (Taylor, pers. comm.) (see **case study 7**). However, it is recommended to check local permitting requirements for coating, as regulations in places like the GBR, Australia mandate that the rebar frames be coated to minimise iron leaching.

Size and configuration

Metal frames are typically modular and can be constructed in various sizes. While larger structures may place higher loads on rubble, trapping it more effectively, they are more cumbersome to move and deploy. Furthermore, larger, higher structures can also more prone to flipping in high-energy environments (Taylor, pers. comm.), due to the increased drag on these structures compared to those with lower profiles.

The number and arrangement of metal frames will depend on resource availability, project goals, the environmental conditions and bathymetry of the site. The modularity of these frames allows for flexible deployment.

They can be deployed:

1) individually across the seafloor, with areas of untreated rubble between them, to cover a larger area, or
2) connected to form a network, completely covering the treated area and providing greater resistance against dislodgement than an individual unit.

A third strategy that sits between these two options, whereby smaller clusters of interconnected structures are interspersed between untreated areas, may yield the greatest habitat diversity and rugosity. This strategy creates varied microhabitats suitable for different species of fish and invertebrates by providing areas beneath structures and between clusters, while not creating a homogenous area of a uniform height like the second approach can do.

When determining the orientation of the frames, it is essential to consider both the design of the frames and the local hydrodynamic conditions. Ideally, the orientation would help optimise water flow for coral settlement and nutrient capture, while trapping and stabilising rubble beneath the structure and against its sides, to facilitate binding and natural coral recruitment.

Metal can be easily moulded into frames of different designs. These frames are commonly produced locally at relatively low cost. These designs can often be tailored to fit the specific requirements of the site. The designs include peaked frames (pyramids (**case study 5**) or A-frames (**case study 7**)), hexagonal frames, and also irregular shapes engineered for specific purposes (**case study 6**). No single design is inherently superior as its suitability depends on the unique characteristics of the site. Frames of different designs can also be used in combination to increase habitat heterogeneity at the site. For information on which designs are most effective in different environments, refer to the "when and where" subsection.

Expert tips

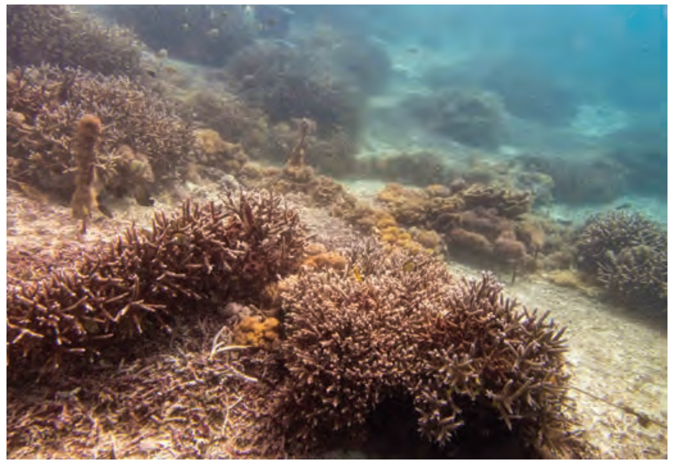
"Initially, we placed metal frames randomly over a large rubble area in an attempt to cover as much area as possible (**Figure 95**). This method caused quite a few frames to become buried (as the rubble had more fetch between frames to move and erode). Over time, we had to put additional frames in the gaps to get effective coral coverage and to reduce rubble erosion. So, initially, it was a slow way to restore the area.

Therefore, we decided to try to be more efficient in an adjacent site. We covered that rubble area with frames in a grid pattern spacing them 1 m apart (**Figure 96**). This reduced erosion and rubble movement right away, so then coral could effectively grow on the frames.

However, after 5-6 years we started to see that the biodiversity of the site with randomly placed frames was greater, and more representative of a real coral reef – as frames had been placed and transplanted at different times throughout the years (rather than all at the same time), so there was a greater variety of coral age classes and habitat heterogeneity. Therefore, the goal of the restoration project will determine which spacing method to use. For example, if the project goal is a rapid increase in coral coverage, then grid spacing will achieve this goal. Whereas, if the goal is restoration of reef diversity to a heterogeneous target state, then random spacing over an extended planting period will achieve this goal."

Andrew Taylor

Andrew Taylor
With a deep-rooted passion for environmental education and coral reef restoration, Andrew Taylor established Blue Corner Marine Research in Bali, Indonesia. He has developed a detailed curriculum with teaching resources for training Indonesian coral restoration practitioners in marine ecology.
Andrew also has extensive hands-on experience in rubble stabilisation.
He has led projects using various methods including meshes, metal frames, and coral transplantation to restore reefs in Nusa Penida and Nusa Lembongan.



Left: Figure 95. Frames which were randomly placed allowed for heterogeneity of reef structure as frames were added at different times over the years. Using an approach that combines both of Andrew's approaches, i.e., randomly placing structures but at a relatively close distance, and varying the coral transplant age across the structures, might be the best approach with individual units.
Right: Figure 96. Frames placed in rows. When multiple frames are spaced out in a grid pattern or rows rubble movement will be slowed down. Source: Andrew Taylor, Blue Corner Marine Research

Case Study 5:

Three rebar frame designs in Bait Reef, GBR

(Eigeland, pers. comm.; Kenyon, pers. comm.)

Background

When the RRAP Rubble Stabilisation sub-program commenced in March 2021, an extensive review on rubble stabilisation methods was conducted. The authors reviewed published papers, unpublished data, and grey literature, and conducted interviews with researchers and practitioners in the rubble stabilisation field. Methods that combined stabilisation of the benthos with vertical relief above the substrate were found to be the most successful in terms of coral recruitment and recovery.

Based on this review, three designs for rebar frames were developed to compare the effectiveness of structures with vertical relief against those without (i.e., flat structures, see **Flat structures** section). The frames were deployed in May 2022, on a 500 x 750 m rubble bed on the southwestern side of Bait Reef, in a lagoonal area easily accessible by vessels for monitoring. Bait Reef was chosen due to the presence of extensive, persistent rubble beds caused by category 4 Cyclone Debbie in 2017, and because **Reef Bags** and **Mars Reef Stars** had also been deployed there, allowing for comparison. The rubble bed has a flat to gentle downward slope toward the west, with a depth range from 6 to 9 m. The predominant benthic cover is soft coral, rubble, and some turf and CCA-covered rock with turf algae and CCA.

Design and deployment

Three variations of 12-mm, sand and epoxy coated rebar frames were constructed, including two metal structure designs, and a flat grid design (**Figure 97**). Design 1 is a flat grid (see **Flat structures** section) that sits directly on top of the rubble bed and physically pins the rubble beneath it (**Figure 97a**). Design 2 is a closed pyramid that combines a flat grid and a latticed peak (**Figure 97b**). The design was expected to both pin and trap rubble while potentially slowing small-scale water flow around the frame and subsequently reducing rubble movement. Design 3 is an open pyramid that consists of a latticed peak only, with no grid base, and was compared to the significantly heavier Design 2 (**Figure 97c**). Researchers wanted to investigate whether the latticed peak of Design 3 could trap rubble - or reduce rubble movement through changed hydrodynamics - to the same degree as when it was directly pinned by the flat grid or closed pyramid. The comparison of these designs facilitated a comparison between rubble stabilisation alone (Design 1 - flat grid), and in combination with vertical relief (Designs 2 and 3 - 3D metal frames).

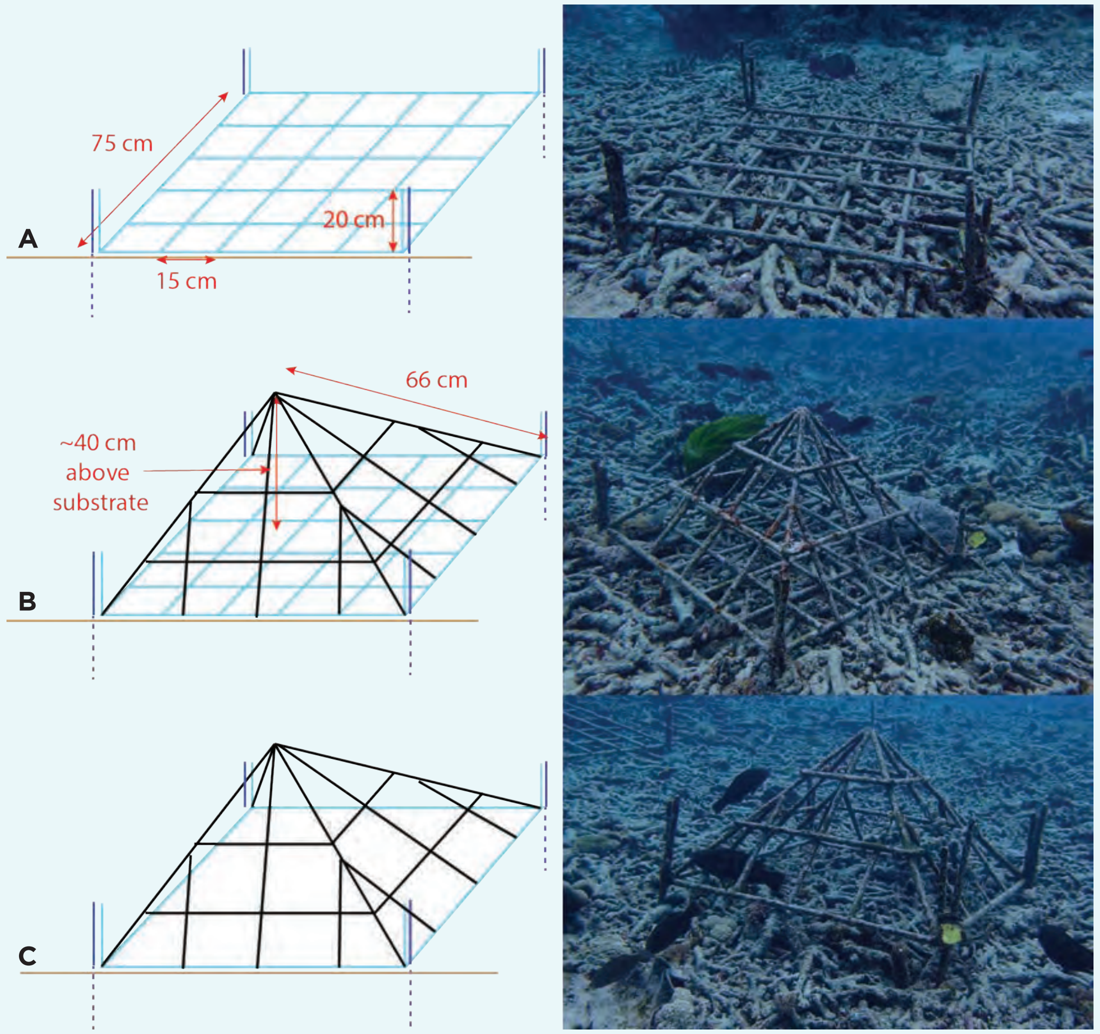


Figure 97. The three designs of rebar frames deployed on Bait Reef, GBR: **(a)** flat grid, **(b)** closed pyramid, and **(c)** open pyramid. Source: Tania Kenyon, The University of Queensland

Results/findings

To determine the effectiveness of the structures for rubble stabilisation, pieces of tagged rubble were placed beneath the three structure types, and in control plots (demarcated areas of rubble that had no structures deployed onto them) in May 2023, and their positions were later monitored in July 2023. All three designs of rebar frames effectively stabilised rubble over this 2-month period, with pieces moving on average only 1 to 2 cm under frames, but nearly 7 cm in control plots (**Figure 98a**). Some pieces in control, rubble-only plots had moved more than 1 m. Comparing the rebar frame designs, the rubble moved least under the closed pyramids, potentially due to their heavy weight pinning the rubble.

Over a 2-year period following deployment of the structures, all plots were monitored to see if the amount of binding between rubble pieces and the number of corals was increasing more under structures compared to control plots. Binding was monitored by picking a number of sampled rubble pieces in each plot and determining whether any organisms (such as sponges, coralline algae, or macroalgae) were bridging between that piece and another piece. If there is more binding, rubble is likely to be more stable and thus coral recruitment might increase.

The number of binds per rubble piece increased over the 2 years. While there is too much variability to detect significant differences, by year 2, there appears to be a trend toward more binds in flat grids and closed pyramids, while the number of binds appears to be plateauing in control plots (**Figure 98b**).

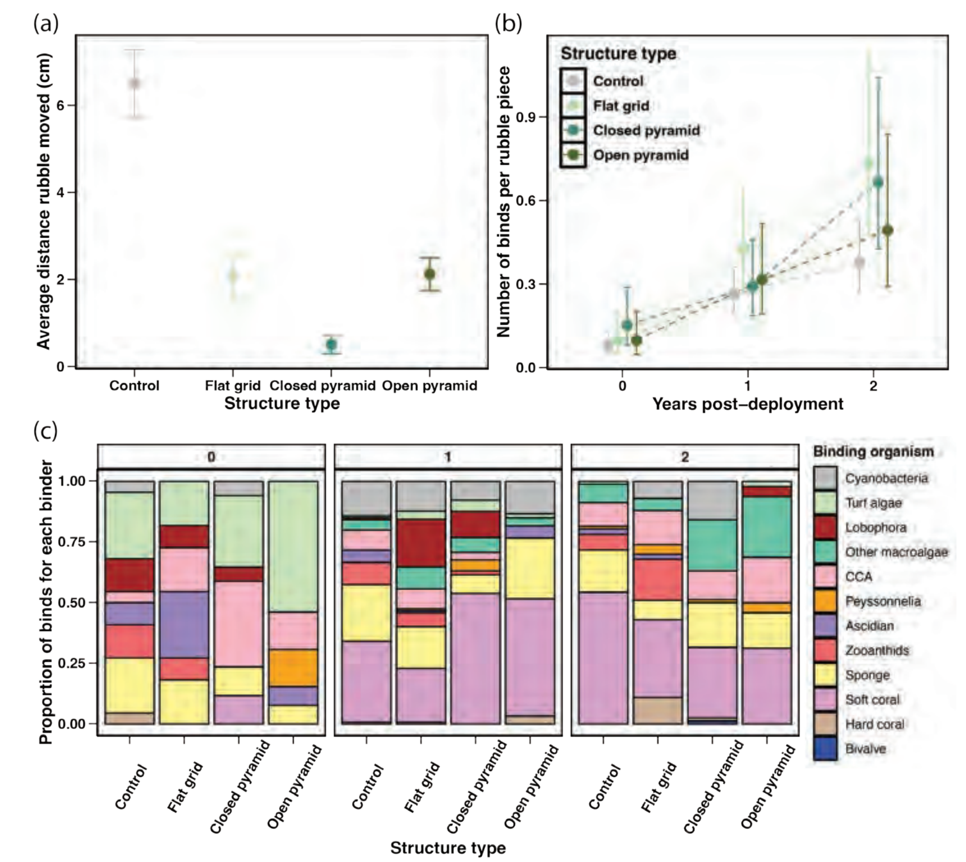


Figure 98. a) Average distance that tagged rubble moved (cm) (± standard error) over a 2-month period under frames and in control plots. **b)** Number of binds per rubble piece (± 95% confidence intervals) over time (from deployment at 0 years to 2 years post-deployment, in June 2024) for frames and control plots. **c)** Proportion of binds between rubble pieces attributed to each binding organism category over time (0-, 1- and 2-years post-deployment) and for all structure designs and control plots. Source: Tania Kenyon, The University of Queensland

Yet, while the amount of binding is increasing, many of the binds are attributed to soft corals (**Figure 98c**). Soft corals began to dominate the benthic cover and were the dominant binding organisms from year 1 onwards (**Figure 99**). This was the case even in the control plots.

Encouragingly though, in flat grids and closed pyramids hard coral was found to be binding some of the rubble pieces in year 2, while there was no binding by hard corals observed in controls. Yet, this did not result in any significant difference in the number of corals between structures and controls. The number of corals in all plots, regardless of structure type or control, did not appear to be increasing or decreasing over the 2-year period, suggesting hindered coral recruitment overall or mortality bottlenecks. Hard corals were observed colonising the frames at the 2-year mark (**Figure 99**).

Lessons learned:

- Both the metal frames and flat grid design were successful in restricting rubble movement, and this appears to be facilitating more binding. However, as yet, this has not translated to an increase in coral recruitment beneath the structures at this site.
- It is important to note that these results are preliminary - having only been collected 2 years post-deployment - and outcomes could rapidly change in future.
- Other factors to consider are impacts other than rubble movement at the site of interest, which in the case of Bait Reef are high sedimentation levels, high levels of competition (particularly with soft corals) and potentially low coral larval supply (Yve-Marie Bozec, pers. comm.). All of these factors could have contributed to a lack of increased recruitment under the structure plots.
- If the restriction of rubble movement is the key issue at a site of interest, the closed pyramid appeared to limit movement the most, likely owing to its weight and pinning by the grid base
- Interestingly, there was no great difference in rubble movement between the flat grid design, that is directly pinning rubble, compared to the open pyramid that is more likely trapping it. Thus, an open pyramid metal structure design is going to be more broadly applicable to a wider range of environments by providing vertical relief while also limiting rubble movement to a similar degree as a flat grid. However, a caveat here is to consider the size of the rubble and size of grid squares. If rubble is *very small*, a small-squared grid may yet facilitate greater rubble stabilisation than an open pyramid.

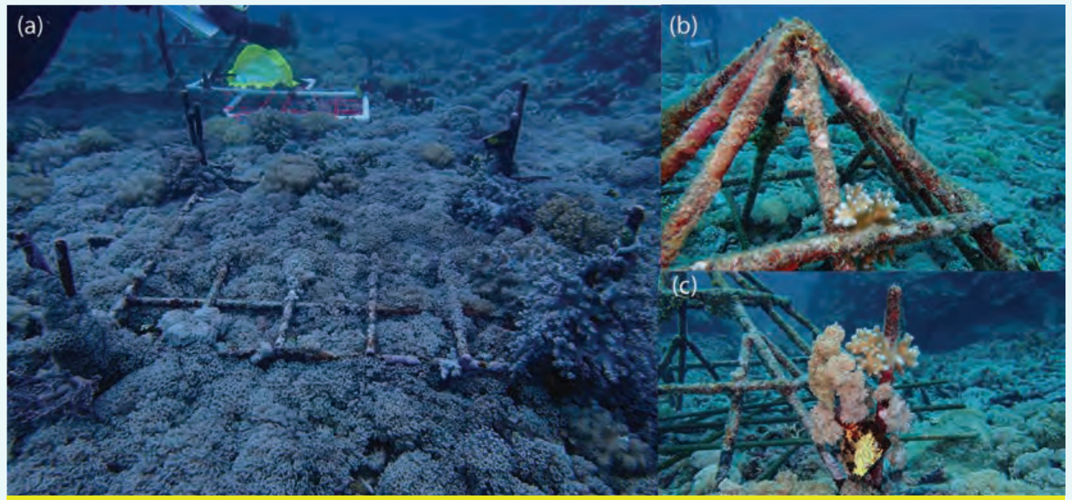


Figure 99. a) Soft corals colonising the benthos under and around many of the stabilisation structures; **b)** and **c)** show hard corals recruiting onto the frames, above the level of the soft coral, after 2 years. Source: Tania Kenyon, The University of Queensland

Expert tips

"The deployment of metal frames at Bait Reef provides an example of how rubble stabilisation in isolation, without vertical relief, may not be able to overcome other limitations to recruitment such as competition (here, with soft corals) and sedimentation.

Comparing the metal frame results with the Reef Bag results, which were both deployed at Bait Reef, we expect rubble under the structures to be more stable than in reef bag piles over a longer period, as there was slumping observed of the reef bag piles over the ~2.5-year period. This is why making larger reef bag piles may be desirable. Yet, while the number of corals is increasing on reef bags and piles compared to the control rubble, we did not see this mirrored for the structures. This could be attributed to the competition with soft coral at the level of the benthos at frames' site.

Hard corals are beginning to recruit onto the metal structure above the level of the soft coral at the frames' site, indicating that vertical relief here is needed. Maintenance of the metal frames in terms of soft coral removal might need to be considered in some cases and certain sites."

Karen Eigeland

Karen Eigeland

University of Queensland researcher Karen Eigeland is a specialist in rubble stabilisation, having conducted comprehensive field-based research on the southern and central Great Barrier Reef from 2021 to 2024, under the RRAP Rubble Stabilisation sub-program. She has been involved in testing the effectiveness of various stabilisation methods such as metal frames and Reef Bags. Karen has spent many hours underwater surveying rubble beds in terms of movement and rubble binding, across sites of different water quality, depths and exposures, and thus has a comprehensive understanding of rubble dynamics.

Case Study 6:

Framed reef modules in Wuzhizhou Island reefs, China

(Liu et al., 2024).)

Background

Given the severe degradation of coral reefs around Hainan province due to years of dynamite fishing and coral chiselling, as well as subsequent damage from frequent typhoons, a group of marine scientists from Hainan University, China, designed a low-cost tool named "framed reef modules" (FRM) to stabilise rubble fields and support reef recovery.

The frames were specifically engineered to withstand the harsh local environment characterised by fluctuating seawater temperatures, high sedimentation rates, and frequent typhoons. FRMs were placed in a rubble field at a depth ranging from 5 to 6 m in the northern area of Wuzhizhou Island, China.

Design and deployment

FRMs were made from 8-mm diameter cylindrical galvanized steel bars coated with epoxy to increase durability. However, they have a unique asymmetrical shape aiming to maximise the attachment points available for coral transplantation. Each FRM covers 1.2 m^2 of area and consists of 16 attachment points for the transplantation of two branching species, *Acropora hyacinthus* and *Acropora microphthalma*, which are dominant at the sites. Each FRM has a counterpart design that is a mirror image of itself. The two mirror counterparts can be connected together, forming a pair, and deployed onto the reef. Alternatively, FRMs can be linked with multiple others to form a form a web-like structure across the rubble bed. Researchers tested various designs of FRMs with leg heights of 15, 35, and 50 cm, which elevate the transplanted coral to prevent burial by loose substrate.

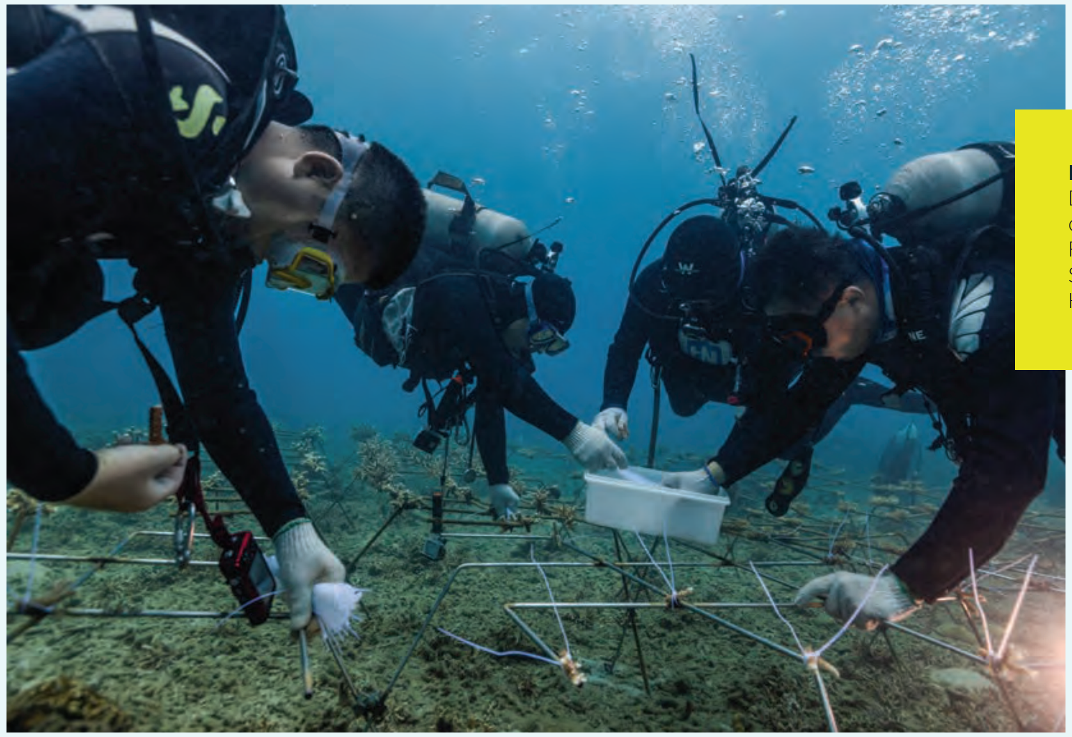


Figure 100.
Divers transplanting coral fragments onto FRMs using cable ties. Source: Xiubao Li, Hainan University

Results/findings

After a monitoring period of just over 1 year (400 days), there was growth of turf algae and macroalgae on the FRMs, particularly on those with the shortest legs (15 cm), potentially due to proximity to the silty substrate. None of the FRMs collapsed or overturned despite the occurrence of typhoons. Coral transplants on the frames with the longest legs (50 cm) showed the highest survival rates and these frames had the greatest increase in coral cover (Figure 101). Notably, the frames also limited rubble movement and showed an increased density of coral recruits from 0.3 recruits/m^2 to 4.8 recruits/m^2 on the rubble substrate a year after deployment (Xiubao Li, Hainan University, pers. comm.).

Lessons learned:

- The design of metal frames can be specifically tailored to withstand harsh local environments.
- Elevation of coral outplants prevent burial by loose substrate.

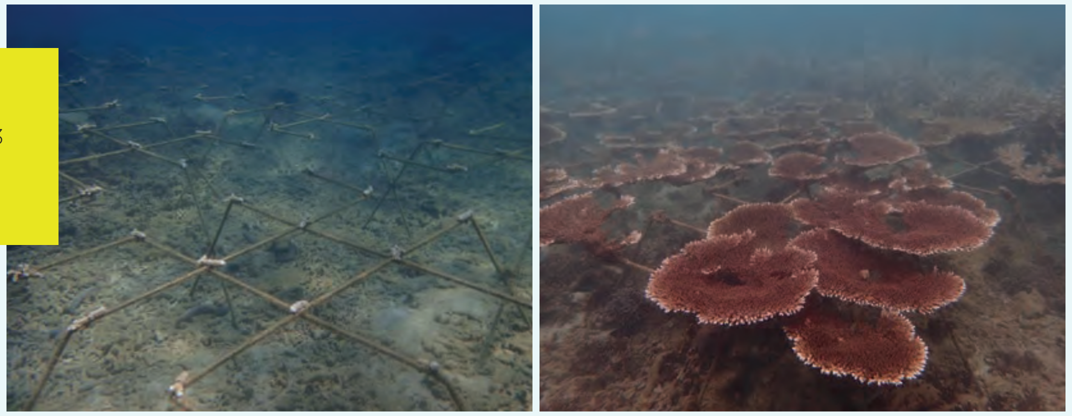


Figure 101. Restoration site with FRMs in 2021 (Left) vs 2023 (Right). Source: Xiubao Li, Hainan University

Costs and maintenance

The costs of metal frames in coral restoration projects vary by country. In China, the deployment of each FRM (**case study 6**) costs US$27 (~A$40) as of 2020. The cost includes materials (except coral fragments which are US$5.1 each), transportation, and diving. Although, the total costs of installing FRMs were subsidised by government assistance, which helped to reduce the fees associated with diving. In Indonesia (**case study 7**), material costs average around US$40-45 (~A$60-65) per unit (**Taylor**, pers. comm.) and labour expenses are minimised due to extensive volunteer involvement. Meanwhile, in the GBR (**case study 5**), each unit cost around US$60 (~A$90), with deployment costs totalling approximately US$23,600 (~A$36,100).

Most of this cost was attributed to labour and vessel hire costs (a crew of 9 divers and 4 surface support).

However, it is crucial to consider that these upfront costs do not represent the full financial commitment for each of these projects. For example, maintenance tasks for metal frames, including removing algal growth, removing coral predators such as crown-of-thorns starfish and *Drupella* snails, and replacing damaged or lost frames and transplants, can add significantly to the overall expenditure of the frames (**Taylor**, pers. comm.).

Case Study 7:

Rebar frames in Nusa Penida and Lembongan, Bali

(Blue Corner Marine Research, 2020; Taylor, 2020; Taylor, pers. comm.)

Background

Rebar frames are frequently deployed as an integral part of the Nusa Islands Restoration Project, aimed at restoring the expansive rubble beds found on reefs along the northern coastlines of Nusa Penida and Lembongan. These rubble beds have formed as a result of various historical disturbances, such as anchor damage, coral clearance for seaweed farming and pontoon tourism, alterations in hydrodynamics due to sea walls, and fishing activities.

When planning the restoration project, the team needed to find a suitable method given the environmental, social, and financial constraints of the area.

The stabilisation structures used had to meet the following criteria:

1. **Cost-effectiveness:** The structures had to be inexpensive and easy to produce through the use of locally available materials and relatively unskilled labour. They also had to be small and lightweight enough to be installed by volunteers.
2. **Flexibility:** The structures had to be modular such that they could be installed in both small or large numbers; as standalone structures or clustered in patch reefs or continuous mat features.
3. **Achievement of restoration goals:** The structures needed to have adequate attachment points for straightforward coral transplantation. They also needed to trap and stabilise rubble movement, while also creating a complex 3-dimensional reef landscape for long-term resilience.
4. **Durability:** The structures could not degrade too quickly in the ocean and had to be able to withstand strong currents and surges.

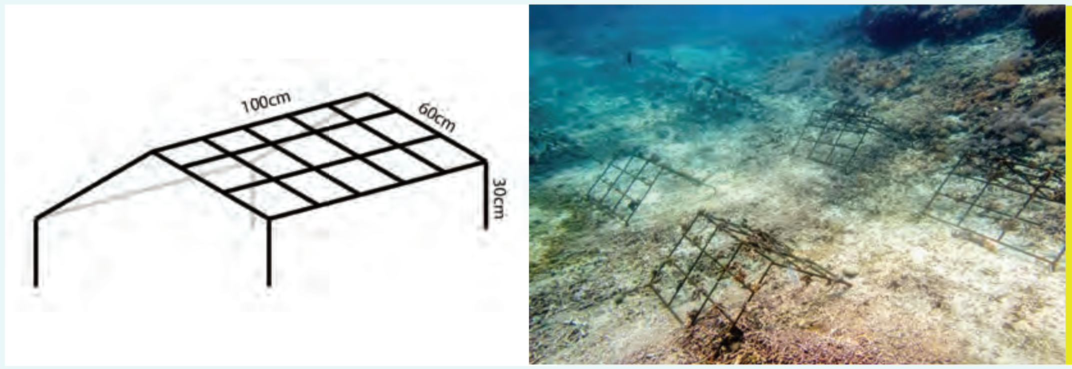


Figure 102. A-frames deployed in the Nusa Islands. The legs (30 cm) are embedded into the substrate. Source: Andrew Taylor, Blue Corner Marine Research

Design and deployment

Frames of different shapes were locally crafted in Indonesia using carbon steel rebar from small suppliers. Builders were employed to weld and coat the rebar frames with epoxy and sand, which were then deployed on the rubble beds on reef flats and along reef slopes. Only half of the frames were coated while the other half were deployed directly without coating. Among the various designs, the A-frame (**Figure 102**) emerged as one of the most successful, particularly on slopes.

The peaked design of the A-frames has the function of creating vertical relief off the reef substrate – which:

- **(i)** creates habitat for mobile marine organisms including fish;
- **(ii)** allows coral fragments to be transplanted above the shifting rubble substrate; and
- **(iii)** slows down or stops rubble movement.

The open design of the rebar frame allows water currents to flow through it, while still trapping some rubble. The structure also provides many attachment points for outplanting, as well as stable surfaces for settlement.

When manufacturing the A-frames, a long piece of rebar, measuring 180 cm, was bent at three points to ensure maximum stability. This creates a peak in the middle and two 30 cm anchors on either side. The 30 cm corner anchors allow for the frame to be hammered into rubble and remain in place in strong current and swell. The corner anchors were found to be necessary to stabilise the frame, especially as coral transplants grow and create greater resistance against the current. These drag forces caused unanchored frames to flip over.

The environmental conditions in which these frames were used include strong currents (2-3 knots) and a moderate to steep slope (20-50 degrees). The substrate was mainly unconsolidated rubble resulting from branching and plating corals. There was high coral and CCA recruitment, as well as minimal effects of nutrient loading at the site.

At the restoration site in Nusa Penida, structures were placed individually across the seafloor randomly at one site and in a grid pattern at others (**Figure 103**). Frames were positioned at least 1 m apart, with coral nursery ropes later strung between structures to increase coral coverage on the rubble between structures. The frames were positioned parallel to the slope to trap rubble moving downslope, preventing corals downslope of the structure from being buried. This alignment also allows the passage of strong currents through the tunnel created by the structure. If placed perpendicular to the current, the structures can overturn if they have a lot of coral growth, which increases drag forces on the structures. The structures might also be buried by rubble if placed perpendicular to the current, as the rubble builds up against the sides.

Left: Figure 103. Rebar frames placed individually in middle of rubble field. Structure in foreground has been placed perpendicular to the current, which places it at risk of being toppled due to increased drag and becoming buried in rubble. **Right: Figure 104.** As coral transplants grow on the rebar frame, their mass and volume increases, disrupting proximal flows which can reduce rubble movement in the surrounding area. Source: Andrew Taylor, Blue Corner Marine Research

As the transplants grow, the increased weight on the frames helps to further anchor it to the substrate (**Figure 104**). Transplanted corals eventually grow beyond the anchor-point of the frame itself, and onto the rubble. Thus, the original frame can degrade after several years while the coral still maintains sufficient mass to remain anchored independently.

Alternative shapes such as hexagonal "star" shaped frames (**Figure 105, Figure 106**) commonly used in many restoration projects, were tested but deemed less effective for the site due to their instability in strong swell and currents. When frames are placed individually, they need to be designed with vertical legs which can be hammered into the rubble and act as anchors (as opposed to frame designs such as **Reef Stars** which sit upon the substrate).

Results/findings

After one year, the amount of loose rubble started to decrease as it was trapped, and binders such as soft corals and sponges started to colonise the immobilised rubble. It was also reported that the natural recruitment on frames without outplants was mostly soft coral (*Xenia spp.*), whereas frames with coral outplants had a greater natural recruitment of hard corals (**Taylor**, pers. comm.). Overall, the use of metal frames and coral outplants over a two-year period resulted in an increase in hard coral cover from 2% to 35% (Blue Corner Marine Research, 2021).

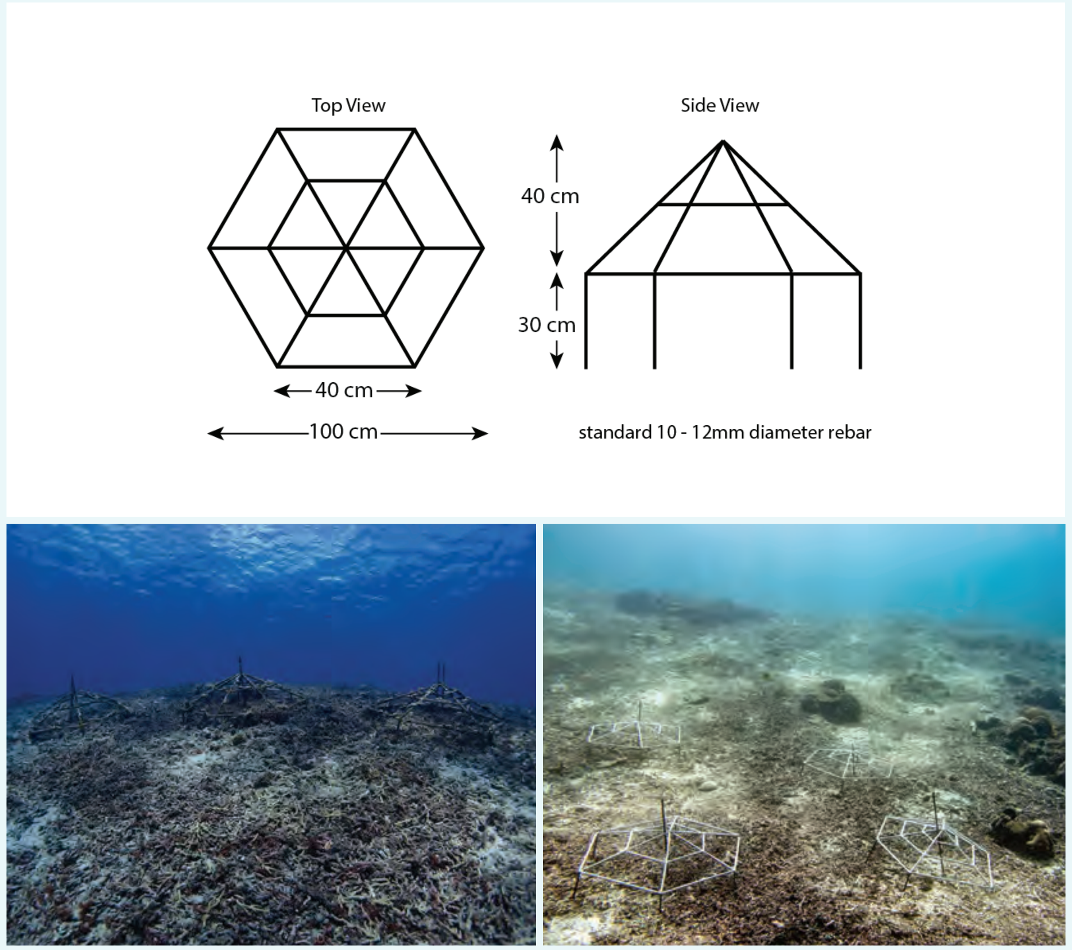


Figure 105. Peaked hexagonal structures were also trialled – these were found to be best suited for stabilising rubble on the reef flat (as some become buried easily on steeper slopes by downslope rubble movement). Source: Andrew Taylor, Blue Corner Marine Research

Lessons learned:

- Although carbon steel rebar is of lower quality and corrodes more quickly than other types of rebar, most structures remained intact underwater after 6 years, which was long enough to achieve restoration goals.
- Frames which were coated with epoxy & sand had coral fragments self-attach slightly earlier than fragments on uncoated frames. However, there was no significant difference in recruitment of natural corals onto coated and uncoated frames after 6 months. Both coated and uncoated frames were colonised by CCA within 6 months, attracting coral recruits and forming a protective layer against corrosion. At this site in Nusa Penida, coating proved unnecessary and added a time-consuming expense.
- The design of the rebar frames should consider the environmental variables of flow speed and direction, slope angle, and the coral assemblage being restored.
- The size of grid cells will determine how quickly rubble accumulates against it. Larger spacing between rebar grid rows will allow more rubble to pass through the frame, trapping only the larger rubble pieces with a slower build up. Smaller spacing, on the other hand will trap more rubble. The 20 x 20 cm grid design of the A-frame trapped rubble at a gradual rate, giving transplanted coral fragments time to grow upon the frames without risk of burial from accumulation of rubble.
- Individual placement of A-frames can:
    1) cover a large rubble area with a small budget,
    2) allow additional structures to be placed in the gaps as more resources become available, and
    3) allow volunteers to work between structures without causing damage to neighbouring structures by fin kicking, etc.

  This strategy also created heterogeneity of coral size/age classes and increased reef diversity.

Figure 106. The hexagonal shape (modified with mesh) was found to be useful for transplanting encrusting and boulder corals such as *Galaxea spp.*, when designed with low topographical relief off the rubble substrate. Photos taken 2 years apart showing *Galaxea spp.* encrusting the frame to form a larger colony. Source: Andrew Taylor, Blue Corner Marine Research

Mars Assisted Reef Restoration System (MARRS) – Reef Stars

Developed by Mars Sustainable Solutions (MSS), a part of the global company Mars Incorporated, the Mars Assisted Reef Restoration System (MARRS) is a comprehensive approach to restoring persistent rubble beds. MARRS includes an integrated framework involving site selection, planning, training, and monitoring, in addition to the deployment of the hexagonal "Reef Star" structures.

The information presented here is only a brief overview of the MARRS process, and MSS encourages all organisations who wish to utilise the technology to contact MSS to explore how they can be trained in the method in order to give their project the best chances of success.

In recent years, Reef Stars have become increasingly popular in the field of coral restoration, with partnerships and applications all over the world. The initiative first took root in the Spermonde Archipelago in Indonesia in collaboration with scientists, regional universities, and local islanders (Smith, 2021). It has since expanded across various parts of Indonesia through a dedicated programme to restore coral reefs within national parks. MSS's global partnerships with conservation organisations, industries, and governments have resulted in its deployment in over 11 countries and more than 40 different sites (Mars Inc., 2021b).

Reef Stars were first introduced to Australia in 2020. MSS has since established partnerships with the government entity, Reef Authority, and tourism operators such as Reef Magic Cruises to stabilise loose rubble beds across multiple reefs in the GBR since 2020 (GBRMPA, 2022b; Mars Inc., 2021b; Mars Sustainable Solutions & Reef Magic, 2020).

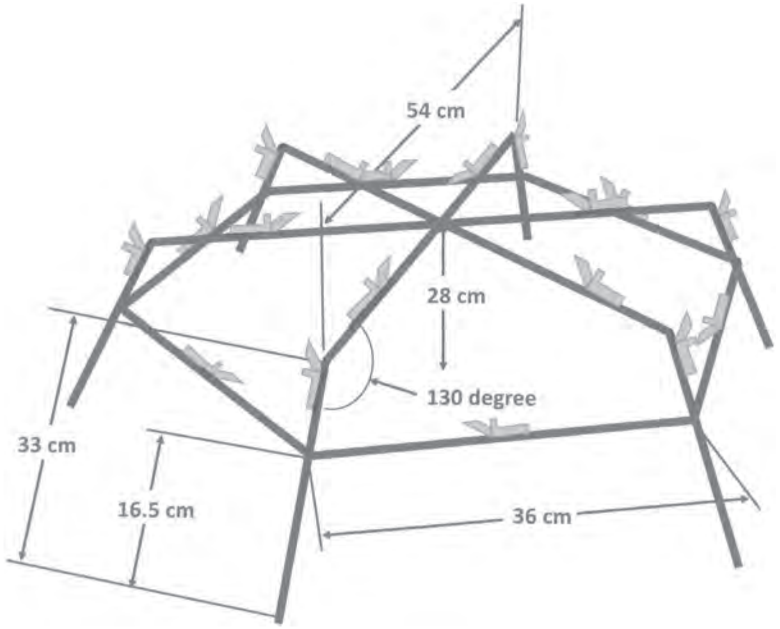


Figure 107. Diagram of a Reef Star. Adapted from "Large-scale coral reef rehabilitation after blast fishing in Indonesia" by Williams et al. (2019)

Scale of implementation

In most cases, Reef Stars are deployed to form inter-connected webs that cover large areas within a single reef or across multiple reefs. In Indonesia, where the method was first implemented, Reef Stars have been applied on a large scale. For example, in Pulau Bontosua, on a patch reef called Salisi Besar, over 19,000 Reef Stars have been installed to date to cover a 1.7-hectare area, with more installations currently underway (Freda Nicholson, Mars Sustainable Solutions, pers. comm.). Another notable project deployed Reef Stars and covered a 7,000 m^2 area within a 2-hectare rubble field in Pulau Badi, Indonesia (Williams et al., 2019). However, in Australia, most projects have been on a smaller scale, having deployed only up to a few hundred Reef Stars to date. The smallest deployment was a pilot study on Humpy Island in the Great Barrier Reef, where 50 Reef Stars were installed to test their use on macroalgae-dominated rubble fields (GBRMPA, 2022d), and the largest to date is a deployment of 439 Reef Stars at a tourism pontoon on Moore Reef (GBR Biology, 2022).

How does this method help with recovery?

Reef Stars support coral recruitment and growth by:

1) allowing greater exposure to water flow,
2) trapping and stabilising broken coral fragments and rubble,
3) providing stable elevated surfaces for settlement,
4) reducing the of likelihood of sediment burial that can inhibit coral recruitment; and
5) providing weight to stabilise the substrate (Smith, 2021; Williams et al., 2019).

Their design facilitates higher flows in a reef column, which may aid nutrient uptake and heterotrophic plankton feeding. Rubble trapped between the legs of the Reef Stars is more likely to bind and stabilise, forming an ideal settlement substrate. By providing surfaces elevated from the substrate, Reef Stars enable recruits to settle without being affected by rolling rubble or sediment at the bottom.

Figure 108. Locations of sites where Reef Stars were deployed (Mars Inc., 2021a). Source: Shu Kiu Leung, The University of Queensland

Expert tips

"One of the main challenges in restoring coral reefs is that non-scientist people often don't have the right knowledge or skills. You need a committed team with adequate human resources capacity.

The local community and need to be on board, and you need sustainable financing to keep the project going. A system like MARRS, which helps with training, managing, and planning, is really important."

Marthen Welly

Marthen Welly
is the Marine Conservation Advisor at the Coral Triangle Center (CTC) in Bali, Indonesia. Since 2008, he has been instrumental in managing CTC's initiatives within the Nusa Penida Marine Protected Area, focusing on marine biodiversity protection, sustainable marine tourism and reef restoration projects. In 2021, CTC partnered with Mars Inc. to establish a specialised task force, aiming to build local capacity for reef restoration through the deployment of Reef Stars which included MARRS competency training.

When and where?

Reef Stars are best deployed in shallow and relatively flat areas of rubble with low sedimentation. This method is not suitable for locations with silt, sandy bottoms, or mixed with seagrass beds. Reef Stars should be deployed near natural reefs to ensure an adequate supply of coral recruits from adjacent sources.

The deployment of Reef Stars can be logistically challenging at deeper sites and areas with complex rubble landscape, requiring long pickets to anchor the stars (Mattocks, pers. comm.). Installing Reef Stars on flat or gently sloping surfaces ensures stability and prevents the stars from being dislodged by currents or waves.

Currently, MSS is collaborating with scientists from the University of Western Australia to conduct laboratory tests to improve Reef Star designs and assess how these structures perform under various wave conditions. The research includes studies of how Reef Stars can be used to attenuate wave energy and provide a nature-based form of coastal protection. These results indicated that Reef Stars with moderate coral cover (typical after 2 years of growth) could reduce wave heights on shallow coral reef flats by 50% for 100 m, highlighting the potential of using Reef Stars on shallow, flat areas near the shore to help mitigate coastal erosion and flooding (Geldard et al., in prep; Westera, 2021).

It is important to note that a thorough site selection and training process using the MARRS protocol is recommended before deciding to use MARRS. For more information, please visit: https://www.buildingcoral.com/

Implementation Strategy

The implementation process involves several key steps:

1) **Collect coral fragments of opportunity:** Ideally, the collection of corals of opportunity would take into account the species diversity and avoid damage to the ecosystem (Smith, 2021). While many efforts have primarily outplanted fast-growing *Acropora* species, a wider range of genera can be selected for outplanting (Nuñez Lendo et al., 2024; Williams et al., 2019). The Reef Stars at Moore Reef include over 60 species of coral from seven families (Eric Fisher, GBR Biology/Reef Magic, pers. comm.) Corals of opportunity could be collected from the same depth contour as the restoration site. If local biomass is insufficient, nursery-grown fragments can be used. More general principles of coral outplanting can be found in the section **Coral transplantation and gardening.**

2) **Attach fragments to Reef Stars:** Corals are ideally placed in a basket and submerged at the coral attachment site. A maximum of 18 coral fragments can be tied onto the Reef Stars using cable ties, leaving sufficient space for the transplants to grow (Williams et al., 2019). However, it is recommended that only 3 fragments are tied between the legs of the Reef Star, leaving one empty space between each leg for growth (**Marthen Welly,** Coral Triangle Center, pers. comm.), to give a total of 15 fragments per Reef Star. Nylon cable ties about 3 mm wide are often used, with two ties needed for each fragment for secure attachment (**Figure 109**). These ties have been observed to be overgrown by coral within 6 weeks (Fisher, pers. comm.). Note that MSS is exploring more environmentally friendly alternatives for attaching coral fragments that do not involve plastic.

Top: Figure 109. Left: A coral fragment tied onto a Reef Star. Right: Divers tying coral fragments onto the Reef Stars using cable ties. Source: Mars Sustainable Solutions

Bottom left: Figure 110. Bottom left: Diver building Reef Star webs underwater in Bali. Source: Marthen Welly, Coral Triangle Center

Bottom right: Figure 111. Bottom right: Completed installation of Reef Stars in Pulau Bontosua. Note how Reef Stars are placed around existing bommies. Source: Mars Sustainable Solutions

3) **Transport Reef Stars with corals to the site:** Once attached, the Reef Stars are transported to their site and being sprayed with seawater on the way to prevent drying (Williams et al., 2019). It would be best if the exposure to air and sunlight is kept under 3 minutes (**Welly**, pers. comm.).

4) **Deploy Reef Stars underwater:** Reef Stars are deployed at the site by snorkelers or using ropes, before being attached together in a specialised manner by divers, forming a web-like structure (**Figure 110, Figure 111**). Precautions are taken to prevent the placement of Reef Stars on existing, living corals, and they can be arranged around existing bommies to mitigate potential damage during installation (Smith, 2021). They can be connected to each other using nylon ropes or cable ties to the legs. Legs are crossed and tied with larger cable ties, often three legs together using two ties (**Welly**, pers. comm.). After the Reef Stars are connected, steel pickets or duckbill anchors are used to secure different locations around it. Anchors can be planted at loose corners, hammered down at an angle facing the current or waves until matching the height of the Reef Stars, and further secured with cable ties (**Welly**, pers. comm.).

To fully evaluate the performance of this method at the particular site, it is recommended that the restoration plots be monitored for at least 5 years (Smith, 2021). Ideally, the monitoring process begins prior to installation and continues with an initial timepoint within 3 months after the installation, then at set timepoints (e.g. annually or biannually) for at least 5 years.

What realistic outcomes can we expect?

In the short (<1 year) to medium-term (1-5 years), Reef stars may offer a variety of benefits, including reduced rubble movement, increased coral cover, coral recruitment, reef accretion rates, fish abundance and diversity, and improved ecosystem function (Lamont et al., 2022; Lange et al., 2024; Nuñez Lendo et al., 2024; Westera, 2021; Williams et al., 2019). However, results on coral cover and coral recruitment varies, and there may be species-specific impacts on the skeletal properties of coral outplants.

Most documented results are short- to medium-term as the MARRS method have only been recently developed. The results presented below are drawn from both anecdotal evidence based on practitioners' personal observations and findings from published studies. Currently, there is no comparative data for transplantation vs. no transplantation scenarios.

Reef Stars have shown to be effective in restricting the movement of rubble and aid in its stabilisation. Rubble became stabilised within a year in Spermonde Archipelago (Smith, 2021) and within 1 to 3 years post-installation in Moore Reef, GBR, in contrast to untreated rubble sites that remained unstable for over a decade after Cyclone Yasi (Fisher, pers. comm.). A recent study by Lange et al. (2024) on 2-3 m deep reefs around Pulau Bontosua found that sites, where Reef Stars were deployed 4 years ago, have partly filled with consolidated coral rubble, potentially providing a hard substrate for future recruitment. In an experimental study conducted in a wave flume (**Figure 112**), the near-bed flows within a canopy formed by Reef Stars was found to not be substantially attenuated by the presence of the frame and attached corals (Westera, 2021).

Figure 112. Wave flume experiment setup for Reef Stars. Source: Justin Geldard, University of Western Australia

As a consequence, individual pieces of rubble were found to initially move under waves at a rate comparable to a bare rubble bed. However, rubble was often found to become stable over time due to interactions with the Reef Star legs that helped to interlock loose rubble. These results suggest that a primary mechanism responsible for rubble stabilisation by Reef Stars is not the reduction of near-bed flows, but instead creating barriers to continuous transport created by the legs of the Reef Stars (Westera, 2021).

There was an increase in coral cover at various locations in Indonesia, such as Pulau Badi, Pulau Bontosua, and the Nusa Penida Marine Protected Area since the deployment of Reef Stars (Figure 113). In Pulau Badi, coral cover increased significantly from less than 10% initially to greater than 60%, with a diverse range of recruits observed within 4 years of deployment (Williams et al., 2019). Even when storms hit, live coral cover bounced back to pre-storm levels within 5 months, as broken fragments were trapped by the legs. Similar outcomes were observed around Pulau Bontosua, where average coral cover increased from 17% to 56% within 4 years (Figure 114) (Lange et al., 2024).

Furthermore, an increased carbonate budget (about 6 times higher than the reference site) with a doubled rugosity index was observed at the Moore Reef site after 16 months of Reef Star deployment (Nuñez Lendo et al., 2024). Pulau Bontosua saw smaller effects, with nearly tripled carbonate budgets resembling healthy reefs within 4 years (from 7.2 to 20.7 kg m^{-2} per year), and a slight 1.2-fold increase in rugosity (Lange et al., 2024).

Lastly, sites with reef stars deployed in Pulau Badi and Bontosua showed similar benthic cover to healthy habitats 1 to 3 years after deployment, but with less massive and foliose coral cover, according to a soundscape study by Lamont et al. (2022). The findings also suggested a similar diversity of biotic sounds from restored and reference sites, indicating a greater abundance and diversity of fish, as well as a return of ecosystem function at the restored site.

Figure 113. Site in Nusa Penida Marine Protected Area where Reef Stars were deployed. Source: Marthen Welly, Coral Triangle Center

Figure 114. Time since coral transplantation (years). Representative photographs of surveyed restoration sites as well as degraded and healthy controls. Adapted from "Coral restoration can drive rapid reef carbonate budget recovery" by Lange et al. (2024)

Table 15. Pros and cons of Reef Stars (Mars Inc., 2021b; Welly, pers. comm.; Westera, 2021; Williams et al., 2019).

Pros	Cons
Similar to other 3D metal frames, but also: • The MARRS method provides a package with training, monitoring, planning services, ensuring practitioners are well-informed. • Includes coral transplantation which instantly increase coral cover. • Provides coastal protection by wave attenuation.	**Similar to other 3D metal frames, but also:** • Use of plastic cable ties may introduce microplastic pollution. • Includes outplanting and potentially a nursery, which could significantly add to the cost and amount of labour. • Use of outplants may also risk introduction of coral diseases.

However, not all outcomes have been positive. For example, trajectories of coral cover can vary significantly even within the same site in Pulau Badi (Williams et al., 2019). There were instances of sudden drops in coral cover due to unexpected disturbances or unknown events, though it is unclear whether these are related to the restoration efforts. Predation by *Drupella* snails and crown-of-thorns starfish, as well as competition with soft corals or macroalgae, have also been observed across various sites.

Moreover, Lange et al. (2024) found that Reef Star structures, quickly overgrown by turf algae and cyanobacteria, had little new recruitment potentially due to a lack of colonisation by CCA (0% cover on reefs 0-2 years post-transplantation). Recruits may settle on the stable rubble under the structure, but this was not thoroughly investigated. The authors suggested that the signs of recovery observed in the study is mainly transplant-driven in the first 4 years since deployment, not from natural recruitment.

While there was no overall impact on the coral outplant skeletal properties (e.g., density and porosity that affect the strength of the reef framework), there were some species-specific effects (Nuñez Lendo et al., 2024). The hardness of *Pocillopora damicornis* outplants decreased after 16 months of deployment, suggesting that different species might have to adjust how resources are collected and distributed for the skeleton-building process in response to the changes brought about by Reef Stars in the environment.

Figure 115. Coating Reef Stars with boat resin (left) followed by coarse sand (right). Source: Marthen Welly, Coral Triangle Center

Materials

Reef Stars, like other metal frames, are typically constructed from steel rods with a diameter of 10 mm, and then coated with a mixture of resin and sand. A 12-metre-long steel rod can be precisely welded into two Reef Star structures (**Welly**, pers. comm.). While rebar can be an alternative material for Reef Stars, their ridged surface can complicate the coating process (Nicholson, pers. comm.).

In the production process, Reef Stars are first treated with a rust converter before being coated with two coats of resin and coarse coral sand (**Figure 115**). This not only reduces corrosion but also creates a favourable rough surface for coral attachment. A study conducted in Pulau Badi, Indonesia, demonstrated that this coating can effectively prevent rust for a minimum of 5 years (Williams et al., 2019). Moreover, because the structures were quickly colonised by CCA after deployment, natural coral recruitment was further enhanced.

Size and configuration

The standard design for a Reef Star is a hexagonal structure elevated 28 cm above the substrate by its six legs, covering an area of 0.8 m^2 on the reef.

While the default layout of Reef Stars forms an inter-connected web, it does not necessarily have to be tightly packed (**Figure 117**).

Gaps and other structures can be incorporated to enhance overall structural complexity. Furthermore, Reef Stars of varying heights and sizes can be utilised to increase rugosity. However, it is unknown whether rubble between the gaps stabilises as effectively as rubble directly underneath the Reef Stars. The trade-off between a stronger structure with higher percentage coral cover (compact design) and an increased coverage area with greater structural complexity (loose design) is one that must be considered in the planning phase. It is also important to note that gaps in the reef structure can make the edges of an array of Reef Stars less stable when not inter-connected to adjacent neighbours.

Costs and maintenance

The costs and maintenance tasks involved in Reef Star projects can vary significantly depending on factors such as location, scale of implementation, materials used, labour requirements, and environmental conditions.

In Pulau Badi, the costs of deploying 11,000 structures across 7000 m^2 were US$174,000, averaging about US$24.85/m^2 (~A$40/m^2) (Williams et al., 2019). This included the materials and labour for all stages of the implementation process, with additional support from volunteer divers.

Box 8

Alternative Reef Star designs

An alternative design standing at a height of 18.5 cm can be implemented in shallower sites, as demonstrated by the Coral Triangle Center (**Figure 116**). Other designs with heights in between 18.5cm and the standard of 28cm can also be used.

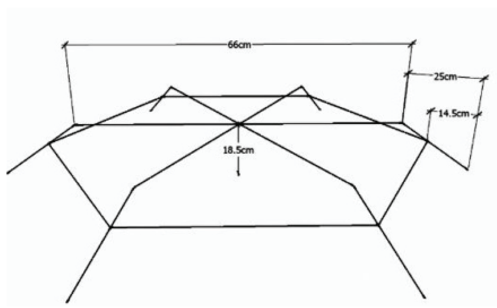


Figure 116. Design of a shallow water Reef Star. Source: Marthen Welly, Coral Triangle Center

On average, a team of 42 was able to deploy 550 Reef Stars over a span of 3 days. In contrast, the material costs for Australia's Moore Reef are approximately A$110 per unit (Fisher, pers. comm.). Costs will vary by location depending on a number of factors such as materials availability, labour costs, transport requirements and availability of volunteers.

Maintenance, if required, is estimated at an additional US$3 per structure for the first 3 months (Williams et al., 2019). Tasks may include removing macroalgae, removing algae-gardening damselfishes, replacing dead fragments, replacing lost or damaged structures, and securing loose structures. A small brush can be used to remove algae from the Reef Stars, taking care not to damage the attached corals. The frequency and extent of maintenance are determined by site-specific factors such as algal growth rates, fish population, sedimentation, etc. Initial maintenance is typically required for the first 3 months, and frequency can gradually decrease over time. The presence of herbivores can significantly reduce the need to remove algae, thus lowering maintenance frequency.

Maintenance may also be necessary following acute disturbance events. For example, in early 2022, the Reef Stars on Bait Reef were affected by elevated sea temperatures, leading to bleaching. Soft coral species were also observed rapidly spreading at and adjacent to the site in 2022-2023. These events led to an estimated mortality across the site of nearly 50% (**Mattocks**, pers. comm.). In response, the Reef Authority decided to replace the dead coral fragments on the Reef Stars in February 2023. A team of six divers spent two days in August 2023 collecting live coral, cleaning the Reef Stars of dead coral, and attaching approximately 850 new live coral fragments.

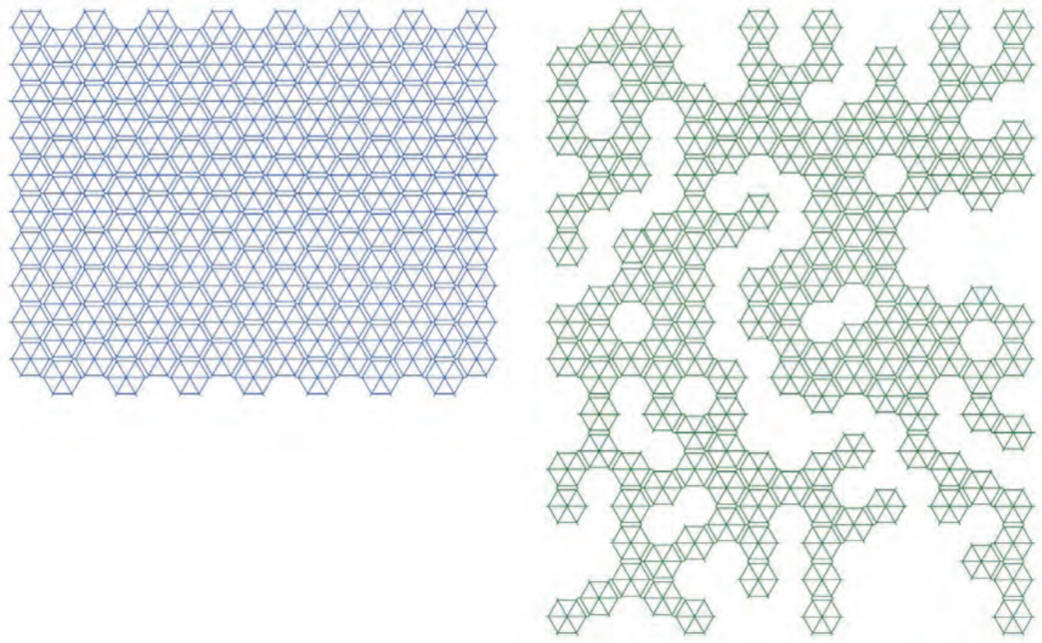


Figure 117. Compact and loose designs of Reef Star arrangement. Left: **Compact design** using 150 Reef Stars – stronger structure, higher percentage of coral cover. Right: **Loose design** using 150 Reef Stars – Increased area, greater structural complexity. Source: Mars Sustainable Solutions

Mineral accretion

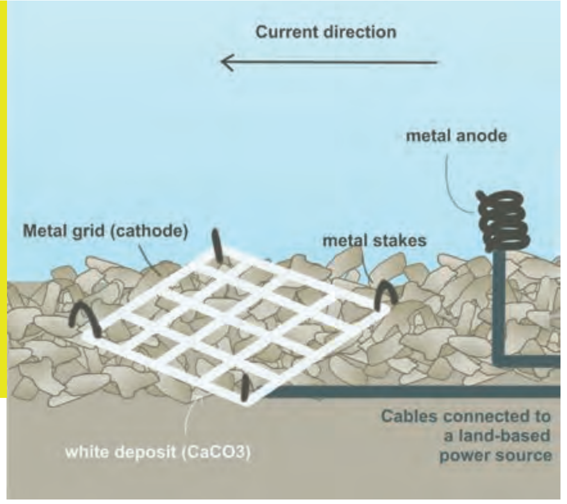
The concept of mineral accretion was first introduced through Biorock technology, which was conceived by architect Wolf Hilbertz in 1976 to accelerate reef growth through metal frames connected to electrical currents (Hilbertz, 1979). This technology, later refined by Goreau and Hilbertz in 1997, was a pioneering example of mineral accretion.

Biorock has been widely applied for various purposes, including shore protection, material production, the construction of artificial reefs, restoring damaged reefs, and stabilisation of rubble beds (Goreau & Hilbertz, 2005; Goreau & Prong, 2017; Hilbertz, n.d.). However, since the patent for Biorock has expired, many projects have adopted similar techniques and are now referred to as mineral accretion.

Reef restoration projects using mineral accretion have been implemented in around 40 countries across the Caribbean, Pacific, Indian Ocean, and Southeast Asia with most projects in Indonesia (Global Coral Reef Alliance, 2009; Goreau, 2010; Goreau, 2014). Globally, approximately 500 Biorock structures have been constructed with 400 located in Indonesia (Global Coral Reef Alliance, 2009).

Despite the lack of evidence published in reputable journals and the scarcity of independent studies, mineral accretion continues to be a subject of interest for many. A recently published study documented its use in the GBR for restoring rubble beds in the Agincourt Reef (Cook, 2020; Cook et al., 2023) (see also **case study 8**).

Figure 118.
Generalised set up of a metal grid with mineral accretion. Source: Shu Kiu Leung, The University of Queensland



Scale of implementation

Most mineral accretion projects are pilot studies, primarily funded by small, often in-kind, donations from local communities (Goreau, 2010; Hilbertz & Goreau, 2001). The largest Biorock installation, spanning 300 metres and covering 2 hectares of reef area, is located in Pemuteran Bay, Bali, Indonesia (Hilbertz & Goreau, 2001).

How does this method help reef recovery?

The electrolysis process uses an electrical current to precipitate naturally dissolved minerals in the water onto a metal structure, forming a layer of calcium carbonate similar to natural coral reef materials (Global Coral Reef Alliance, 2009). The alkaline conditions generated by the process convert bicarbonate ions into carbonate ions, leading to the supersaturation and deposition of limestone minerals (Hilbertz & Goreau, 1996).

Preliminary studies by the method proponents suggest that the accreted mineral creates a suitable, elevated substrate for coral recruitment and growth, which is otherwise challenging in loose rubble beds (Hilbertz, 1979). The open frame designs, similar to other **metal frames**, can allow water to flow through, providing food and promoting recruitment. When placed atop rubble beds, mineral accretion structures can trap rubble and alter substrate-level flow, indirectly stabilising the rubble beds.

Moreover, the proponents proposed that reef-forming organisms near the cathode may uptake and transport essential dissolved calcium ions more efficiently as the technology reduces the metabolic energy required for growth (Hilbertz & Goreau, 1996). This benefit can extend up to about 10 metres around the metal structure (Nitzsche, 2013).

When and where?

Mineral accretion is a technologically complex approach that requires significant expertise and commitment to be implemented. We recommend consulting experts before starting a project to ensure its effectiveness. It has been observed to work equally well on the reef flat as the reefs slope, without a notable increase in coral cover in both environment types (Cook et al., 2023). However, reef flats were deemed more suitable for deployment (Nathan Cook, KAUST, pers. comm.) due to risks of dislodgement or burial on slopes like other metal structures.

When using land-based power sources, the structures would ideally be placed within 100 yards (~90 m) of the power source (Global Coral Reef Alliance, n.d.-a). However, by increasing the voltage at the source to compensate for voltage drops, the structures can be placed as far as 400 m from the power source.

While there is no depth limit for building these structures, they are typically built in shallow waters (1 to 7 m) where corals thrive due to bright light. The structures can also be placed deep enough to avoid collision with boats.

Implementation Strategy

Mineral accretion structures (the cathode) can be directly installed on top of rubble beds and secured with stakes like other flat metal grids or 3D frames (Cook et al., 2023). It is recommended to collaborate with external contractors or electricians for the power system installation, as the specifics can greatly vary from site to site. The details will not be discussed in this section given the great variability of the installation process. The versatility of the cathode metal structures allows them to be used in conjunction with coral transplantation, as demonstrated in the Agincourt Reef (Cook et al., 2023).

Figure 119.
Locations of mineral accretion projects. Source: Shu Kiu Leung, The University of Queensland

What realistic outcomes can we expect?

The use of mineral accretion remains controversial. Method proponents argue that mineral accretion may promote coral growth and survival, coral recruitment and settlement, and increase fish densities (Global Coral Reef Alliance, n.d.-b; Goreau, 2014; Goreau & Prong, 2017; Nitzsche, 2013). However, some independent studies reported negative outcomes or insignificant benefits. These findings were dismissed by proponents as results of "unauthorized projects," attributing the outcomes to inadequate training or poor design. Some consider mineral accretion a temporary solution due to trade-offs, as well as diminishing and/or negative effects on coral growth and survival over time (Romatzki, 2014; Sabater & Yap, 2004; Taylor, 2008).

There is limited transparency, quantifiable data, and independent studies in mineral accretion research. Previously, independent research was not allowed without permission from patent holders of the technology. The results of available studies vary significantly due to factors such as study design and human error, making it difficult to deduce a general trend of reef recovery.

Project proponents have reported significant increases in coral growth, survival and settlement rates in sites with Biorock installations (Goreau, 2014). According to the study, on average, the growth and survival rates of reef-building corals, soft corals, oysters, and salt marsh grass were about 3 times faster, and coral settlement was about 25 times higher at restoration sites compared to control sites.

However, Goreau (2014) also attributes failures of the method to the lack of training and improper setups, such as reversed, absent, or excessive current, which led to rapid cathode rusting, overgrowth of soft minerals on the anode, and death of corals. While technical issues may explain some failures, attributing negative outcomes solely to human error may overlook the method's inherent limitations. It also raises concerns about the method's robustness and practicality when implemented in the field. The method's apparent susceptibility to these errors suggests that its effectiveness may be more variable and harder to achieve consistently than reported.

Some independent studies have reported negative outcomes, such as decreased or unchanged growth rates (Cook et al., 2023; Romatzki, 2014). The direct contact with charged metal negatively affected coral growth and survival. For example, the survival rates of transplants of two *Acropora* species varied significantly based on treatment conditions and placement (Romatzki, 2014). Also, Taylor (2008) observed trade-offs between growth rates, fecundity (number of brooded larvae), and polyp density in Stylophora pistillata corals outplanted onto structures with mineral accretion treatment in Lombok, Indonesia. Corals exposed to a year-long continuous DC electric current showed significantly lower fecundity compared to naturally growing colonies in the reference site despite having higher growth rates and cover. Cook et al. (2023) found no significant effects of improved growth and survival of coral transplants between restoration and control sites. Furthermore, continuous accretion led to negative feedback between electrodes, diminishing the effect of mineral ion enrichment over time (Sabater & Yap, 2004). This suggests that growth enhancement, which occurs during active mineral accretion, may not essentially be a viable long-term strategy.

Table 16. Pros and cons of mineral accretion (Cook et al., 2023; Goreau, 2010; Goreau, 2014; Goreau & Hilbertz, 2005; Goreau & Prong, 2017; Hilbertz, 1979; Uchoa et al., 2017)

Pros	Cons
Similar to metal frames, but also: • Accreted materials have a mechanical strength similar to concrete, making it highly stable. • May provide coastal protection and prevents erosion. • The structures are self-repairing and grow over time, allowing adaptation to sea level rise.	**Similar to metal frames, but also:** • Installation and maintenance require technical knowledge, particularly for proper power connection. • The electric field may influence the behaviour of some animals. • Initial investments (e.g. installing power supply) are high, with ongoing electricity costs. • Prohibitive costs and logistical challenges limit scalability.

Case Study 8:

Mineral accretion on metal frames at Agincourt Reef #3, GBR

(Cook, 2020; Cook et al., 2023; Nathan Cook, pers. comm.)

Background

In 2018, Reef Ecologic and Quicksilver Connections launched a trial using mineral accretion technology to help restore a cyclone-damaged reef near Quicksilver Connection's floating tourist platform (pontoon) at Agincourt Reef #3 in the GBR.

The site, which attracts between 100 to 400 visitors daily, was chosen due to its value in eco-tourism. The project aimed to increase the coral cover and visual appeal of the 20 m^2 loose rubble patch near the diving entry point in front of the pontoon. Despite being sheltered from wind and waves, the site is vulnerable to severe weather and cyclones.

Design and deployment

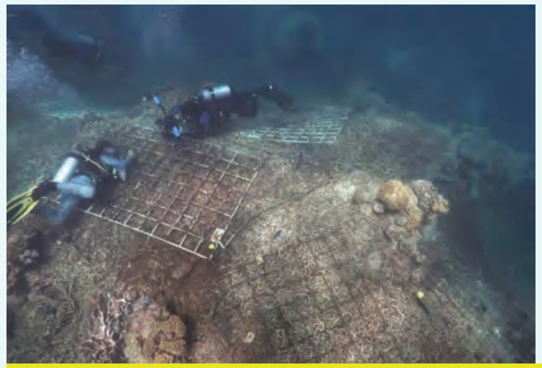
Rebar frames, each covering an area of 4.5 m^2 with a diameter of 6 mm, were installed on the rubble bed to test the effectiveness of coral transplantation with and without an electricity connection (**Figure 120, Figure 121**). The frames were flexible enough to follow the natural contours of the reef, such that two panels were installed on top of a rubble mound and four on the sloping sides.

A power system was installed at the pontoon site in September 2018 with the help of external contractors. An insulated heavy-duty cable was connected to two 12 V batteries powered by the pontoon's generator, providing a continuous power source (**Figure 122**). Real-time data on the voltage and amperage was made available using a heads-up display to allow monitoring.

Results/findings

Despite substantial mineral accretion on the frames (bars with electricity grew to 11.7 mm mean diameter, while those without reduced to 4.17 mm due to corrosion), there were no positive effects on the survival or growth of transplants observed in the first 13 months. This could be attributed to the high amperage of 5 A/m^2 as opposed to the suggested level of 1 A/m^2. In addition, coral cover decreased while macroalgae cover increased in sites when the current was active.

After 13 months, electrolysis was discontinued, and an additional 296 coral fragments were transplanted. Over 4 years, mean live coral cover increased immensely in both treatment locations compared to control sites, with no significant difference between the two treatment sites (**Figure 123**).



Left: Figure 120. Divers setting up frames at Agincourt Reef #3. Frames with white deposits are connected to a power system that facilitates mineral accretion. **Right: Figure 121.** Frame deployed at the site with transplanted corals. Source: Nathan Cook

In the powered treatment sites, coral cover increased from 1.7% in 2018 to 80.8% in 2021. Meanwhile, in the unpowered treatment sites, coral cover increased from 0% in 2018 to 75.8% in 2021.

Despite having minimal effects on accelerating coral cover, the deployed metal frames with mineral accretion technology were highly effective in limiting rubble movement due to their inherent stability. The experimental sites were impacted by severe Tropical Cyclone Owen in December 2018, yet no structures were broken or lost, highlighting their stability and their potential to withstand strong wave action.

Lessons learned:

- The method requires significant technical expertise and may necessitate collaboration with electricians and contractors to ensure its effectiveness.
- Although the use of mineral accretion technology did not improve coral growth or survival in the first year in this case, it may have potential application in the creation of a new, solid substrate for rubble stabilisation.

Figure 122. Two 12 V batteries connected to the charging device powered by the onboard generator **(a)**, heavy-duty electrical cable **(b)** connecting onboard battery pack to the underwater step-down junction box **(c)**. Three 6 mm cables converted the 24 V DC to low voltage current for delivery to each individual treatment converter **(d)**. Titanium anode mesh **(e)** and titanium connector to a steel mesh panel (cathode) **(f)**.

Adapted from "Lessons learned implementing mineral accretion and coral gardening at Agincourt Reef, Great Barrier Reef" by Cook et al. (2023).

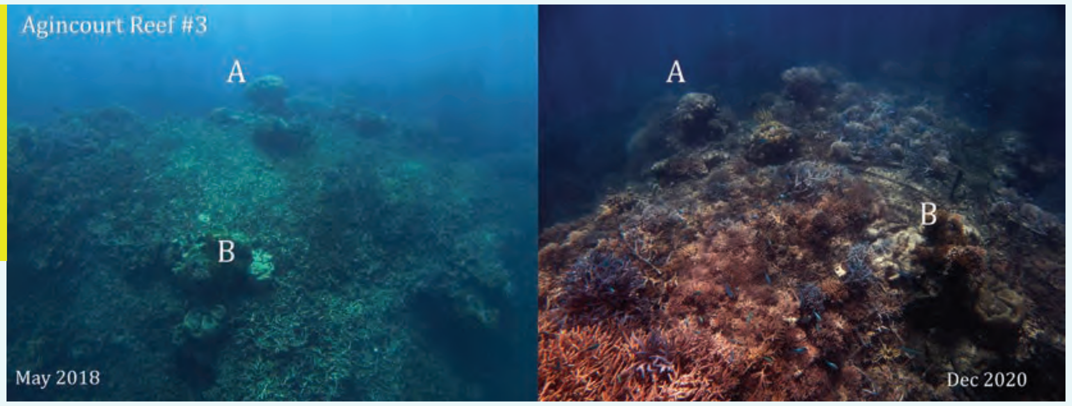


Figure 123. The same site 2 years apart (2018 to 2020) after frames were deployed. Source: Nathan Cook

Expert tips

"Our project on the Great Barrier Reef did not suggest a difference in coral survival and growth between frames with or without electricity. It would have been ideal to explore the effects of different voltage and amperage levels, but this was beyond the scope of our available resources.

Future projects might consider experimenting with different designs of electricity setup."

Nathan & Kailash Cook

Nathan & Kailash Cook

Nathan Cook, an applied marine scientist with over 20 years of experience, specialises in coral reef restoration in the Pacific, Southeast Asia and in the Middle East. His assistant, Kailash Cook, shares his dedication to marine biology. Together, in collaboration with numerous community groups and organisations, they have implemented restoration projects in Koh Tao, Thailand using coral nurseries, and in Australia using mineral accretion technology, aiming to reverse the decline of degraded reefs.

Materials

The mineral accretion process uses electrically conductive materials like iron or steel to construct artificial reef structures of any size or shape (Global Coral Reef Alliance, 2009).

In the electrolysis process, two metals, the anode and cathode, are submerged in water and subjected to electricity, causing the cathode to accumulate limestone minerals while the anode gradually degrades (Bakti et al., 2013). The accreted materials, primarily limestone ($CaCO_3$), along with some brucite ($Mg(OH)_2$) and portlandite ($Ca(OH)_2$), have a strength similar to concrete (Hilbertz, 1979).

The electrical currents not only promote the deposition of minerals but also protect the metal cathode from rusting (Hilbertz, 1979). If the cathode material lacks corrosion resistance, it corrodes when the electricity is cut off.

However, the accreted minerals can inhibit oxidation and limiting oxygen access to the metal, thereby preventing rusting for a short period of time (Hilbertz & Goreau, 1996).

The power and energy requirements can vary from site to site. Copper cables connect the electrodes to a power supply, often land-based and chosen for cost-effectiveness, such as batteries, chargers, solar panels, and windmills (Global Coral Reef Alliance, 2009; Goreau & Prong, 2017). The applied Direct Current (DC) power ranges from 0.001 to 4000 W per square metre of cathode surface, with a suitable current density of 0.1-30 A per square metre of cathode surface (Hilbertz & Goreau, 1996). A low voltage (>1.2 V) is preferred for optimal growth of minerals. The energy needed ranges from 0.4 to 2 kW per kg of accreted mass (Hilbertz, 1979).

Size and configuration

Similar to other metal structures, the shape and size of the cathode metal frame and overall setup are largely determined by project goals, site requirements, and costs (Goreau & Hilbertz, 2005).

There are, however, some general principles for the configuration according to the method proponents. The anode is ideally positioned to ensure water flows from the cathode towards the anode, minimising the transfer of acidic electrolytes to the cathode that may inhibit the growth of marine organisms (Hilbertz & Goreau, 1996). Although it is beneficial to place the anode close to the cathode to minimize electrical losses, it is equally important to ensure precautions are in place to prevent acidic electrolytes from reaching the cathode. The anode's position, whether bottom-mounted or suspended in the water column, depends on local conditions such as currents and wave patterns, as well as the desired substrate thickness and composition.

Costs and maintenance

The costs of installation can vary significantly based on factors such as the amount and local cost of materials, the strength required for the structure to withstand local wave energy, the distance from power sources, and the type of power source used (Goreau & Hilbertz, 2005). Typical unit costs for larger mineral accretion installations are between US$3.20-4.00/$m^2$ (~A$5-6/$m^2$) of covered sea floor for applications in rubble stabilisation and coral stimulation (Goreau & Hilbertz, 2005). These costs, which are based on 2005 figures, apply to rubble stabilisation and coral stimulation projects that are primarily in Indonesia. Please note that these figures do not account for travel, time, or inflation. The installation costs can escalate significantly when experts are consulted for the setup due to the advanced technical knowledge it necessitates. A restoration project initiated in Raja Ampat in 2023 reported an expenditure of over €20,000 to engage professionals for the installation (Brival, pers. comm.). Maintenance costs are largely dependent on the size of the structures, with most structures consuming less than 200 W of power (Goreau & Hilbertz, 2005). However, it is important to consider that electricity costs can also vary significantly across different locations.

Maintenance tasks include the periodic removal of algae, soft corals, and sponges that could outcompete corals, as well as eliminating corallivores like crown-of-thorns starfish and *Drupella* snails (Global Coral Reef Alliance, n.d.-a). Regular inspections are conducted to ensure that cables and connections are intact. Divers can check for tiny bubbles rising from the structures, which indicates that the electrolysis is happening. If any issues are detected with the cables or system components, it would be a good idea to replace them to maintain a consistent electricity supply.

Concrete structures

Concrete structures are the preferred choice for many when constructing artificial reefs due to their numerous advantages, such as their excellent mouldability, cost-effectiveness, durability, and availability (Baine, 2001; Ramm et al., 2021).

Like metal structures, they can be moulded into different shapes and sizes to serve different purposes. The use of concrete as artificial reefs has seen a steady rise over the years, particularly in recreational fishing applications (Ramm et al., 2021). Nevertheless, they hold significant potential in rubble stabilisation by offering weight and stability, as well as providing surfaces for settlement.

This section will explore the use of various forms of concrete structures, including concrete blocks and specifically designed structures, using the widely adopted Reef Balls™ design as an example.

Concrete blocks

Concrete blocks, first used in 1990 for rubble stabilisation in the Maldives (Clark & Edwards, 1994), have become a versatile and popular method for rehabilitating degraded reefs. Their affordability and flexibility have led to widespread use in Southeast Asian countries like Indonesia and Malaysia, usually by NGOs addressing human-induced reef degradation (Chen et al., 2018; Coral Reef Care, n.d.; Stacey, 2020).

While concrete blocks are often the default choice for artificial reefs, primarily due to their perceived low risk and proven effectiveness, their popularity does not automatically equate to them being the best option in restoration.

Scale of implementation

Projects are usually conducted on a local scale, covering up to a few hectares within a single reef. For example, some are small pilot studies like the Step Reef project in Pom Pom Island, Sabah, Malaysia by Tropical Research and Conservation Centre (TRACC) (Philippo, pers. comm.; Stacey, 2020) (see also Box 9). Meanwhile, the largest experimental study to date spans an area of 40,000 m^2 and tests different concrete block designs and arrangements (Clark & Edwards, 1994). These include large SHED blocks (1 m^3 hollow concrete cubes) and Armorflex units connected to form a mattress, which were deployed in 50 m^2 plots across the study area.

Figure 124. Locations of sites where concrete blocks were deployed. Source: Shu Kiu Leung, The University of Queensland

How does this method help with recovery?

Concrete blocks contribute to reef recovery in several ways. They provide elevated and stable surfaces that are suitable for coral recruitment. Recruits can settle on vertical concrete surfaces to avoid sedimentation and abrasion by loose, mobile rubble. The hollow designs of some blocks not only provide additional settlement surfaces but also allow water to flow through, bringing more recruits and nutrients. Clusters of blocks or larger blocks may disrupt water flow at the benthic level, which can indirectly reduce rubble movement and accelerate the rubble binding process. Furthermore, these blocks may provide protective spaces that can house a diversity of species, thereby enhancing reef resilience.

When and where?

The best time to deploy these structures is when it aligns with local coral spawning patterns, as this can greatly influence the rate of coral recruitment (Clark & Edwards, 1999).

Concrete blocks, depending on their size and design, can be effectively used in a variety of environments, including reef crests, reef flats, and reef slopes. For instance, step reef units are particularly suitable for steep reef slopes (see Box 9).

Although larger concrete blocks may provide greater stability, sometimes deploying these blocks alone is not enough to resist hydrodynamic forces, especially in shallow waters and high-energy environments (Rolf Voohuis, Coral Reef Care, pers. comm.). In these environments, it is recommended to take extra care and make stability calculations before deployment. It may be beneficial to also consider combining the use of blocks with other methods, such as rubble removal, to minimise potential damage.

Implementation Strategy

Deploying smaller blocks can be relatively straightforward. These blocks can be transported to the restoration site via boats, and divers can manually arrange them *in situ*.

Concrete blocks may require additional anchorage in high-energy environments, or in the face of storms or other extreme events (Veenland, 2023). For example, when arranging concrete blocks into clusters, iron rods can be inserted at the cluster's corners, and rocks can be placed along the sides for added stability (Chen et al., 2018). The deployment of larger blocks may require the use of larger barges and heavy machinery, such as cranes to lower structures onto the seafloor (Clark & Edwards, 1994).

In some cases, glass bottles are embedded into the blocks for upcycling purposes. A notable example of this can be found in Tioman Island and Pom Pom Island, Malaysia, where community projects involved attaching used glass bottles to concrete blocks (Figure 125, Figure 126) (Chen et al., 2018; Philippo, pers. comm.). Coral fragments were then tied to the bottlenecks and these structures were deployed on rubble beds for both restoration and bottle upcycling purposes. A recent study by García-Baciero et al. (2023) demonstrated that coral fragments, when tied to glass bottles using cable ties, generally had a higher success rate of self-attachment compared to when they were tied to rebar. Similar techniques were implemented in Pom Pom Island, Sabah to restore areas affected by blast fishing (see Box 9).

Left: Figure 125. Coral fragments are attached to the necks of glass bottles that are anchored in cement blocks. Source: Kee Alfian Bin Abdul Adzis **Right: Figure 126.** New bottle reef project on Pom Pom placed quarter 1 2024 named "Bottle Bottle." Source: Robin Philippo, TRACC Borneo

Box 9

Step Reef Project in Pom Pom Island, Malaysia

(Philippo, pers. comm.; Stacey, 2020)

Decades of **blast fishing** have left the coral reefs around Pom Pom Island, Malaysia with zero coral cover in most areas. Blast fishing was a quick way to make money and became a widespread practice due to geopolitical issues in the region. Sites damaged by blast fishing saw zero recovery and virtually 0% coral cover despite having adequate coral larval supply over 9 years of monitoring. Persistent, loose rubble beds have been found in areas with steep slopes (25-45°) and strong currents.

Many methods are not suitable for steep slopes due to the inherent instability and risk of burial. TRACC developed a method for steeper slopes using concrete blocks to create step-like structures. These structures, known as "step reefs", are designed to provide a stable surface for coral settlement and transplantation. The step reef units are made with a mixture of sand, rubble, microfiber, and 15-18% cement, with glass bottles embedded in the design (Figure 127). Additionally, the spaces between the glass bottles serve as hiding spots for fish and invertebrates.

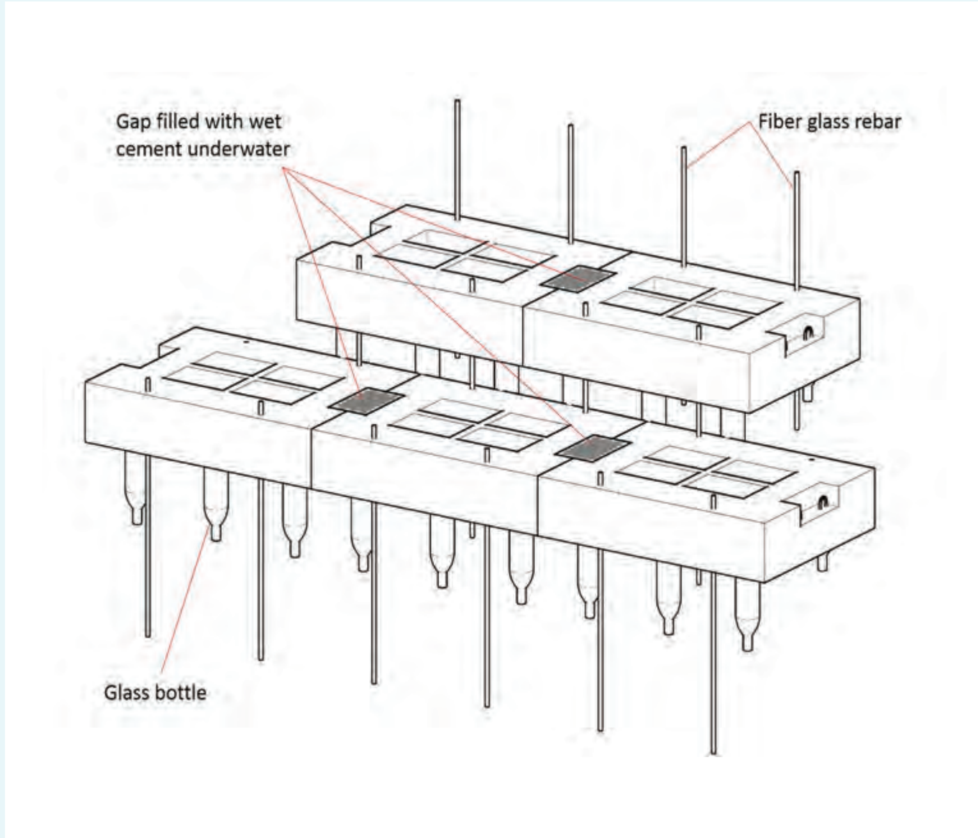


Figure 127. Early design of a step reefunit, incorporating 12 mm fiberglassrebar rods. Source: Robin Philippo,TRACC Borneo

The initial trials of the step reef units encountered several challenges. These challenges included a rubble landslide that buried the structure and intense competition among the transplanted corals due to overcrowding, resulting in high mortality rates. Recognising that these outcomes were far from ideal, modifications were made to the design to enlarge the units and reduce the number of coral transplants. This allows more space for each transplant and increases the surface area available for recruitment.

Moreover, meshes were added to the top and bottom of the units to prevent landslides and erosion. These modifications led to significantly improved coral recruitment and growth compared to the original design (**Figure 128**). The new design was able to sustain on steep slopes of 30° and 35°. However, specific numbers of coral recruitment, coral cover, and other metrics were not reported.

Figure 128. The revised design of step reef units, initially installed on Rugged Reef in Pom Pom Island (top), and their condition one year after installation (bottom). Source: Jeethvendra and Robin Philippo, TRACC Borneo

Expert tips

"When cement structures are the method of choice there are a few things to really take into consideration prior to moving forward.

Firstly, consider modular work rather than large, singular structures. This will not only limit the cost (think of barges, cranes, trucks etc) but gives you a far better ability to place structures.

Secondly, prioritise diver safety. It is crucial for diver safety to maintain "military precision" when deploying cement artificial reefs. Ensure there are safety divers in place to keep smooth communication between the boat crew (lowering the units by rope) and the bottom crew (releasing the structure and attaching it to a lift bag). Despite knots are vital for safety, there is always a risk of an unpredicted release which could incorporate significant damage.

Lastly, never use buoyancy control devices (BCDs) as a replacement of lift bags, particularly at depth. Although this may sound silly, it is readily used in the industry. Invest in a proper lift bag, even two and do the necessary training before involving any divers."

Robin Philippo

Robin Philippo
leads the TRACC, a volunteer-funded organisation in the Celebes Sea. TRACC's mission is to protect sea turtles and restore bombed coral reefs in Malaysia. The organisation has trialled multiple innovative rubble stabilisation methods using custom-made concrete structures and glass bottles.

Conditioning, i.e., placing concrete blocks in the marine environment for a period of time before deployment, is often considered necessary for two main reasons: to leach toxic substances from the concrete and to facilitate the colonisation of CCA that attracts coral recruits (Clark & Edwards, 1999). The high alkalinity of Portland cement-based concrete blocks can render them toxic to invertebrates for 3 to 12 months (Lukens & Selberg, 2004). Therefore, the conditioning of concrete blocks aims to minimise the impact of high pH on recruitment. On Pom Pom Island, structures were allowed to cure for at least 4 weeks after manufacturing to ensure sufficient time for the pH to drop to a suitable range before deploying them at the site (**Philippo**, pers. comm.).

The method is often used with **coral transplantation and gardening** as concrete blocks have sufficient surface area provided for attachment. Coral fragments of opportunity are usually attached to blocks using marine-grade epoxy or cement (Chen et al., 2018; Clark & Edwards, 1994).

What realistic outcomes can we expect?

Concrete blocks may promote coral recruitment, fish and invertebrate abundance, and fish diversity in the short term (Clark & Edwards, 1995; Clark & Edwards, 1999; Philippo, pers. comm.). Meanwhile, increase in coral cover and other effects on ecosystem function are expected to take place over the medium to long term. However, outcomes can vary depending on the environment, and risks of dislodgement, movement, or fracture can significantly reduce the effectiveness of concrete blocks.

Figure 129. Natural recruitment on the surface of SHED blocks, 3.5 years after deployment in Galu Falhu. Source: Alasdair Edwards

While concrete blocks are commonly used, most of the available data are anecdotal evidence from practitioners. The information outlined below primarily draws from these practitioner observations and an early, detailed study conducted in the Maldives (Clark & Edwards, 1994; Clark & Edwards, 1995; Clark & Edwards, 1999), which was among the first to investigate rubble stabilisation methods.

A study in the Maldives showed that recruits first became visible on vertical surfaces of blocks 10 months after deployment at a density of 18 recruits/m^2 (Clark & Edwards, 1995). On the SHED blocks, reef fish species richness and abundance increased by five-fold within the first month. Within a year, the artificial reef structures exhibited similar or even higher species richness and densities of reef fish compared to reference sites, although the community structure differed significantly (Clark & Edwards, 1999). This effect was observed to "spill over" to areas surrounding the concrete blocks within 5 years (**Alasdair Edwards**, Newcastle University, pers. comm.). However, the signs of reef recovery in terms of ecosystem function were not expected until 5 years after installation (Clark & Edwards, 1999).

Similarly, concrete blocks deployed on a reef crest on Pom Pom Island showed remarkable short-term success within a year, with fish abundance and invertebrate abundance increasing by 225% and 218% respectively (**Philippo**, pers. comm.) (**Figure 130**). Other installations involving blocks with embedded glass bottles on Pom Pom Island also showed significant increase in coral cover over time (**Figure 131, Figure 132**).

Despite these positive outcomes, it is important to consider potential risks. For example, in northeast Bali, small concrete blocks became unstable and started sliding over the ocean floor, scattering after a storm hit the area in 2023 (Veenland, 2023). Such movement of structures can cause abrasion to recruits, setting back the progress of recovery. Similarly, Jaap (2000) reported that concrete mats did not survive well after hurricane Georges hit the site in Florida. The author observed not only the displacement of the mat but also damage to the cables that were integral to the mat's structure.

Figure 130. Concrete blocks first deployed on a rest crest in 2018-2019 (left) and after 4-5 years in 2023 (right). Source: Robin Philippo, TRACC Borneo

Figure 131. Bottle reefs placed in 2019 on TRACC's house reef on Pom Pom Island. Photo shows the results of the restoration project 5 years since installation. Source: Robin Philippo, TRACC Borneo

Figure 132. "Ribbon Reef" on Pom Pom Island, where 2 rows of bottle reefs were placed in 2015. Photos show the results of the restoration project 9 years since installation. The once-barren rubble flat is now fully overgrown with hard corals, with only the tips of the bottles still visible. Source: Robin Philippo, TRACC Borneo

Table 17. Pros and cons of concrete blocks (Chen et al., 2018; Clark & Edwards, 1999; Edwards & Gomez, 2007; Stacey, 2020).

Pros	Cons
• Offers high stability and weight, although the stability of smaller blocks depends on their arrangement. • Provides instant structural complexity. • Provides a stable settlement surface area above the substrate level, potentially reducing the impacts of sedimentation and competition. • Provides habitat, including crevice spaces, for fish and invertebrates. • The modular design allows for deployment flexibility, with as many or as few structures used as needed, or arranged in different formations, depending on the size of the site, site layout and restoration goals. • The modular design also allows usage in scenarios where budgets are low but there are ample human resources, which is common in many reef restoration projects powered by volunteers. • Relatively simple to deploy. • Larger blocks may provide coastal protection by wave attenuation.	• High carbon footprint – contributes to 10% of global emissions. • Conditioning the concrete blocks may be time-consuming. • Inexperienced practitioners using an inappropriate mixture may lead to detrimental outcomes. • May require extensive and complicated logistical considerations involving barges and machinery if the blocks are large, which could significantly increase installation costs. • Without a healthy population of herbivores to keep the frames clean, they will require maintenance by divers at most sites, particularly in the very early stages post-deployment. • Introduction of foreign materials into the environment can potentially lead to pollution if structures degrade or fracture. • There is a risk of damaging benthic organisms during installation.

Materials

The choice of a concrete mixture is critical in the design and effectiveness of the blocks, with considerations for cost, environmental impact, bio-receptivity (whether recruits will settle on the structure), stability, and durability.

The use of cement in concrete production contributes to 8% of global carbon emissions (Belaïd, 2022). While the carbon emissions from transporting concrete structures may exceed those from cement production, sourcing low-carbon or carbon-neutral concrete for manufacturing structures is recommended to minimize environmental impact, particularly in light of climate change. Eco-friendly alternatives like industrial by-products, waste materials, and natural fibres can partially replace Portland cement and aggregates, reducing the carbon footprint (Evans et al., 2017). However, not all of these alternatives may be suitable for use or remain durable when submerged underwater. An alternative approach is to reduce the proportion of cement in the mixture.

For example, using a mixture with around 25% cement (Philippo, pers. comm.), supplemented with other materials such as metal rods (see Box 9 for example), granite, and microfiber to maintain structural strength, may further reduce the carbon footprint from concrete production.

The bio-receptivity of concrete blocks can be influenced by factors such as surface chemistry and roughness. The physiochemical properties of a concrete surface can alter the composition of the biofilm that colonises it, and this effect can vary with environmental conditions (Natanzi et al., 2021). As a result, much effort has been made to optimise concrete texture and chemistry to attract diverse and natural assemblages, enhancing ecological outcomes. For example, beach sand could be added to the mixture to create a rougher surface that is easier for coral recruits to attach.

Including beach sand in the mixture can also help reduce the amount of cement needed in concrete production, but its use must be balanced carefully to avoid compromising the strength and durability of the structure. Moreover, for large-scale projects, excessive extraction of beach sand can lead to beach erosion. In such cases, importing sand from external sources may be necessary, though this can significantly increase costs.

Furthermore, alternative materials have been used in place of Portland cement in an attempt to lower the pH of concrete structures (Perkol-Finkel & Sella, 2014). Portland cement, which is primarily composed of lime, has a high pH of ~13, compared to the pH of ~8 in seawater. This high pH in cement can cause the concrete block to become alkaline, potentially posing a threat to marine life and promoting the growth of alkali-resistant species over others during early succession (Hylkema et al., 2021; Perkol-Finkel & Sella, 2014). Conditioning concrete blocks (see Implementation Strategy) could be a potential solution to this issue. However, a systematic study showed that while a reduced pH had minor positive effects on early colonisation in the tropics, eventually, species composition remains the same regardless of pH (Hsiung et al., 2020). Whether pH plays a significant role in recruitment remains debatable.

In order to make concrete blocks more durable and resistant to chloride ions in seawater, Pulverised Fuel Ash (PFA) can also be added to the concrete mixture (Cheewaket et al., 2010). PFA, commonly known as fly ash, is a pozzolanic industry by-product that presents a "greener" alternative to Portland cement but can be costly (Chen et al., 2018; Evans et al., 2017).

Size and configuration

The size of these structures can vary greatly – from small concrete or cement bricks typically used in construction (e.g., Chen et al. (2018)) to larger hollow cubes measuring up to 1 m^3 (e.g., Clark and Edwards (1994)).

The size of blocks presents a compromise between logistic requirements and the stability of the setup. Installation is relatively straightforward with smaller blocks (Figure 133), but these may lack the necessary weight for use in more exposed areas. Conversely, larger structures (Figure 134), although providing the needed weight, have higher logistic requirements during installation. They are also more prone to fracturing, which could potentially cause substantial damage to the ecosystem.

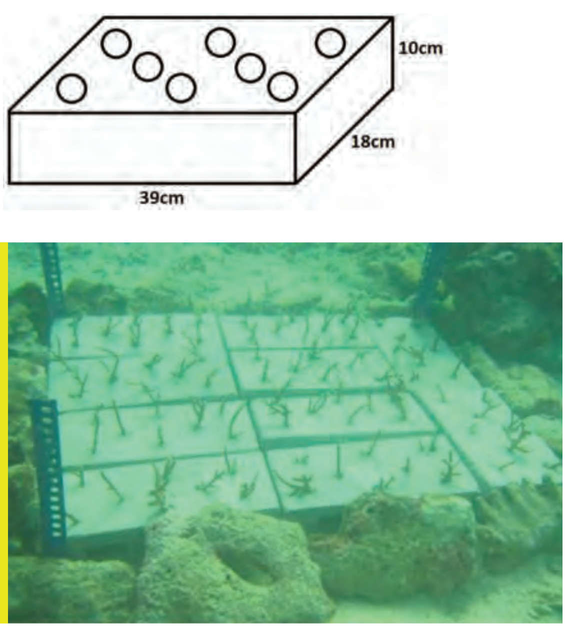


Figure 133. Small cement blocks with transplanted corals deployed in Pangkor Island. Source: Reef Check Malaysia; Adopted from Chen et al. (2018).

Figure 134. Large 1 m^3 SHED block (hollow concrete cube) being lowered into position on the reef-flat at Galu Falhu, Maldives. Source: Alasdair Edwards

Larger blocks can also alter the hydrodynamic conditions of the area, leading to consequences that inexperienced practitioners may not expect. However, with a deep understanding of the structure and site conditions, large blocks can be strategically placed to take advantage of their wave attenuation properties. They can obstruct strong currents to reduce rubble movement or provide coastal protection.

When arranging the blocks, it is crucial to take hydrodynamics into account to ensure they remain stable enough to withstand waves and currents. For example, one strategy could be to arrange the structures parallel to the wave direction, which can help minimise the direct impact of hydrodynamic forces (Veenland, 2023; Voohuis, Coral Reef Care, pers. comm.).

To increase structural complexity, blocks can be arranged in a manner that provides more cryptic protective spaces (Figure 135). This encourages a diverse range of fish and invertebrates to inhabit these spaces.

Incorporating blocks of different sizes can further enhance the structural complexity. A practical example of this can be seen in the northeast shore of Bali, Indonesia, where concrete bricks and hollow concrete cubes of varying sizes were used to restore reef areas damaged by blast fishing (Coral Reef Care, n.d.; Veenland, 2023).

The arrangement of concrete blocks into a mat, known as a stabilisation mat, is a common method used to increase the stability of a reef area. For example, small concrete units are threaded together using polyester cables, forming the Armorflex concrete mattresses which were laid onto loose rubble beds and anchored with flooring slabs (Figure 136) (Clark & Edwards, 1994). A similar approach was taken in Florida, where concrete tiles were connected by ropes and placed over an exposed sewage pipe after a hurricane to provide a stable substrate (Mickelfield, 2018).

Figure 135. Divers deploying concrete blocks of different sizes in Bali, Indonesia. Source: Coral Reef Care (https://www.coralreefcare.com/projects/)

Figure 136. Armorflex mattress anchored with flooring slabs, 3.5 years after deployment in Galu Falhu. Source: Alasdair Edwards

Expert tips

"Armorflex mattresses have a challenge with sedimentation on their large horizontal surfaces, which aren't ideal for coral recruitment. Most recruits were observed on the vertical edges instead of the top surfaces. Therefore, a key principle in design is to maximise the vertical surface, while minimizing the horizontal surface for a given weight so it will still be stable.

We also tested the effectiveness of coral transplantation on these mattresses. Results showed little difference since the site had high recruitment rates in the first place. When suitable surfaces and good water quality are present, natural recruitment can restore reefs substantially within 3-4 years without the need for transplantation."

Alasdair Edwards

Alasdair Edwards

Professor Alasdair Edwards is renowned for his research on coral reef restoration and rubble stabilisation. His work primarily revolves around the recovery patterns of coral reefs from physical damage and mass bleaching events, and how reef restoration technologies can aid these natural recovery processes. His pioneering work with Dr Susan Clark using concrete structures in the Maldives has paved the way for research and development in the field of rubble stabilisation.

Costs and maintenance

The costs can vary significantly based on the location, the materials used, and the complexity of the structures (Clark & Edwards, 1999). For example, a unit of the cement block design in Pangkor Island, Malaysia can be obtained for RM8 (~A$3) from ordinary hardware shops (Chen et al., 2018). In Sabah, Malaysia, a concrete block deployed on a reef crest costs US$7.5 (~A$10) (**Philippo**, pers. comm.). For smaller blocks, manual mixing and small moulds can simplify the production process. This can also be more cost-effective if carried out by volunteers (**Lennon**, pers. comm.). On the other hand, in Maldives, the large 1 m^3 SHED blocks cost £210/m^2 (~A$430/$m^2$) and the Armorflex mattresses cost £66/m^2 (~A$130/$m^2$). Please note that these figures are from 1990 and may have been affected by inflation. The authors also noted that the SHED blocks may not be a cost-effective or aesthetically acceptable option for rubble stabilisation (**Edwards**, pers. comm.).

Like **rocks and boulders**, maintenance of concrete blocks is typically minimal, but it can vary based on local conditions such as seasonal algal blooms. Occasional monitoring is necessary to check for potential algal growth or displacement of structures. Any required maintenance, such as algae removal, repositioning of blocks, or addition of structural support, contributes to the overall costs.

Reef Balls™

Reef Balls are patented artificial reef structures designed for various purposes, such as coral and oyster reef restoration, coastal protection, and fish aggregation (Reef Ball Foundation, 2024c). Reef Balls have gained popularity among marine tourism operators and NGOs due to their innovative design and numerous potential applications (Tallman, 2006). To date, over half a million Reef Balls have been deployed across more than 62 countries, making them one of the most extensively used structures for artificial reefs (Reef Ball Foundation, 2024a).

Scale of implementation

Reef Ball projects can be implemented on a large scale, but primarily for coastal protection purposes, serving as breakwaters that can extend along hundreds of kilometres of coastline (Reef Ball Foundation, 2024b). When it comes to reef restoration, Reef Ball projects are usually local or small-scale, covering a few hundred square metres to a few hectares (Boström-Einarsson et al., 2020b).

One of the largest implementations, combined with coral transplantation, involved deploying 3500 modules, transplanting **"corals of opportunity"**, and stabilising loose live coral rock by attaching it to the Reef Ball in Antigua (Society for Ecological Restoration, 2024). In this project, Reef Balls also served as a breakwater and aided in mangrove restoration.

In Australia, around 4,000 Reef Balls have been deployed and are mainly used to enhance recreational fisheries, as demonstrated by the deployment in Lake Macquarie (Folpp et al., 2013). 180 individual mini-bay Reef Balls were deployed in replicate artificial reef groups of 30, each group covering about 10.5 m^2.

How does this method help with recovery?

Reef balls provide a stable substrate for coral recruits to settle and avoid abrasion or burial in loose rubble beds (Meesters et al., 2015). They also provide vertical relief, which helps recruits and/or coral outplants avoid sedimentation, a common issue that can hinder their growth and survival. Furthermore, larger Reef Ball units have the potential to break waves, which indirectly limits rubble movement. This function assists with the rubble binding process and may eventually lead to the formation of a stable rubble substrate that encourages recruitment.

Figure 137. Pallet Ball manufactured by Reef Ball Australia in New South Wales. Source: Reef Ball Foundation (www.reefball.org). Retrieved from https://www.reefball.org/album/index.html.

When and where?

Reef balls may yield the best results when placed in rubble beds over a hard substrate (Kojansow et al., 2013). However, their adaptable design allows for application in a broad range of environments with complex underwater terrain. The optimal timing and locations for their deployment generally align with those of **concrete blocks**.

Implementation Strategy

Reef Balls, similar to **concrete blocks** and **rocks**, can be transported via boats or large barges (**Figure 139**). The size of the Reef Balls determines whether they can be manually placed by divers or heavy machinery such as cranes (**Figure 140**).

Reef Ball units are designed so that the majority of weight is in the bottom 1/3 of the unit and with the top hole that dissipates upward lift by wave action, making them stable and usually able to resist movement on their own (**Lennon**, pers. comm.). However, in high-energy environments where they may slide or overturn, they can be pinned to the seafloor for added stability. This can be done by driving rods or pilings through the reef units into the seafloor or attaching Reef Ball units to an articulated mat (Harris, 2007). The rods and pilings could be inserted at an angle through the Reef Ball to reduce movement.

Like **other concrete structures**, Reef Balls are often used with **coral transplantation and gardening** efforts as they have sufficient surface area provided for attachment.

Figure 138.
Locations of sites where Reef Balls were used for coral reef restoration (Barber, 2024). Source: Shu Kiu Leung, The University of Queensland

What realistic outcomes can we expect?

> Reef balls are generally recognised as effective fish aggregation devices, but coral reef recovery outcome varies. Under suitable conditions, natural coral recruitment may be observed on Reef Ball surfaces in the short term (<1 year), with coral cover increasing over time.

There is limited research on Reef Ball's effectiveness for reef restoration despite it has been extensively used worldwide (Meesters et al., 2015). Most studies tend to concentrate on fish abundance, rather than indicators of reef recovery such as coral recruitment. While there is some grey literature, such as monitoring reports and presentations, these are not readily accessible, making it difficult to deduce a general trend of expected outcomes. The results presented in this section are based on the scarce available data, including anecdotal evidence.

Fish aggregation is well-documented for Reef Balls in both scientific and grey literature (Folpp et al., 2013; Sherman et al., 2002; Society for Ecological Restoration, 2024). Reef Balls, especially when grouped in clusters of 3 or 4 (similar to a coral bommie), may provide fish shelter from currents (**Lennon**, pers. comm.). Also, the inner voids, with their multiple entrances, ensure good water exchange and provide protection from predators. Short-term observations (~1 year) often report rapid increases of fish diversity and abundance, despite potential differences in assemblage compared to natural reefs (Folpp et al., 2013; Mills et al., 2017). For example, Folpp et al. (2013) reported that fish assemblages at the Reef Ball site in Lake Macquarie may differ significantly from nearby rock reefs due to factors such as reef isolation and species-specific behaviour.

There are varied results regarding coral recruitment on Reef Balls. The roughened surface of Reef Balls is expected to encourage more coral recruits than ordinary concrete (Bachtiar & Prayogo, 2010). However, no studies have systematically compared Reef Balls with other concrete structures. A study in Indonesia found that 3 years post-deployment, recruit numbers on Reef Balls ranged from 1 to 76 colonies per unit, primarily growing on the outer vertical surface and upper side (Bachtiar & Prayogo, 2010).

Figure 139.
Pallet Ball manufactured by Reef Ball Australia in New South Wales. Source: Reef Ball Foundation (www.reefball.org). Retrieved from https://www.reefball.org/album/index.html.

Figure 140.
A crane lowering a Reef Ball into the water at Cherokee Reservoir. Source: Reef Ball Foundation (www.reefball.org). Retrieved from https://reefballfoundation.org/reef-ball-world-images/

The diameter of these colonies varied between 5 to 290 mm. Anecdotal evidence also suggests a lack of hard coral recruitment on Reef Balls, possibly due to competition from sponges and fire coral, and suboptimal material texture (Meesters et al., 2015). Site-specific factors such as depth, sedimentation, substrate type, and fish grazing patterns, also play significant roles in coral recruitment on Reef Balls.

For example, Bachtiar and Prayogo (2010) observed low recruit numbers at 10 m depth (1-5 colonies per ball), while Kojansow et al. (2013) reported optimal recruitment rates between 5 to 15 m depth, and optimal diversity at 20 m depth after 14 years of monitoring. Kojansow et al. (2013) also demonstrated an increase in coral cover on Reef Balls over the monitoring period (Figure 141).

Figure 141. Coral growth on Reef Balls: **(a)** Initial deployment; **(b)** recruits and encrusting organisms observed on Reef Ball surface at 1 year; **(c)** hard coral colonies observed at 5 years (growth extent varies by site); **(d)** Reef Balls remain visible at 10 years; **(e)** Reef Balls at 14 years. Source: Jerry Kojansow; Adapted from "Coral Species Diversity on Reef Balls at Ratatotok Waters North Sulawesi, Indonesia: A 14 Years Observation" by Kojansow et al. (2013)

Table 18. Pros and cons of Reef Balls (Meesters et al., 2015; Reef Innovations, 2023).

Pros	Cons
Similar to concrete blocks, but also: • By mixing in silica, the pH is reduced, making it more eco-friendly due to the decreased use of Portland cement. • The wavy bottom and interconnecting holes not only provide habitat for marine organisms but also generate eddy currents, creating an ideal environment for filter feeders.	**Similar to concrete blocks, but also:** • The production of Reef balls requires a specific mould, making the process potentially more labour-intensive and time-consuming.

Materials

The Reef Ball Foundation has developed an adjustable concrete mixture specifically for the construction of Reef Balls. This mix, which includes micro-silica and a variable amount of Portland cement, is designed to achieve appropriate pH levels and allows for deployment within 24 to 48 hours of construction (Bachtiar & Prayogo, 2010; Harris, 2007). However, it is recommended that three to four weeks of curing is allowed before deployment so that units reach maximum strength (Lennon, pers. comm.).

A lower concrete pH is thought to encourage the settlement of a wide range of sessile organisms while also being less toxic to marine organisms (Perkol-Finkel & Sella, 2014). For inexperienced users, particularly for island projects or beginners without help from the Reef Ball Foundation or contractors, a higher Portland cement content is recommended to ensure the strength of the Reef Balls and prevent fracturing during handling (Lennon, pers. comm.; Reef Ball Foundation, 2017). To ensure good pH neutralization, the organisation recommends the use of fresh cement, thorough mixing, and optimal curing conditions (high humidity for at least 30 days). However, as discussed in the concrete blocks section, despite ongoing debates about the potential benefits of reduced pH levels on recruitment, a systematic study has shown that these effects are minimal and only significant during early colonisation (Hsiung et al., 2020).

Size and configuration

Reef Balls are available in a variety of sizes to accommodate different needs. Their heights range from 0.2 m to 1.8 m, and custom sizes can be made to order (Reef Innovations, 2023). The Reef Ball Foundation (2017) mandates that the use of Pallet Ball and larger sizes, which measure between 1.22 m to 2 m in width and 1 m in height per unit, requires special training.

These structures are typically deployed in clusters. It is recommended to use various sizes and shapes of Reef Balls to enhance the aesthetic appeal and structural complexity of the site (Tallman, 2006). In New South Wales, Victoria and Queensland, Australia, Reef Balls are deployed in groups of at least four, either touching or spaced no more than 2 m apart (Lennon, pers. comm.), providing fish with additional protective gaps against predators.

Box 10.

How are reef balls made?

Concrete is poured into an assembled mould with an inflated buoy in the middle to create a hollow space (Harris, 2007). Small balls of various sizes are attached to the mould to create external holes. After the concrete solidifies, the buoy and small balls are deflated and removed (**Figure 142**). Finally, the surface of the Reef Balls is roughened (Bachtiar & Prayogo, 2010).]

Figure 142. Construction of Reef Balls. Source: Reef Ball Foundation (www.reefball.org). Retrieved from https://www.reefball.org/album/index.html

Costs and maintenance

As per the latest price sheet from Reef Innovations (2017), the wholesale price for their models varies. The smallest model, the Oyster Ball, is priced at approximately US$38 (~A$60), while the largest model, the Goliath Reef Ball, costs around US$625 (~A$960). On average, the material cost of Reef Balls for reef restoration is about ~US$40/m^2 (~A$53/m^2) (Fox et al., 2005). However, it is important to note that these costs only account for materials and do not include transportation and labour expenses. These prices also would have increased due to inflation. In 2020, The cost of manufacture, delivery, and deployment of a 280 kg Bay Ball, as supplied for recreational fishing reefs in Australia, was approximately A$480 per unit (**Lennon**, pers. comm.).

Nevertheless, concrete prices can vary by area due to supply differences. For example, the cost for each m^3 of high-strength marine concrete is around A$580 per m^3 on the East Coast of Australia, while the cost can reach up to A$1,500 per m^3 in Western Australia (**Lennon**, pers. comm.), significantly increasing overall costs.

Similar to **other concrete structures**, maintenance for Reef Balls is generally minimal and depends on site conditions. Common maintenance tasks, such as algal and predator removal, can contribute to the overall cost.

EcoReef™ modules

Patented EcoReef modules are artificial reef structures designed to have a natural appearance, support reef fish and corals, and be cost-effective for large-scale restoration projects (Moore & Erdmann, 2002). These snowflake-shaped structures have been deployed in Indonesia, the Philippines, Qatar, and Jamaica (Moore & Erdmann, 2002; Pappagallo, 2012; Seacology, 2024a).

A notable example is their use in Manado Tua Island in Bunaken National Park, Indonesia, where large areas of reefs were reduced to rubble due to blast fishing. Here, EcoReef modules were specifically deployed for the purpose of stabilising loose rubble (Seacology, 2024b).

Scale of implementation

Small-scale community projects were carried out by locals and non-profit organisations. These projects usually cover small to medium areas of up to a few hectares, deploying up to a few hundred modules. For instance, on Manado Tua Island, 620 EcoReef modules were deployed on a degraded reef slope to create an artificial reef covering 1200 m^2 of area within the local "no-take" zone (5 acres, or ~20,000 m^2) (Razak, 2010; Seacology, 2024b) (see also **case study 9**).

This project was funded by Seacology, an environmental NGO, and supported by the Bunaken National Park management authority, the North Sulawesi Water Sports Association, and local communities (Morris et al., n.d.). Similarly, in Tres Marias, 600 EcoReef modules were used to aid in coral growth and reef restoration (Seacology, 2024a).

How does this method help reef recovery?

EcoReef modules provide an elevated platform for coral recruitment, and their branching morphology provides habitats for small fishes (Moore & Erdmann, 2002). Settling plates in the middle of each module create a shaded environment that encourages coral recruitment. They may also help moderate water flow and trap rubble between branches which helps to stabilise rubble beds. Over time, the EcoReef modules would fragment and integrate into the reef or help establish new coral colonies.

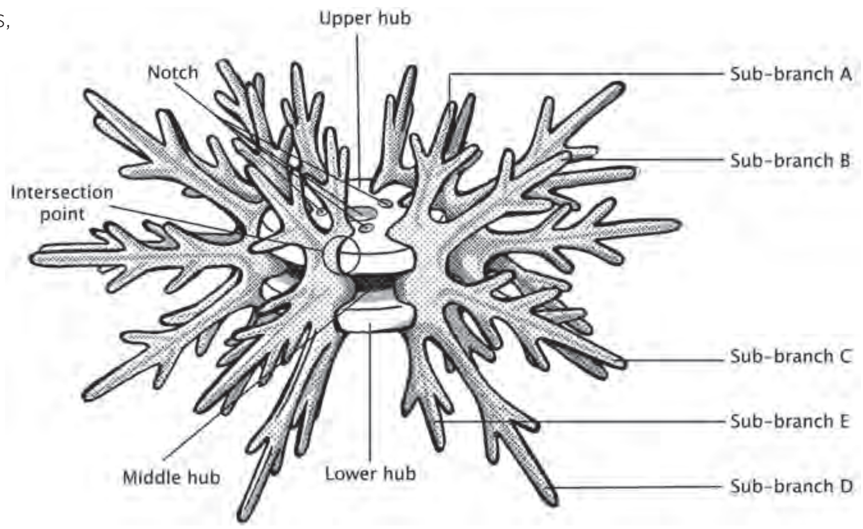


Figure 143. Diagram of a snowflake-shaped EcoReef module. Adapted from "Study on Marine Invertebrates Growing on Ceramic-based Artificial Reefs (EcoReef) and Reef Fish Populations at the Blast-damaged Reef Rehabilitation Area in Bunaken National Park, North Sulawesi, Indonesia" by Razak (2010)

When and where?

Although EcoReef modules were designed for placement in a variety of locations, including slopes (Tallman, 2006), long-term monitoring has indicated that flat areas may be more suitable. This is due to the potential instability of modules on steeper slopes, which could lead to breakage or loss (Tries Razak, IPB University, pers. comm.). Furthermore, EcoReef modules may not work well in high-energy environments as their branching morphology could make them prone to fragmentation. Therefore, when the goal is to restore rubble beds and increase fish populations, it might be beneficial to place them in calmer, flat areas.

Implementation Strategy

EcoReef modules are transported to designated sites using boats and are manually deployed and arranged by divers. Coral fragments can be attached to the branches of the modules using cable ties (Moore & Erdmann, 2002). According to Moore and Erdmann (2002), the transplanted fragments can quickly adhere to the structure and will resume growth within a few weeks.

Figure 144.
Locations of sites where EcoReef modules were deployed.
Source: Shu Kiu Leung, The University of Queensland

What realistic outcomes can we expect?

In the short term (<1 year), EcoReef modules may promote coral recruitment and increase the abundance of fish and benthic invertebrates (Seacology, 2024b). Over a longer period, they may help to increase coral cover, fish diversity, and have a higher likelihood of rubble binding (Razak, 2010; Razak, pers. comm., Seacology, 2024a).

However, these outcomes can vary as the modules are susceptible to breakage, which can diminish their effectiveness.

While there is a single long-term monitoring study providing high-quality data on the use of EcoReef modules for stabilising rubble fields (see **case study 9**), the majority of the data remains unpublished or is sourced from NGOs. There is a high degree of uncertainty regarding how widely these outcomes can be expected in other scenarios.

Three weeks post-installation in Manado Tua, strong currents expedited the establishment of coral recruits, transplants, and fish, two to three times faster than anticipated (Seacology, 2024b). According to Seacology, within two months, the modules were covered with CCA, bryozoans, serpulid worms, and coral recruits, and a diverse range of fish had moved in. After a year, the modules became integrated into the reef framework, hosting approximately 20 recruits per module. Similar increases in fish abundance, benthic invertebrates, and coral cover have been observed in other regions.

Table 19.
Pros and cons of EcoReef Modules (Moore & Erdmann, 2002; Morris et al., n.d.; Pappagallo, 2012; Razak, 2010).

Pros	Cons
• The ceramic material has chemically inert, non-toxic, and microporous properties, which promotes coral recruitment. • The branching shape provides a large surface area for coral recruitment. • The modular design allows for deployment flexibility, with as many or as few structures used as needed, or arranged in different formations, depending on the size of the site, site layout and restoration goals. • Provides a stable settlement surface area raised above the substrate level, potentially reducing the impacts of sedimentation and competition on coral recruitment. • Provides habitat, including crevice spaces, for fish and invertebrates.	• Ceramic is fragile and the branching design makes it easy to break. The modules may not withstand high energy and need to be handled with care to avoid breakage before the rubble is stabilised. • Without a healthy population of herbivores to keep the frames clean, they will require maintenance by divers at most sites, particularly in the very early stages post-deployment. • Introduction of foreign materials into the environment can potentially lead to pollution if structures degrade. • There is a risk of damaging benthic organisms during installation.

Case Study 9:

Long-term monitoring of EcoReefs in Bunaken National Park, Indonesia

Background

Located in North Sulawesi, Indonesia, Bunaken National Park was designated as a marine protected area in 1991 (Razak, 2010). It has since evolved into one of the most popular ecotourism and diving hotspots in the country.

Coral reefs on Manado Tua Island, an extinct volcano island in the Bunaken National Park, suffered extensive damage due to blast fishing that begun in the 1970s and peaked in the 1980s (Razak, 2010; Seacology, 2024b). Even though the bombing activities stopped, the reefs did not show much recovery as the decades passed. Baseline surveys conducted in 2003 showed the damaged rubble site had significantly lower fish diversity and coral cover than a typical healthy reef (Moore et al., 2003).

Hard coral cover at damaged sites was under 1%, far below the 2001 park-wide average of 38.8%. Recruits were found on the rubble, but they were small (diameter of 40-70mm) and sparse (<10/m²).

As a result, EcoReef modules were deployed in an attempt to rehabilitate the damaged reefs. The project hoped to bring back the economic benefits of local fishing, which is essential for food security and income generation (Morris et al., n.d.). The modules were also intended to reduce fishing and tourism pressure on nearby healthy reefs, ensuring their long-term protection.

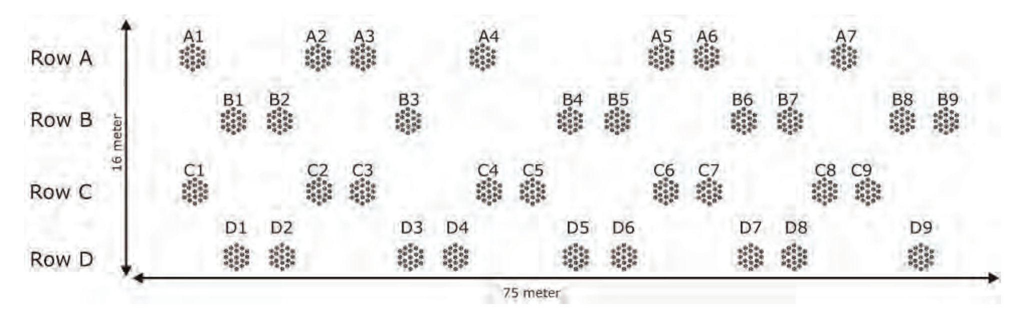


Figure 145. Layout of 620 EcoReefs modules installed on the rehabilitation site at Manado Tua Island. Adapted from "Study on Marine Invertebrates Growing on Ceramic-based Artificial Reefs (EcoReef) and Reef Fish Populations at the Blast-damaged Reef Rehabilitation Area in Bunaken National Park, North Sulawesi, Indonesia" by Razak (2010)

Design and deployment

A pilot test was conducted in October 2001, and it received positive feedback from dive operators and achieved key biological milestones (Morris et al., n.d.). These included the quick formation of a fouling community, reef fish community acceptance, algae control by resident herbivorous fish, and successful coral transplantation and recruitment.

Following the success, the project team scaled up the effort and installed 620 EcoReef modules in December 2003 at Muka Gereja, located in front of the Negeri Village on Manado Tua Island (Razak, 2010). This deployment marks the first extensive use of EcoReefs in the Indo-West Pacific region. The site features a sloping fringing reef descending to 12-13 m with the substrate primarily comprises of loose rubble and sand. The reef is characterised by strong currents and adjacent live corals.
At the site, EcoReef modules were organised into 34 clusters of 19, each numbered and anchored across four rows in a 1200 m² area (**Figure 145**). Each row corresponds to a depth: Row A (2.5-4m), Row B (4-6m), Row C (6-8m), and Row D (8-10m).

Results/findings

A 20-year monitoring study was conducted to compare the restoration outcomes at the Manado Tua EcoReef site with nearby control rubble beds in Tawara, Fukui, and Siladen, which had similar conditions but without intervention (**Figure 146**).

Of the 69 modules monitored between 2006-2010 (6 years post-installation), hard corals made up 19.4% of marine invertebrates, with soft corals (42.9%) and sponges more prevalent (Razak, 2010). Healthy hard coral populations declined over this period, with soft corals becoming more common, especially on the upper row modules. Of all the corals, 79% were juveniles, averaging 4.83 cm in length and 3.45 cm in width. Less than half (47.5%) of the hard corals were alive and healthy.

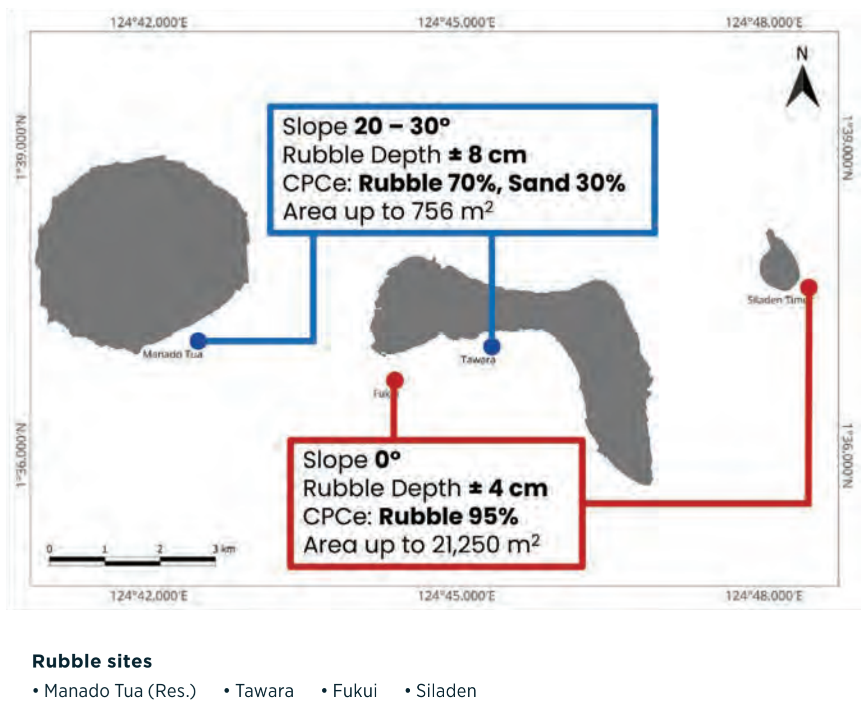


Figure 146.
Restoration (Res.) and control rubble sites monitored in the study. CPCe is a program that helps to determine benthic cover using transect photographs. Source: Tries Razak

Symptoms of bleaching (Figure 147) and coral diseases were notably observed, with smaller colonies being particularly affected, potentially due to the presence of CoTS (Figure 148). Interestingly, the majority of new recruits favoured the upper branches for settlement, which could be attributed to the lower intensity of sunlight and higher sediment accumulation found in the lower parts.

On the positive side, the modules have been extensively used by a diverse range of fish. The monitoring program showed that EcoReefs attracted a total of 1,068 reef fish from 92 species and 24 families. These fish have been observed at depths of 3, 6, and 9 metres, and half of them are small fish that are less than 5 cm long. Most importantly, 41.9% of these fish have commercial value for consumption, and 77 of the species are popular in the aquarium trade.

Over 20 years, the study found a statistically significant difference in the probability of rubble pieces binding together between the natural rubble bed and the restoration area (Razak, pers. comm.). However, this difference was not huge – the probability of binding in the restoration site was about 20%, compared to an average of around 15% in the three surveyed natural rubble sites. In other words, while the restoration effort did result in a measurable improvement in rubble binding, the magnitude of this improvement was modest.

A variety of binding organisms, including Bryozoans, CCA, hard corals, soft corals, sponges, and turf algae, were observed in the restoration sites. Despite the observed rubble binding and the presence of binding organisms at the restoration site, there was no evidence to suggest that the rubble bed's stability had increased. However, the restored site did show a higher abundance and diversity of fish, including carnivorous, corallivorous, herbivorous, omnivorous, and planktivorous species.

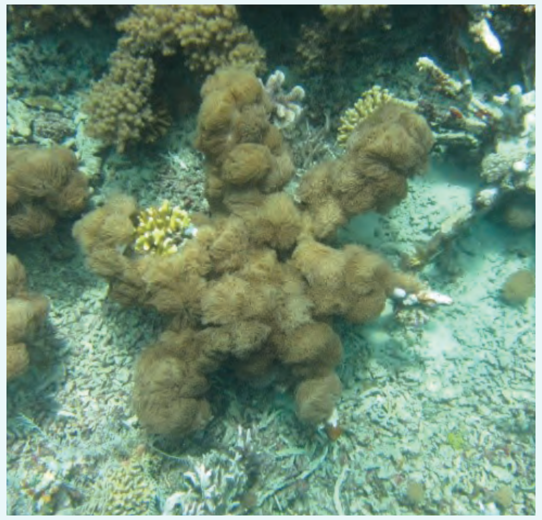
Left: Figure 147. A half-bleached colony of *Pocillopora verrucosa* on the tip of module's branch.
Right: Figure 148. Crown-of-thorns starfish feeding on juvenile hard corals on EcoReef modules.

Adapted from "Study on Marine Invertebrates Growing on Ceramic-based Artificial Reefs (EcoReef) and Reef Fish Populations at the Blast-damaged Reef Rehabilitation Area in Bunaken National Park, North Sulawesi, Indonesia" by Razak (2010)

The restoration site, located on a steep (20-30 degrees) and deep (around 8 m) slope, may not have been the best choice. Over the years, structures were lost or broken (only 475 out of 620 remained by 2023), especially those located in deeper areas. The EcoReef modules in the shallower areas were dominated by soft corals, which outgrew the hard corals (Figure 149). Only the modules at mid-depth were observed to have coral recruits growing on top of the structures, but not on the rubble (Razak, pers. comm.).

Lesson learned:

- EcoReef modules could be effective fish aggregators and help to increase fisheries value.
- Sites on steep and deep slopes may not be ideal due to the risk of breakage and structure loss.
- Long-term monitoring is beneficial for assessing the success of restoration efforts and detecting ecological changes that cannot be captured in short-term monitoring.



Top left: Figure 149. A large amount of soft coral colonies has covered almost an entire EcoReef module. Adapted from "Study on Marine Invertebrates Growing on Ceramic-based Artificial Reefs (EcoReef) and Reef Fish Populations at the Blast-damaged Reef Rehabilitation Area in Bunaken National Park, North Sulawesi, Indonesia" by Razak (2010)

Top right: Figure 150. EcoReef modules are still visible 20 years after installation at the restoration site. Source: Idris, The Indonesian Coral Reef Foundation

Bottom left: Figure 151. Close-up photo of EcoReef modules showing some hard coral growth on the structures. Source: Idris, The Indonesian Coral Reef Foundation

Over the long term, observations have shown varying success of the method. For example, a 2014 visit to Tres Marias suggested that nearly a decade after installation, the modules were almost indistinguishable and covered in corals (Seacology, 2024a). On the other hand, a long-term monitoring study conducted in Bunaken National Park revealed less favourable outcomes (case study 9).

Materials

EcoReefs are constructed from unglazed ceramic (Moore & Erdmann, 2002). According to Moore and Erdmann (2002), this material is particularly suitable for invertebrate settlement due to its chemically inert, non-toxic nature, and its microporous texture.

Size and configuration

An EcoReef module is a composite of six Branch elements and two Hub elements (EcoReefs, 2012). The elements are assembled into EcoReef modules using high-strength plastic band clamps or marine-grade epoxy.

The standard dimensions for a module are a diameter of 92 cm and a height of 42 cm. A single module covers a reef area of 0.67 m^2 and offers a surface area of 1.27 m^2. The modular design of EcoReef modules provides flexibility in their configuration on the reef, although they are typically arranged in clusters (Figure 152).

Costs and maintenance

The cost-benefit analysis of EcoReef reveals that the estimated cost per settled organism is around US$2 (Pappagallo, 2012). Overall, the deployment of EcoReef modules costs around US$70/$m^2$ when implemented on a scale of 1000 to 10,000 m^2 (Morris et al., n.d.).

Maintenance tasks, such as algae removal and repositioning of modules, are necessary and typically on a monthly basis. The frequency of these tasks is higher during the first few months following deployment. After this initial period, the need for maintenance visits tends to decrease.

Figure 152. EcoReef modules were arranged in clusters and deployed at Manado Tua Island, with each cluster containing 19 modules. Note that the photo was taken 20 years after installation, so some modules were damaged or lost. Source: Idris, The Indonesian Coral Reef Foundation

Source: Peter Mumby

Propagation of corals and sponges

Deploying **marine organisms like corals and sponges** often serves as a **supplementary approach** to directly manipulating the substrate and/or introducing structures to restrict rubble movement or provide an alternative stable substrate.

This section explores how coral transplantation and gardening can kick-start coral growth on rubble beds, and how using sponges as binding agents can accelerate the consolidation process of rubble.

Coral transplantation and gardening

Sometimes, physical methods like directly stabilising the rubble substrate and adding structures are insufficient on their own. In such cases, biological methods, namely coral transplantation, and gardening, can be employed.

The concept of coral transplantation for restoration purposes first emerged in grey literature in 1979 (Boström-Einarsson et al., 2020a, 2020b). Coral transplantation, as the pioneering concept in active restoration, also became the most commonly used approach (Boström-Einarsson et al., 2018). It essentially mimics the asexual reproduction process, where corals naturally grow from broken pieces. Over time, this technique has evolved into what is now known as coral gardening. This concept, which surfaced in 1997, was inspired by silviculture – a practice of planting trees in forests (Rinkevich, 2014). In addition to transplanting corals in restoration sites, coral gardening includes an intermediate nursery phase where corals are "farmed" and grown to suitable sizes before transplantation.

In this section, we briefly discuss coral transplantation and gardening as complementary techniques to other physical methods in the context of rubble stabilisation. These techniques are typically not used in isolation, as corals are attached onto structures or stabilised substrates. In less common cases, corals are treated as stabilisers and placed directly onto loose rubble (Rojas Jr et al., 2008).

Scale of implementation

Coral transplantation and gardening are often done on small scales of a few hundred square metres due to logistical challenges and prohibitive costs.

How does this method help with recovery?

Coral transplantation and gardening aid in recovery by introducing new corals to stabilised areas, promoting diversity and accelerating reef recovery. This strategy effectively bypasses the recruitment bottleneck in areas where there is a low larval supply or high post-settlement mortality (Boström-Einarsson et al., 2018; Edwards & Gomez, 2007). Transplants, especially those with a branching growth form, increase habitat complexity and rugosity to enhance broader biodiversity (**Nathan Cook**, pers. comm.). Furthermore, these coral colonies may facilitate the stabilisation of remaining rubble, which is achieved by trapping rubble between branches of the transplanted corals.

Read more:

We also recommend readers to consult the **Reef Rehabilitation Manual** (Edwards, 2010) for more detailed guidance on coral transplanting and gardening.

When and where?

To ensure successful coral transplantation, it is crucial to minimise stress on transplants. It might be a good idea to avoid transplanting coral during periods of high sea surface temperatures and spawning seasons, as corals are more susceptible to stress during these times (Edwards & Gomez, 2007).

While transplantation can be done anywhere to speed up recovery, it is most effective in areas with limited recruitment (Clark & Edwards, 1995; Edwards, 2010). If natural recruitment is sufficient and loose substrate is the only limiting factor for reef recovery, then transplantation could be a waste of time and resources.

When transplanting corals onto stabilisation structures, it is best to choose those with vertical relief situated on gentle slopes unless the transplants are of a large size (**Taylor**, pers. comm.). This reduces the risk of abrasion and burial by rubble.

Transplant loss is likely in sites with higher energy, regardless of the attachment method (Clark & Edwards, 1995). Therefore, this method works best in relatively calm environments where wave action and associated storms and currents are minimal (**Nathan Cook**, pers. comm.).

Implementation Strategy

The strategy for coral transplantation and coral gardening involves the following steps (Boström-Einarsson et al., 2018):

1. **Collection**
2. **Transportation**
3. **Nursery phase***
4. **Outplanting (attachment of corals onto structures or substrates).**

The following text intends to serve as a guide only. For the detailed procedures, it is best to consult the relevant permitting requirements to ensure compliance with local legislation, which is particularly important when the method involves handling live organisms. It is also important to ensure personal protective equipment (PPE), such as gloves, is worn when handling corals (Edwards & Gomez, 2007).

*Optional and only for coral gardening

1. Collection

Corals can be harvested from donor colonies or collected from **"corals of opportunity"** using tools such as a hammer and a chisel. When combining coral transplantation with other stabilisation methods, studies prefer using corals of opportunity, which have a higher average survival rate than donor-sourced corals (Boström-Einarsson et al., 2020a, 2020b).

Harvesting fragments may induce stress on donor corals. To mitigate the impact on donor corals, it is recommended to limit collection to a maximum of 10% from each colony and spread the collection over a wide area (Boström-Einarsson et al., 2018; Edwards & Gomez, 2007; Harriott & Fisk, 1988). Additional details about the quantity of corals that can be collected should also take into account the conditions stipulated in permits and local legislation. Usually, only a small proportion of corals, which are of suitable size, are easily breakable at the base and belong to target species that reflect the restoration site, are likely to be collected (Harriott & Fisk, 1988).

Important considerations during the collection of coral fragments are location, species and health of the corals. Introducing new species, genetic variants, or diseases to an area may come with a host of additional problems, so it is recommended that corals are sourced locally from a healthy parent stock.

2. Transportation

During transportation, it is important to keep coral fragments submerged and shaded to prevent drying and UV damage, especially when they are transported over a long distance and duration (>2 hours) (Boström-Einarsson et al., 2018).

3. Nursery phase (coral gardening)

The nursery phase in coral gardening is a more sustainable but relatively costly alternative to harvesting large amounts of corals from donor colonies. Coral fragments are grown to suitable sizes for outplanting after collection, with the appropriate size varying between species (Edwards & Gomez, 2007). These nurseries, usually situated in sheltered waters, protect fragments from disturbances and increase their survival rates following outplanting (Boström-Einarsson et al., 2018). Additionally, nurseries can function as genetic repositories to help reefs recover from large-scale natural disasters (Rinkevich, 2014).

Box 11

Corals of opportunity

(Edwards & Gomez, 2007; Edwards et al., 2024; Edwards, 2010)

Corals of opportunity (**Figure 153**) refers to detached coral fragments found on reefs, which, unless reattached, have a low survival rate. The use of these corals is often less controversial than harvesting from donor colonies, as these fragments would likely die without intervention.

These fragments, often partially dead, require trimming or further fragmentation before transplantation. After trimming, fragments are gently cleaned and further fragmented if necessary.

Once dead or diseased tissue is removed, these fragments can become healthy transplants. However, corals of opportunity may not provide an accurate representation of the natural coral assemblage. These corals are often dominated by branching species that are more prone to fragmentation and less stress-tolerant, which often makes them unsuitable for sites requiring intervention.

Figure 153. Divers collecting corals of opportunity in a basket. Source: Mars Sustainable Solutions

Box 12

In situ or *ex situ* nurseries?

(Boström-Einarsson et al., 2018; Rinkevich, 2006)

Nurseries can be grouped into two categories - *in situ* and *ex situ*. *In situ* nurseries are placed underwater near the restoration site, allowing corals to adapt to natural reef conditions and open to the recruitment of reef organisms. On the other hand, *ex situ* nurseries are isolated, often in sterile laboratory conditions, which supports the survival and growth of small coral material like settled planulae larvae or delicate nubbins. Despite requiring ongoing maintenance, *in situ* nurseries usually result in greater success rates and are more cost-effective. Nevertheless, both methods can yield a substantial amount of material year-round, reducing the need for harvesting corals.

The size of coral fragments plays a crucial role in their growth and survival. Smaller fragments typically require a longer period and more favourable nursery conditions to reach a size suitable for outplanting. The ideal size for transplantation varies with species and site conditions, and while there is no consensus, fragments around 5-10 cm may generally have better survival rates (Edwards & Gomez, 2007). Given optimal conditions, fragments from many coral species can develop into large colonies within 1-1.5 years (Rinkevich, 2014).

The construction of coral nurseries involves a variety of materials and designs (**Figure 154**), each with its own benefits and drawbacks. Materials such as PVC pipes, metal frames, and ropes are commonly used for their durability underwater (Boström-Einarsson et al., 2018). However, each material presents certain risks: plastics can introduce pollution; metals may rust without a protective coating; and wires or ropes can entangle marine life and sag as corals grow larger. While most coral nurseries are built at or near the sea bottom in shallow reef areas, some research suggests the use of mid-water floating nurseries (Rinkevich, 2006).

Figure 154. Examples of different coral nursery designs. **(a)** a tree-shaped nursery; **(b)** coral ropes; and **(c)** PVC frames.
Source: (a) NOAA (2014a); (b) Andrew Taylor, Blue Corner Marine Research (c) Kee Alfian Bin Abdul Adzis

4. Outplanting (attachment of corals)

During outplanting, spacing is crucial to prevent conflicts between individuals, both within and across species, thereby preventing significant damage and hindered growth (Rinkevich, 2014). An experimental study that compared various outplanting strategies for *Acropora cervicornis* colonies revealed that plots with lower transplant densities exhibited significantly higher survival rates (Goergen & Gilliam, 2018). They also had a significantly lower incidence of disease, predation, and missing colonies compared to plots with higher densities. Therefore, it is recommended to transplant colonies at densities of approximately 3 colonies/m^2 while preserving their original orientation (Boström-Einarsson et al., 2018).

Secure attachment of transplants is important to encourage self-attachment to structures or substrates over time, as even small movements can inhibit self-attachment (Boström-Einarsson et al., 2018). Common attachment methods include chemical adhesives like cement or epoxy, cable ties, or metal wires (**Figure 155**) (Boström-Einarsson et al., 2020a; Edwards & Gomez, 2007; Suggett et al., 2020). Epoxy is the most used method, with about 60% of projects using it or cable ties (Boström-Einarsson et al., 2020a). (Boström-Einarsson et al., 2020a; Edwards & Gomez, 2007; Suggett et al., 2020). Epoxy is the most used method, with about 60% of projects using it or cable ties (Boström-Einarsson et al., 2020a). A study tested 3 different attachment techniques – epoxy, nail and cable tie, and puck – on *Acropora cervicornis* colonies across 3 different sites (Goergen & Gilliam, 2018).

Figure 155. Examples of different attachment methods. **(a)** corals secured to a Mars Reef Star using cable ties; **(b)** coral attached to a metal mesh using wires; **(c)** corals embedded in a cement mixture that hardens over time and then placed onto concrete blocks; and **(d)** corals wedged directly into the rubble bed.
Source: (a) Mars Sustainable Solutions (b) Nathan Cook; (c) David Palfrey and Julian Atkins, TRACC Borneo; (d) John Edmondson

Box 13

Coral transplants as rubble stabilisers

(Rojas Jr et al., 2008)

Two species of **corals of opportunity**, *Porites rus* and *Porites cylindrica*, were transplanted to a 50-year-old rubble bed in Guam to test their effectiveness as rubble stabilisers. After a 12-week acclimation period in a nursery, 15 colonies of each species were fragmented and cemented to rubble pieces using epoxy. Over the course of 3 months, the coral tissue began to overgrow the epoxy and rubble. Surprisingly, *P. rus* demonstrated a survival rate of 93.3% and a mean basal growth of 0.8 mm per month, overgrowing the rubble within six months. In contrast, only 23.3% of *P. cylindrica* survived, with a mean basal growth of 0.07 mm per month. The findings suggest that live coral transplants, particularly *P. rus*, can stabilise rubble in low-energy environments. However, the success of *P. rus* may not solely be attributed to its growth form, which includes upright columns and basal plates, but also to its potential for adjusting to new conditions.

The study found that colonies attached with a nail and cable tie had the highest survival rate, irrespective of the colony size. However, it is important to note that plastic-based methods (epoxy and cable ties) may degrade in warm, shallow, and high-UV environments (Boström-Einarsson et al., 2020a). Alternative attachment methods include wedging fragments into reef openings to minimize cost. Larger, branching colonies can be directly inserted into loose rubble substrate, which will likely remain stable without the need for adhesives (**Nathan Cook**, pers. comm.). Below is an example of a case where corals are transplanted onto rubble beds as stabilisers (see **Box 13**).

Figure 156.
Coral fragment attached to the substrate using a Coralclip®.
Source: John Edmondson, Wavelength Reef Cruises

In addition to the attachment devices previously discussed, a new tool called Coralclip® has emerged in recent years (**Figure 156**). Coralclip® was developed in 2018 as a novel, cost-effective solution for coral transplantation. This device was tested as part of the Coral Nurture Program, a research project funded by the Australian/Queensland Government and partnered by UTS and tourism operators (Suggett et al., 2020). Coralclip® is designed around a torsion spring clip and a masonry nail, which securely hold fragments in place. It is considered a low-cost (US$2.34 per coral per trip on average) and less time-consuming solution for deployment (Scott et al., 2024).

Ultimately, the optimal way to attach transplants may depend on factors including environmental conditions (e.g. exposure to waves and currents), the size and growth form of the transplant, material availability (Boström-Einarsson et al., 2018; Edwards & Gomez, 2007), and permitting restrictions.

What realistic outcomes can we expect?

In locations where coral larval supply is insufficient, combining coral transplantation and gardening with other stabilisation methods may accelerate the rate of reef recovery. However, coral transplantation might not be as effective when used independently on a loose rubble bed.

Most studies to date focus on the survival and growth of transplants, rather than overall coral recovery metrics (Boström-Einarsson et al., 2020a). The results of transplantation and gardening can vary significantly. In a comprehensive synthesis by Boström-Einarsson et al. (2018), the overall average survival rate of corals in restoration projects was 69%, with most genera falling within the 60-70% range.

We can anticipate increased recovery rates with the aid of coral transplants. When combined with coral transplantation and gardening, the time until benefits can be reduced for most rubble stabilisation methods (Ceccarelli et al., 2020).

In optimal scenarios, combining transplantation with structures like meshes can significantly increase coral cover in 1-2 years. Without transplantation, this process could take 4-5 years. However, there were cases where transplantation did not make much difference. In a study in the Maldives, using concrete mats to stabilise rubble and transplanting corals was not cost-effective due to the lack of clear benefits over a period of 5-10 years (Clark & Edwards, 1995). The findings suggested that natural recruitment alone was sufficient, and there would not be much difference between transplanted and control areas 5 to 7 years post-deployment.

Reef recovery will be slower if coral transplantation or gardening is used as a standalone method. For example, a restoration project in Koh Tao involved growing corals in nurseries to large sizes (>20 cm diameter) before directly transplanting them onto a loose rubble field (**Figure 157**). Live coral cover at the restoration increased from less than 5% to well over 50% 5 years after deployment (**Figure 158**).

Figure 157.
Large coral colonies grow in in situ nursery pre transplantation.
Source: Nathan Cook

Table 20.

Pros and cons of coral transplantation and gardening (Boström-Einarsson et al., 2020a; Ceccarelli et al., 2020; Edmondson, pers. comm.; Edwards & Gomez, 2007; Nathan Cook, pers. comm.; Rinkevich, 2014).

Pros	Cons
• Instant increase in coral cover. • The time to yield results can be sped up for most techniques by transplanting corals onto the artificial structures. • Transplantation efforts can be easily adjusted to suit specific needs, such as maintaining employment during off-season or responding to storms. • Increases structural complexity and rugosity to attract fishes and invertebrates. • Nursery phase ensures coral colonies are large enough for successful transplant and produces hundreds of small colonies from a few, promoting sustainability. • If farmed *ex situ*, corals may be healthier and free from parasites and diseases.	• Limited scalability due to the intensive nature of the process. • May risk introduction of coral disease into the ecosystem. • High costs and labour-intensive, which may not be worth it if the site is not recruitment limited. • Harvesting may damage source colonies and compromise source reefs if coral cover is already low. • Some species may be less suitable for transplantation due to their growth forms and slow growth rates. • Nursery phase (if applicable) requires significant maintenance efforts

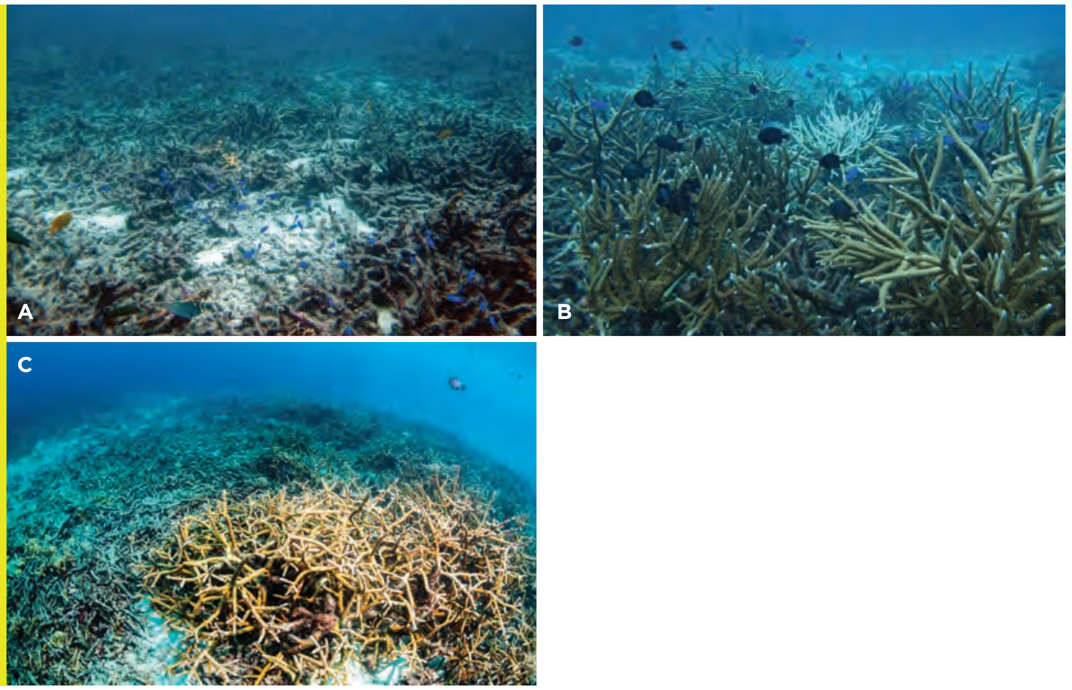


Figure 158.

Coral transplantation project at Twins, Koh Tao, Thailand.

(a) Rubble location before transplantation,

(b) Individual coral colonies attached to rubble substrate 1 year after transplantation from coral nursery, and

(c) Restored area (bottom right corner) 3 years after transplantation.

Source: Nathan Cook

Materials

The choice of corals is critical for project success. Ideal candidates for transplantation would be fast-growing, use fragmentation for reproduction, be resistant to stress with excellent healing abilities, be representative of local species, and be resilient to long-term climate change impacts (Boström-Einarsson et al., 2018; Clark & Edwards, 1995; Rinkevich, 2006, 2014). Fast-growing branching species are often chosen as they can be easily collected and provide diverse coral material types (e.g. single branches, nubbins, small colonies) (Rinkevich, 2014). They also help in rapidly increasing coral cover and topographic complexity (Edwards & Gomez, 2007). However, other species representing the local coral assemblage could also be considered, as branching corals may be more susceptible to bleaching, transplantation stress, and diseases.

Genetic diversity is another key to success. Different genotypes within the same species can show varying susceptibility to environmental stress such as thermal bleaching (Baums, 2008). As climate change poses significant threats to reefs worldwide, nurseries are encouraged to cultivate heat-tolerant genotypes (Caruso et al., 2021; Morikawa & Palumbi, 2019; Shaver et al., 2020). This can be challenging due to the technical knowledge required, but sourcing fragments from **"corals of opportunity"** or taking a small portion from various donor colonies can help ensure genetic diversity (Edwards & Gomez, 2007). Furthermore, it is important for nurseries not to dismiss certain genotypes that are considered "weaker" or less productive, as what appears "weak" in one context may be advantageous in another (Boström-Einarsson et al., 2018). Including a range of genotypes can contribute to the overall resilience and adaptability of coral populations.

Given the various trade-offs between the ideal characteristics, it is nearly impossible to find a single coral species that is particularly suitable for transplantation (Clark & Edwards, 1995). A more effective strategy is to transplant a mix of species and genotypes that reflects the natural assemblage and to avoid over-reliance on branching species (Edwards & Gomez, 2007). Another added benefit of this mixed-species approach is its ability to attract a greater variety of fish, despite competitive effects between coral species that may result in slower initial growth rates (**Taylor,** pers. comm.).

Costs and maintenance

The main expense of coral transplantation is labour, with additional costs for boat operations, diving gear, and some equipment for handling corals (Harriott & Fisk, 1988). Costs and time-efficiency calculations may vary by species, location, and procedures and it is hard to generalise (Forrester et al., 2019). It is encouraged to evaluate the costs and benefits of different protocols on a case-by-case basis. For example, a study by Forrester et al. (2019) in the Caribbean, near the British Virgin Islands, found that although the nursery method and direct transplantation had comparable transplant survival rates, the former was found to be more costly and time-intensive.

According to Bayraktarov et al. (2019), overall median costs for direct transplantation are approximately US$22/$m^2$ (~A$23/$m^2$) and US$35/m^2 (~A$38/$m^2$) for coral gardening, assuming 4 colonies were planted per square metre. Please note that these figures are from 2010 and may have been affected by inflation. The material costs per transplant would be approximately US$0.1-0.2 at a spacing of 0.5 m (Edwards & Gomez, 2007).

Maintenance, especially in the nursery phase, is crucial to keep the nursery free of pests and fouling organisms (Boström-Einarsson et al., 2018). This includes removing algae and predators, excising diseased tissues, and replacing dead transplants. These are most frequent in the first few months of deployment, with the frequency reducing over time.

Sponge seeding

Sponge seeding is another biological technique aimed at stabilising loose rubble generated following local reef damage. The method has only been tested in small-scale studies in the Caribbean, including at Curaçao and San Blas Islands, where sponges are prolific (Biggs, 2013; Wulff, 1984).

How does this method help with recovery?

Sponges play an important role in the preliminary binding process by holding rubble stable until stronger, more permanent binders like CCA and corals can grow over the pieces and facilitate subsequent consolidation processes (Kenyon et al., 2023a; Rasser & Riegl, 2002; Wulff, 2016). Within 2 to 4 days, erect, branching forms of sponges can attach to rubble pieces, and bridge across to other rubble pieces within a few months (Biggs, 2013). Providing there are still sufficient cryptic spaces and surface areas for settlement (i.e., sponges do not cover the entire surface), the resulting stable rubble can be an appealing substrate for coral recruits.

When and where?

Given the limited number of studies conducted on sponge seeding, we do not have a comprehensive understanding of the most suitable environments for this method. However, based on the available data, we can make some informed suggestions.

Rubble beds with relatively smaller pieces are ideal for sponge seeding, particularly in relatively flat areas (Wulff, 1984). Smaller rubble pieces can be bound by smaller fragments of sponges, which are more easily harvested in higher numbers. and used in this method. On steeper slopes, the binding strength of sponges may not be sufficient to hold the rubble together, resulting in the rubble rolling down to form a talus at the base (Wulff, 1984). Water depth and motion are key to sponge seeding, with shallow and relatively sheltered areas being preferred (Biggs, 2013; Wulff, 1984). While high-energy environments might disturb and lead to the loss of sponge-seeded rubble, it has been found to withstand occasional extreme weather events such as tropical storms Felix in 2007 and Omar in 2008, if sponges are sufficiently established in the bed (Biggs, 2013).

Not all sponges bind rubble, and the correct "rubble-binding sponges" to target are discussed below. Areas that already have suitable sponges growing nearby to the disturbed area are most suited to this method, because introducing foreign sponge species is highly undesirable.

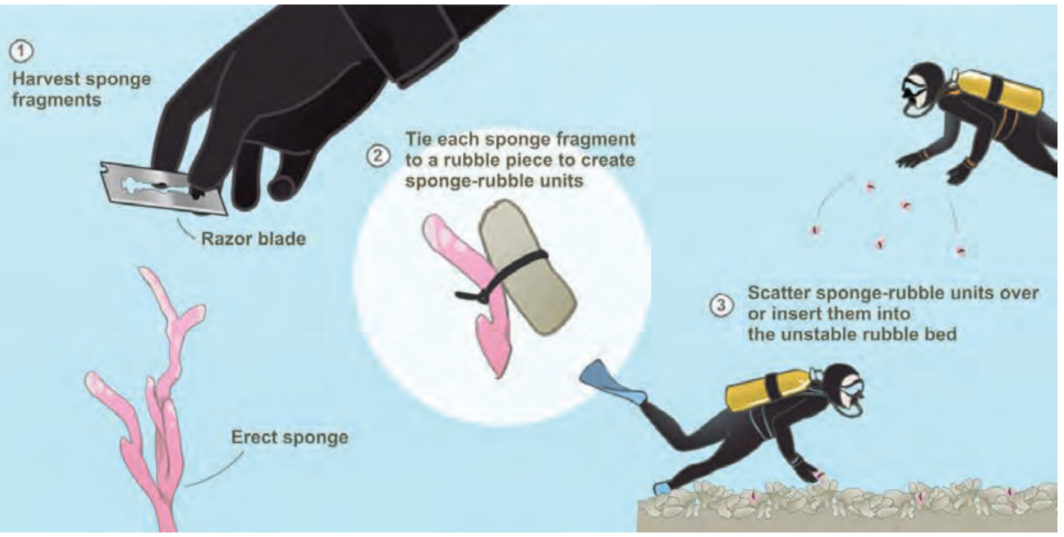


Figure 159.
Generalised process of sponge seeding. Step 2 is optional and may be undesirable if only plastic cable ties are available – sponge fragments can be "sprinkled" directly over the rubble bed without being tied to a rubble piece. Source: Shu Kiu Leung, The University of Queensland

Implementation Strategy

The process of sponge seeding typically involves the following steps: harvesting and preparing sponge fragments, attaching sponges to rubble (optional), and placing the sponge-rubble units within the rubble bed at the restoration site.

Sponge fragments (from erect or cryptic sponges), ranging from 4 to 10 cm in length, can be harvested using razor blades. Alternatively, naturally fragmented sponges can also be collected, in a similar manner to "**corals of opportunity**". According to a study in Curaçao (Biggs, 2013), fragments of approximately 10 cm long can be sustainably harvested annually, depending on the species. Although, it is important to note that sustainable harvesting rates will vary by region; this study is from the Caribbean where sponge biomass is up to six times higher than on the GBR, where wild harvesting is not sustainable, or feasible (Wilkinson, 1987), smaller fragments can be cultivated in sponge nurseries, using techniques similar to coral nurseries.

After harvesting, the fragments can be left alone prior to deployment, to allow them time to heal the cut edge. For example, in Biggs (2013), they were placed in baskets in mesh dive bags anchored to the seafloor for 48 hours to recover from the excision. When transporting the sponge fragments to the restoration site, keep them submerged in seawater and away from air exposure, which can quickly kill sponges. Also, it is good practice to wear gloves when handling sponge fragments.

Once healed, sponge fragments can be tied onto pieces of rubble using cotton string or nylon cable ties and left to attach themselves to the rubble piece, which may take a few days to weeks, depending on the species (Biggs, 2013; Wulff, 1984). Once the sponges have attached to the rubble, these sponge-rubble units can be randomly inserted into or scattered over the rubble bed at the restoration site, to attach to adjacent rubble pieces. Note that if sponge-rubble units or sponge fragments are scattered directly onto the rubble bed, instead of being inserted into crevices, there may be a higher proportion of fragment mortality. Exposed sponge fragments sitting on top of the bed could be swept away or eaten in high-energy areas, and/or there is a high rate of sponge consumption by other organisms.

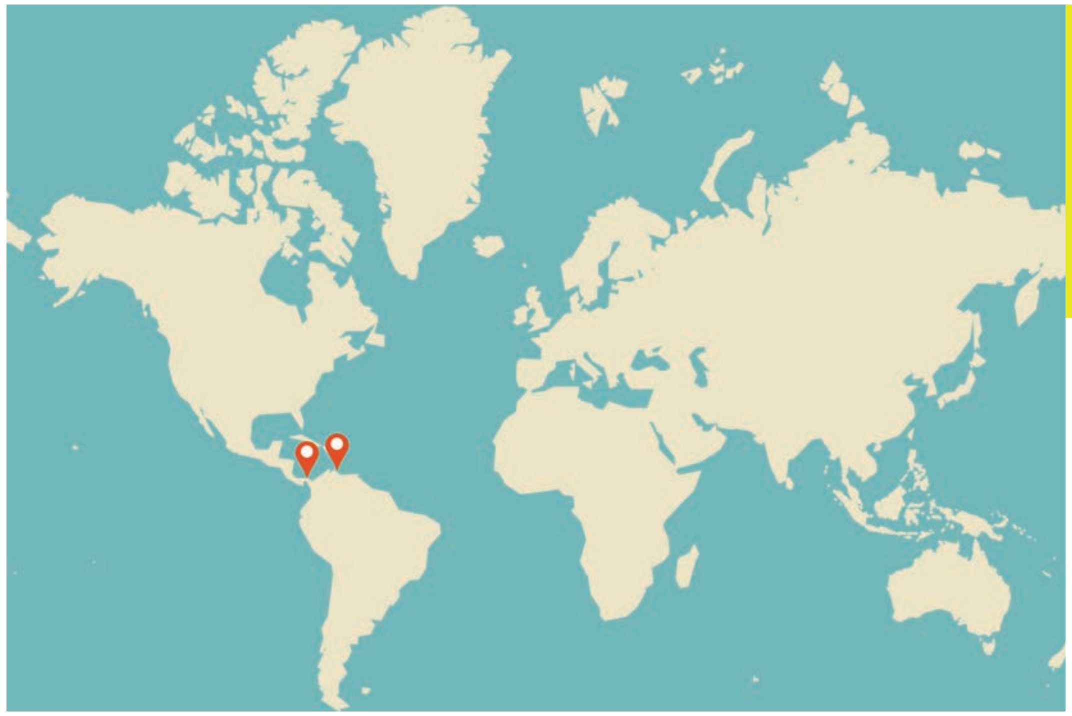


Figure 160.
Locations of sponge seeding sites. Source: Shu Kiu Leung, The University of Queensland

What realistic outcomes can we expect?

> Sponge seeding may increase rubble binding and stability of rubble beds in a short period of time (<1 year). Over a longer period, the method may result in increased coral recruit settlement and survival rates on rubble beds stabilised by sponges.

There have been only two studies to our knowledge on the effectiveness of sponge seeding in stabilising and binding loose rubble, and aiding coral reef recovery. Both studies reported increases in rubble binding, stability of rubble piles, and an increased number of coral recruits in sponge-seeded rubble piles in contrast to untreated, loose rubble piles.

Importantly, however, these studies were conducted at a small, experimental scale (on small rubble 'piles', as opposed to in rubble beds). Thus, the method has not been tested at a scale relevant to restoration.

In Panama, Wulff (1984) found that 73% of sponge-seeded rubble piles became stable in 5 months, while piles without sponges never stabilised in 4 years of surveying. CCA began to colonise rubble in sponge-seeded piles as early as 7 weeks and were binding rubble in the piles by the fifth month. By the tenth month, individual rubble pieces were indistinguishable due to the growth of CCA. A more recent study by Biggs (2013) found similar results but at a slower rate. In this study, 62% and 85% of sponge-seeded rubble piles at two different sites in Curaçao, respectively, became temporarily stabilised after 12 months. However, some of the piles were lost over time, demonstrating that temporary stabilisation did not always become permanent. The author attributed the slower stabilisation rates to Curaçao's declining CCA recruitment over the past three decades.

Table 21.

Pros and cons of sponge seeding (Biggs, 2013; Wulff, 2016; Wulff, 1984).

Pros	Cons
• No foreign material is introduced into the environment (unless cable ties are used to make sponge-rubble units, but a biodegradable option could be employed instead). • As sponge fragments grow, their ability to bind rubble multiplies, much like a snowball effect. • Sponges regenerate quickly, replacing the tissue exposed following excision faster than corals do. This makes harvesting more sustainable. • Sponges are less fragile to work with compared to corals. • Similar to coral outplanting, sponge seeding can be easily integrated with other methods, for example, the patches between rock piles or frames could be seeded with sponges.	• Limited scalability due to the intensive nature of the process. • May risk introduction of coral disease into the ecosystem. • High costs and labour-intensive, which may not be worth it if the site is not recruitment limited. • Harvesting may damage source colonies and compromise source reefs if coral cover is already low. • Some species may be less suitable for transplantation due to their growth forms and slow growth rates. • Nursery phase (if applicable) requires significant maintenance efforts

In Panama, coral recruits started appearing on the sponge-seeded rubble piles by 10 months, with *Agaricia* and *Porites* species found at 12 weeks and 10 months, respectively (Wulff, 1984). Recruits were less likely to be damaged on stabilised sponge-seeded rubble piles, leading to a higher survival rate of 13% over 4 years, compared to just 1% on loose rubble. Similarly, Biggs (2013) found 6 species of coral on stabilised sponge-seeded rubble piles after 4 years. The recruitment on these piles was higher than on loose rubble after 2 years. Furthermore, the abundance and diversity of recruits was highest on sponge-seeded rubble piles.
Curiously, the number of coral recruits on sponge-bound piles was even higher than piles that were artificially bound by concrete. This suggests that not only do corals preferentially recruit to stable structures, but also to substrates bound by natural agents like sponges, most likely due to chemical cues that facilitate larval settlement (Heyward & Collins, 1985; Morse et al., 1988; Tebben et al., 2015).

Materials

Choosing the right sponge species is crucial due to morphological and functional differences between species. Rubble can be bound to the reef and each other by two types of sponges: cryptic and erect (Kenyon et al., 2023a; Wulff, 1984). Among these, erect, branching sponges are preferred as they naturally fragment and regrow rapidly post-fragmentation (Biggs, 2013; Wulff, 2016). Some erect sponges include *Iotrochota birotulata, Haliclona rubens, Niphates erecta*, and *Aplysina cauliformis* (Wulff 1984, Biggs 2013). Cryptic, 'void-filling' sponges include *Mycale laevis* and *Halichondria melanodocia* (Wulff 1984). While we have a limited understanding of which sponge species might lead to the most successful results, using a variety of erect, branching and cryptic, void-filling reef sponges could be beneficial.

Importantly, some sponges that contribute to bioerosion (breaking down rubble rather than binding it together) may also have an erect growth form, which can be misleading (Biggs, 2013). Sponge identification is inherently difficult, but divers will need to learn to recognise bioeroding species (e.g., from the Cliona and Cliothosa genuses) and avoid collecting them for sponge seeding.

Costs and maintenance

The costs and scalability of this process are currently unknown, though the main costs – if wild harvesting - would be associated with labour for harvesting and deploying sponge-rubble units, with material costs being relatively minor. It is also unknown whether maintenance tasks would be required for a larger-scale sponge-seeding project. Monitoring of sponge growth would be required at a minimum, to ensure that sponges are adhering to adjacent rubble pieces as expected, but not dominating the entire space and precluding corals. In this manner, monitoring of sponge seeding is expected to be similar to coral transplantation.

Monitoring and evaluating project success

Monitoring is a crucial part of reef restoration projects to assess project outcomes and determine necessary corrective actions within the adaptive management framework (Edwards, 2010; Wapnick & McCarthy, 2006).

For marine ecosystem restoration projects to succeed, a long-term monitoring program of 15–20 years, rather than <5 years, should ideally be implemented (Bayraktarov et al., 2016). However, the majority (60%) of coral restoration projects report less than 18 months of monitoring (Boström-Einarsson et al., 2020a). Short-term monitoring may not reflect the long-term success of restoration projects. Similarly, very short-term success does not always translate to long-term success. For example, published data from coral transplantation projects are skewed towards higher survival rates due to the limited scope of monitoring (Boström-Einarsson et al., 2020a). Some projects don't even have a monitoring program at all. There is a huge concern that unmonitored, unmaintained artificial structures from failed projects could result in underwater junkyards that are unsightly and contrary to restoration goals (Edwards et al., 2024). For example, in Indonesia, over 100,000 artificial structures and 50,000 coral transplants were deployed across 533 projects between 1990 and 2020 (Razak et al., 2022). Yet only 16% of these projects had post-installation monitoring. Among those monitored, only one reported the physical condition of the deployed structures.

An ideal long-term monitoring program that encompasses a complete range of ecological, social, and economic metrics is usually impossible due to funding, permitting, and logistical constraints (Boström-Einarsson et al., 2020a). Given these considerable challenges and costs associated with long-term monitoring, it is crucial to ensure that the monitoring program is designed effectively to maximise return on investment (Fox et al., 2017). Importantly, long-term monitoring should be incorporated into project budgets and workplans, though this is rarely the case.

In addition to short monitoring durations, a common pitfall of reef restoration projects is the selection of monitoring parameters that do not accurately represent the intended goal (Boström-Einarsson et al., 2020a). For example, most restoration efforts (60% of literature reviewed in Boström-Einarsson et al. (2020a)) focus solely on measuring coral outplant survival and growth regardless of the defined project goals. This may not adequately reflect overall success, particularly for broader goals like ecological restoration, which require additional factors to be evaluated, such as the reproductive capacity of corals, species diversity of corals, invertebrates, and fish, as well as structural complexity and quality of the habitat (Boström-Einarsson et al., 2018; Goergen et al., 2020).

In the case of rubble stabilisation projects, efforts should be made to monitor how well the method has actually stabilised the rubble (e.g., tracking pieces, photographing plots), and if it has, what other factors might be affecting coral recruitment other than instability. Environmental variables of light, flow, temperature and sediment should be measured where possible, to allow comparison of results between projects deployed at different sites.

This section outlines the recommended design for a monitoring program, including how to collect and analyse monitoring data, which parameters to measure, and the appropriate methods and timing for these measurements.

Box 14

BACI design

(Goergen et al., 2020; Hein et al., 2021)

Before

This is the stage where data is collected at the restoration site before any rubble stabilisation work begins. It provides a baseline to compare future data with. **If pre-restoration surveys are not feasible, control site surveys can act as a substitute (Goergen et al., 2020).**

After

Once the rubble stabilisation method is implemented, data is later collected again at the same site during monitoring. This demonstrates the changes that have occurred as a result of the stabilisation.

Control

Data can be collected from both negative and positive control sites. A negative control site is essential, and represents the pre-restoration conditions where no rubble stabilisation has been implemented. It indicates the changes, if any, that might have happened naturally in the rubble bed, without any intervention. A positive control, or a reference site that is typically a healthy and undisturbed reef, represents the ideal state or the goal of the project (the 'fully recovered' state). The comparison of restoration and control sites helps to answer:

1) whether rubble stabilisation is better than doing nothing; and
2) whether rubble stabilisation accelerates reef recovery to match reference sites, and in what timeframe?

Impact

The difference between the 'Before' and 'After' at the restoration site represents the impact of the stabilisation efforts, and at negative control sites, represents the result that can be expected if no stabilisation intervention were implemented.

Monitoring program design

Ideally, monitoring programs would be science-based, tailored to each unique site and incident, and clearly linked to project goals (Boström-Einarsson et al., 2020a; Wapnick & McCarthy, 2006). It is essential to design monitoring programs that allow comparison with control sites or follow a before-after-control-impact (BACI) design (Gann et al., 2019; Hein et al., 2021) (see also **Box 14**).

Data collection and analysis

It is recommended to consider a monitoring strategy that combines expert-led baseline data collection with long-term capacity building of staff and local communities (Fox et al., 2017). This approach can lead to more informed decision-making and better conservation outcomes. Experts like statisticians and field scientists would ideally be consulted in the early stages of sampling design as well as data collection and analysis (Wapnick & McCarthy, 2006). For example, baseline surveys conducted by experts help deliver high-quality data, which provide valuable, time-sensitive information that serves as a reference point for future changes (Fox et al., 2017).

Moreover, well-designed pilot studies further guide sampling design by informing the sample size needed to meet monitoring goals. These goals are often defined by the anticipated benefits from the restoration effort over time. Essentially, more sampling is needed to detect smaller, more rapid benefits. For example, if we want to spot any problems early on and adjust the implementation strategy accordingly, more frequent measurements may be needed. However, resource constraints may limit sampling efforts, potentially missing the minor effects on the system, or only detecting coarse, long-term changes. Therefore, it is recommended to use information from past experiences or pilot studies to decide how many samples are needed to maximise the cost-effectiveness of the monitoring program.

When it comes to data interpretation, incorporating statistical analyses is advisable. Consulting with experts can yield statistically valid data that addresses project goals. In the long term, training staff, volunteers, or members of the local community to effectively monitor restoration efforts is likely to become more financially and socially sustainable (Fox et al., 2017).

Monitoring efforts at different timescales

It is advisable for monitoring programs to evaluate project outcomes against initial goals across suitable timescales (Hein et al., 2021). This involves using different metrics for various time frames. As time progresses, the focus of monitoring efforts could shift from immediate, local effects of interventions to long-term reef-scale effects such as the recovery of ecosystem functions (Shaver et al., 2020).

Monitoring efforts can be categorised into three phases based on the duration (Ceccarelli et al., 2020; Clark & Edwards, 1995; Goergen et al., 2020; Shaver et al., 2020):

- **Short-term monitoring (<1 year)** assesses the design and execution of the initial restoration phase. It measures parameters such as the number and survival of outplants, and the number of damaged or lost structures.
- **Medium-term monitoring (1-5 years)** assesses how well the restoration design aligns with the desired goals and measures the project's success based on these goals. It measures parameters such as rubble binding and movement, coral cover, ratio of coral to rubble, coral recruitment, as well as diversity and abundance of reef fish and invertebrates.
- **Long-term monitoring (>5 years)** assesses the broader ecosystem's response to the restoration activities. It measures parameters such as community assemblage structure (e.g., percentage of juvenile and mature corals), structural complexity, reef accretion rates, and spill-over effects (i.e., is coral cover expanding and spilling over, from just on the stabilisation structures, to the surrounding, unrestored rubble areas?)

Table 22 presents recommended environmental parameters to measure and report for a typical rubble stabilisation project. The table follows a BACI approach. If no baseline survey is done (i.e., there is no before information), parameters can still be measured as per a Control-Impact design to compare rubble beds with and without intervention (negative control), and nearby healthy reefs (positive control). Please note that not all parameters may be relevant to every project depending on the monitoring goals. Also see Figure 161 for the timeline of the ideal monitoring scenario.

Table 22. Environmental parameters to measure and report for a typical rubble stabilisation project. * = *if applicable*

Parameter(s) to measure	Frequency of measurement	Method(s) of measurement
Physical characteristics of the site	Baseline survey if possible	**During field survey, measure:** • Location (coordinates) • Type and timing of recent disturbances • Reef zone • Wave height (m)* • Current speed (m/s)^ • Depth (m) • Slope (degree)
Rubble piece and bed characteristics	Baseline survey if possible, and then rotate areas for stability and binding sampling, or ideally, leave the project go as long as possible before monitoring binding. Note that sampling areas should be rotated because the binding progress may be impeded if sampled repeatedly (because binds can be broken while sampling is being conducted)	**During baseline survey:** If there is very limited time, determine the type of rubble bed and whether intervention is likely to be needed, using the Rapid Rubble Assessment (**Appendix A**) and measure: • Widest span of replicate rubble pieces (e.g., ~50 pieces in a 10m² area). • Bed thickness at multiple random points in the rubble bed (e.g., 50 points in a 10m² area). • Extent of the rubble bed (width x length). If more time is available, complete the Detailed Rubble Assessment (**Appendix B**), sampling individual rubble pieces to measure: • Widest span (cm) • Number of branches • Morphology • Bed thickness • Slope angle • Dimensions of the rubble bed • Stability • Binding **During subsequent monitoring trips:** Complete the Detailed Rubble Assessment (Appendix B), sampling individual rubble pieces to monitor: • Stability • Binding (e.g., check if it is bound by organisms such as hard corals, soft corals, turf algae, macroalgae, CCA, sponges, ascidians, bryozoans. If so, either just note the dominant binder type, or to provide more information and reveal further distinction between sites, count the number of binds by each organism per rubble piece). • Note that rubble size and morphology doesn't really need to be measured repeatedly, although bed thickness might change over time if the bed is consolidating vs dispersing. The impact of structures on rubble movement should be tested. This can be conducted too if stability and binding testing will be too destructive, and areas sampled are not able to be rotated: • Track distance of movement by marking individual rubble pieces and their original location
Benthic cover/ composition	Baseline survey if possible, and then annually	Use transects, quadrats, underwater photographs, and/or photogrammetry to measure the percentage cover (%) of coral, rubble, sand, hard carbonate substrate, macroalgae, soft corals, sponges etc. **Do this:** • In the rubble bed • In an adjacent healthy site (if available) Note that the **Detailed Rubble Assessment** (**Appendix B**) suggests taking photos of quadrats to get benthic cover (as above), as well as counting all corals within the quadrat and noting their size. This provides greater resolution on how the coral community is changing over time than coral cover does alone (see below).

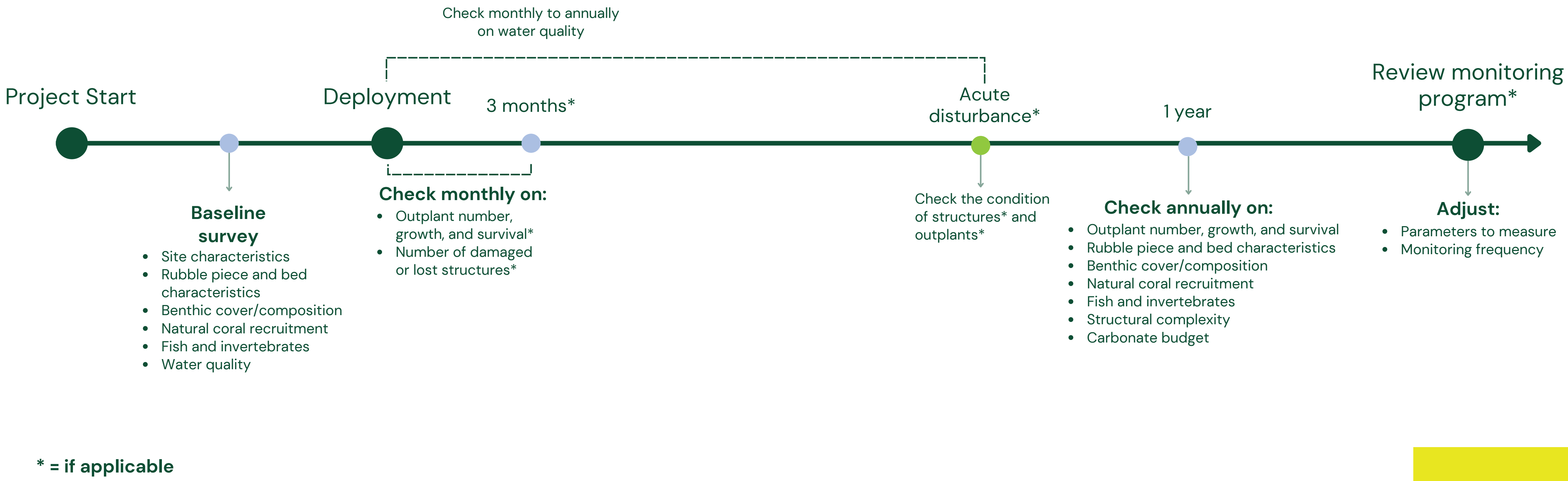
Parameter(s) to measure	Frequency of measurement	Method(s) of measurement
Natural coral recruitment	Baseline survey if possible, and then annually (also consider the timing of spawning events)	**Count the number of recruits:** • On deployed structures* during field surveys. • On rubble (in quadrats/plots) during field surveys. • On settlement tiles that can be removed and examined under a microscope. Ensure that tiles are placed at varying orientations (e.g., horizontal, vertical, and angled) to account for different preferences of recruits. If sampling rubble with the Detailed Rubble Assessment (Appendix B), you can count recruits that are settling directly on the sampled rubble pieces too. Settlement tiles provide information on larval supply, while assessing recruits on the rubble tells you what is actually settling in the bed. **Also, take underwater photographs of recruits and:** • Identify recruits to their lowest taxonomic rank (or morphology). • Record the size and survival of recruits over time.
Outplant number, growth, and survival*	Measure monthly during the first 3 months, then annually	**During baseline survey:** • Count number of outplants. • ake underwater photographs and record change in colony size over time. **During subsequent monitoring trips:** As per baseline survey but also record survival status (e.g. alive, bleached, dead).
Number of damaged or lost structures*	Within first 3 months to ensure proper attachment, then after significant events (e.g., storms) or annually	Count number of structures and record degree of damage.
Fish and invertebrate species diversity, abundance, and density	Baseline survey if possible, then annually	Use underwater visual census (e.g., transects, quadrats, timed swims, and/or video surveys) to record number of individuals and their species. **Calculate:** • Species diversity (e.g. using the Shannon-Wiener index) • Abundance (total number of individuals per species) • Density (number of individuals per unit area).
Water quality	Baseline survey if possible, and then monthly to annually	Use water quality sensors or take water samples for analysis using test kits or in a laboratory to measure parameters such as: • Temperature • pH • salinity • turbidity • sedimentation • nutrient levels (e.g. nitrates and phosphates)
Structural complexity	Baseline survey if possible, then annually	Use rugosity index or photogrammetry with 3D modelling.
Carbonate budget	Baseline survey if possible, then annually	Census-based assessment (e.g., ReefBudget) to determine reef accretion and erosion rates, as well as net carbon production rates (kg $CaCO_3$ m^{-2} $year^{-1}$).

* If wave height cannot be measured, note the site's exposure in terms of prevalent winds. For example, if the location is on the south-east side and winds are predominantly south-easterly, record it as 'exposed to predominant wind direction'. Also, consider site accessibility, for example, if it is accessible by diving or small boat year-round, consider it sheltered; if only accessible part of the year when winds are low, consider it exposed.

^ If current speed cannot be measured, provide an indication of the current speeds based on your knowledge of the site. For example, if you need a reef hook when currents are strong, mark this as high current speed. If currents are mild enough for you to work anytime regardless of tides, mark as low. If you must time your trips due to strong currents, mark as high.

Source: Peter Mumby

Figure 161.
Timeline of an ideal monitoring scenario.
Source: Shu Kiu Leung, The University of Queensland



Read more:

For further details on designing specific metrics and parameters to meet restoration goals, we recommend referring to:

- **'Coral Reef Restoration Monitoring Guide: Methods to Evaluate Success from Local to Ecosystem Scales'** (Goergen et al., 2020); and
- **'Coral Reef Restoration Monitoring Manual – Maldives'** (Montano et al., 2022).

RRAP Rubble Stabilisation Intervention Toolbox

The RRAP Rubble Stabilisation Intervention Toolbox includes expert-based, interactive **Bayesian Belief Networks (BBN)** designed to visualise the likely outcomes of various stabilisation interventions in different environments.

This toolbox helps users compare the effectiveness of different stabilisation methods at specific sites and supports informed decision-making.

The toolbox includes two BBNs: one predicts the benefits of restoration in terms of coral cover over time, while the other reflects expert opinions on the expected success rates of restoration across different environments. The tool can be used in two ways: users may either enter a target outcome to find the best set of conditions to reach that goal or input different stabilisation methods and environmental variables to see the likely outcomes.

The tool utilized survey data collected during the RRAP Rubble Stabilisation Workshop 2023 (see **Box 4**), capturing expert opinions on stabilisation methods, restoration site details (e.g., depth, exposure, slope, rubble characteristics), and restoration outcomes over time (in terms of coral metrics, e.g., coral cover, density of recruits, and species composition at the site). Participants also shared whether they would recommend applying these methods in different environments and their expected success. Additional insights were drawn from academic papers authored by participants to supplement the survey data. A total of 24 responses were collected, covering data from 71 sites across Australia, Indonesia, Malaysia, China, Puerto Rico, the Philippines, Guam, the Maldives, and Thailand. The full set of survey questions is available in **Appendix C**. For further details on the methodology, please refer to the "readme.txt" in the toolbox package.

User access:

Users may access the BBNs using the Netica software (Norsys Software Corporation, 2024).

The free version of the software can be downloaded from: **https://norsys.com/download.html**

And you can download the toolbox **here**

Please read the **'Limitations'** section below and the 'readme.txt file in the package carefully before using the toolbox.

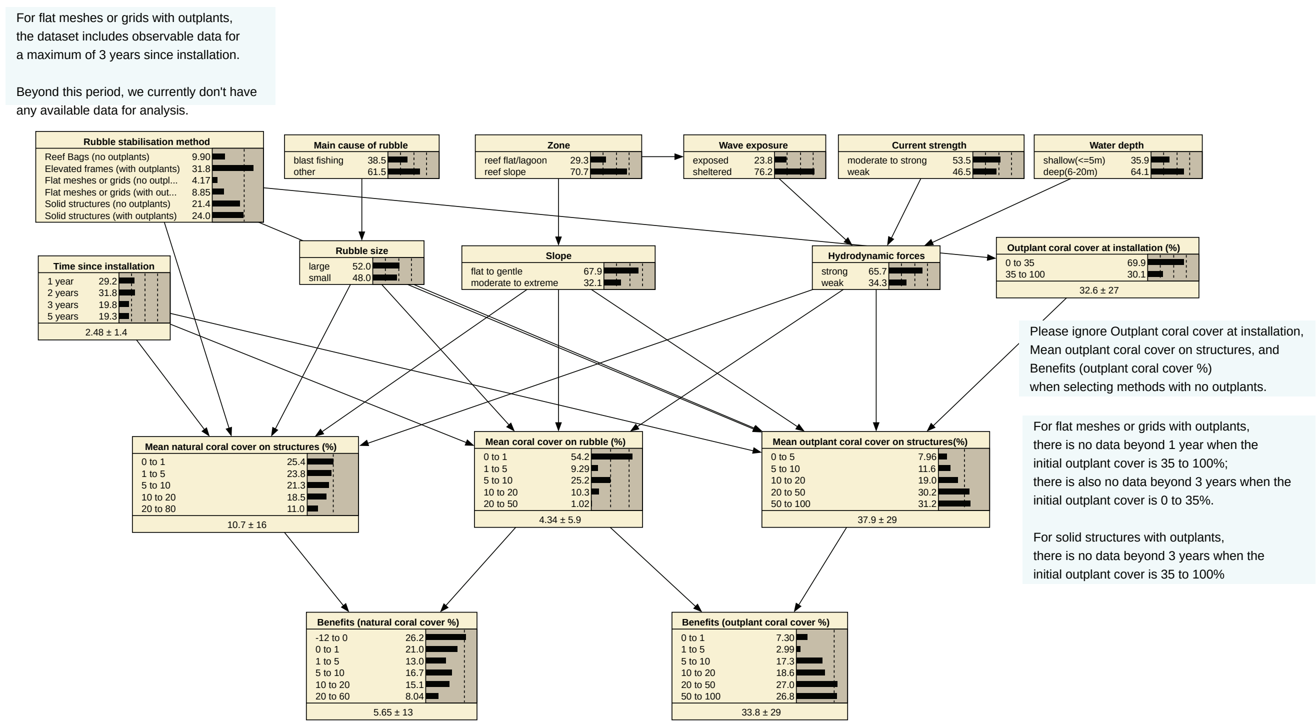


Figure 162. Screenshot of coral_cover_benefits.neta, which estimates the benefits of restoration in terms of coral cover over time.

Source: Shu Kiu Leung, The University of Queensland

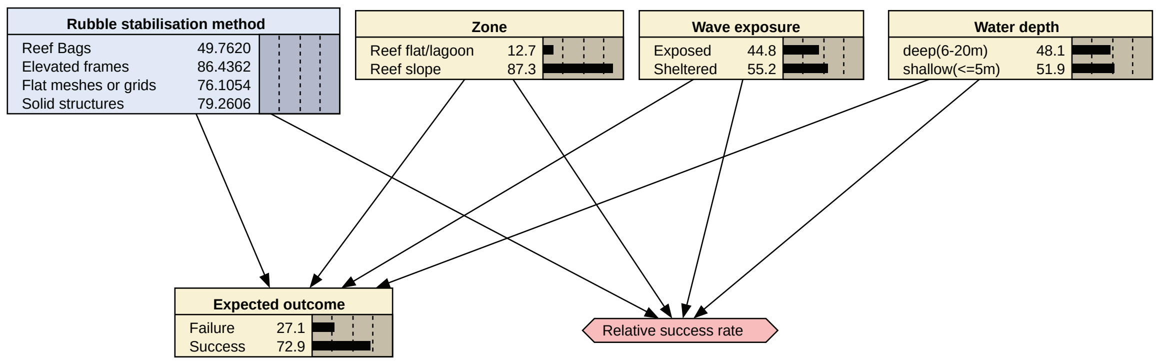


Figure 163. Screenshot of expected_success.neta, which reflects expert opinions on the expected success rates of restoration.

Source: Shu Kiu Leung, The University of Queensland

What is a Bayesian Belief Network (BBN)?

A Bayesian Belief Network (BBN) is a statistical model designed to explore the relationships between input variables and model outputs.

It represents these relationships using conditional probabilities, helping users understand the likelihood of certain outcomes given specific conditions.

The "Bayesian" aspect refers to Bayes' Theorem, a mathematical approach for updating probabilities as new information becomes available. This makes BBNs a simple and efficient tool for decision-making.

BBNs are particularly beneficial in the context of rubble stabilisation, where there is often uncertainty and incomplete knowledge. Despite this, BBNs allow for accurate predictions using machine learning algorithms, making it suitable for modelling complex environmental systems (Aguilera et al., 2011). Given the lack of research and monitoring in rubble stabilization methods, a BBNs' ability to infer missing data is especially valuable. Additionally, BBNs offer high transparency by providing access to all model results and can be used in reverse to identify the input conditions most likely to achieve desired outcomes (Baldock et al., 2019; Landuyt et al., 2013), thereby simplifying and optimising the decision-making process.

How to use the toolbox

A BBN mainly consists of **nodes**, **links**, and **probabilities**:

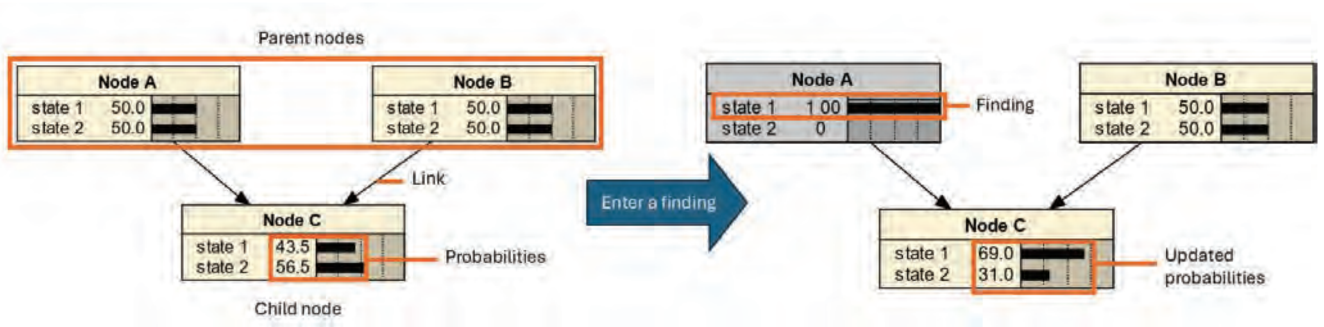


Figure 164. Example BBN showing nodes, links, and probabilities.
Source: Shu Kiu Leung, The University of Queensland

Nodes represent variables and each has a finite set of mutually exclusive states. For example, coral cover can be either high, medium, or low, but never be in more than one state at the same time.

Links indicate directional relationships between nodes. For example, a link from node A to node C suggests that A (parent node) influences C (child node).

Probabilities describe the likelihood of a child node being in a specific state given the states of its parent nodes or vice versa.

Findings or actions can be entered directly by clicking on the name of the observed state (located left of the bar graphs) for the node to specify a known value. Once a finding is entered, the beliefs of all connected nodes are immediately updated based on the new information. Users can enter findings to indicate evidence based on observations; and/or use actions to represent decisions made.

Using **Figure 164** as an example, Node A and B are parent nodes of Node C. When a finding of "state 1" was entered for Node A, the probabilities of getting state 1 or 2 in Node C updates with this information. Given that node A is in state 1, it is now more likely for Node C to be state 1 than in state 2.

To learn more about a node, users can double-click it to view its description or right-click and select **Properties...**.

To observe the details of the node's relationship with each of its parent nodes, right-clicking on the node and selecting **Table...** will display the conditional probability table (**Figure 165**).

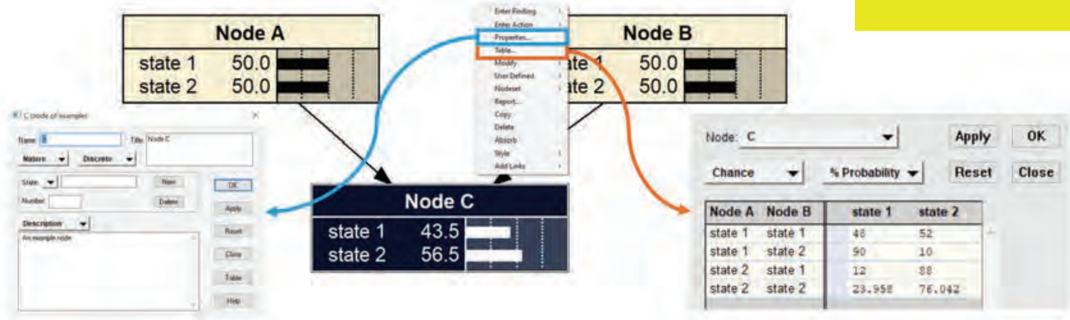


Figure 165.
Right-click on Node C and select **Properties...** to view its description, or **Table...** to see the conditional probability of Node C being either state 1 or state 2, based on the combinations of states of Node A and B.

Source: Shu Kiu Leung, The University of Queensland

Box 15

Example 1 - Application of the coral cover benefits BBN

A tourism operator wants to estimate the benefits of using Reef Bags at a specific site. The operator wants to know if the project can lead to at least 10% difference in natural coral cover vs the negative control in 2 years. The site is situated on a **sheltered, gentle reef slope (in the "< 20 degrees" category) at a depth of over 6 metres ("deep").**

To begin, open the file "coral_cover_benefits.neta" in Netica by selecting **File > Open...** (top left corner) and choosing "coral_cover_benefits.neta" in the file directory.

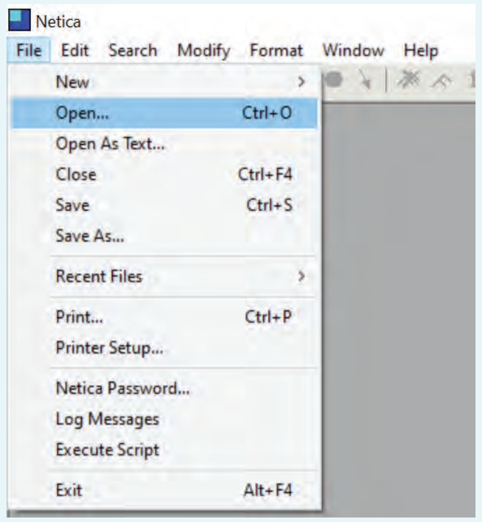


Figure 166. Opening a file in Netica.

Source: Shu Kiu Leung, The University of Queensland

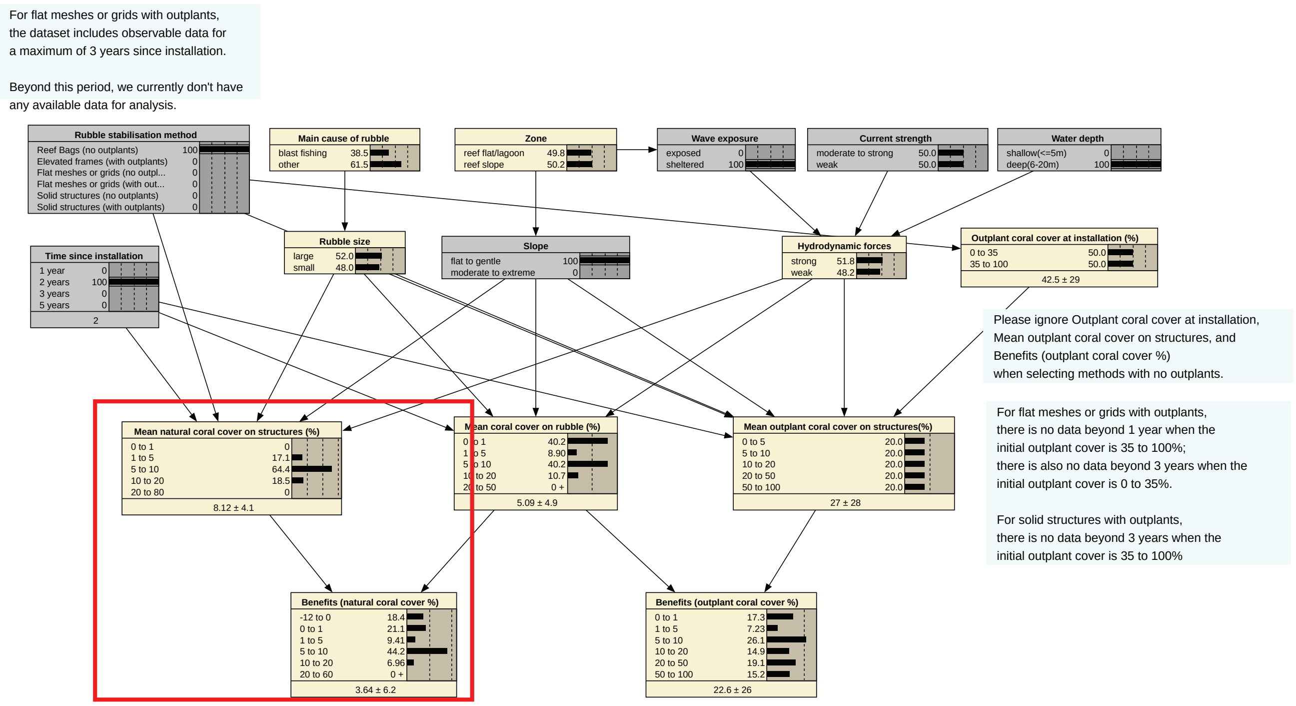


Figure 167. Screenshot of coral_cover_benefits.neta with findings entered. The nodes **Mean natural coral cover on structures (%)** and **Benefits (natural coral cover %)** provide insights on restoration outcomes.
Source: Shu Kiu Leung, The University of Queensland

Using site information, the operator can input findings by selecting the appropriate states for the environmental variables to reflect the site conditions. If some input parameters, like current strength for example, are uncertain or unknown, the operator can enter a 50/50 probability for strong and weak currents, assuming both conditions are equally likely. The operator also inputs "Reef Bags" for *Rubble stabilisation method* and "2 years" for *Time since installation.*

The BBN predicts that natural coral cover will likely reach 8.12% ± 4.1% two years after installing Reef Bags at the site, representing a 3.6% ± 6.2% benefit (coral cover increase compared to the negative control) (Figure 167).

At this particular site, and without outplanting coral onto the Reef Bags, the probability of achieving more than 10% benefit after two years is relatively low, at just 6.96%, with the most likely outcome being in the range of a 5-10% benefit (44.2% chance).

Box 16

Example 2 - Application of expected success rates BBN

A user wants to determine which method experts believe has the highest success rate for a restoration project on a **sheltered, shallow reef slope**. The user then opens the file "expected_success.neta" and inputs the relevant findings and reviews the success rates for different methods in the decision node. The user can also view the overall success rates regardless of the method in the expected success node.

Among the methods, elevated frames are expected to have the highest success rate (95.8%), followed by flat meshes or grids at (92.3%), solid structures at (82.4%), and reef bags at (66.7%) (Figure 168). Overall, a restoration project in this type of environment is projected to achieve an (84.3%) success rate.

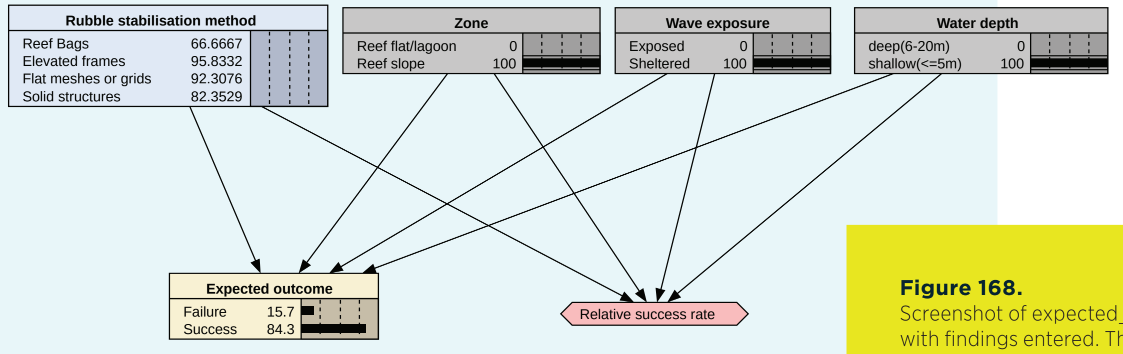


Figure 168.
Screenshot of expected_success.neta with findings entered. The node **Rubble stabilisation method** shows the expected success rates of the four methods, while the node **Expected outcome** shows the overall success rate regardless of methods.
Source: Shu Kiu Leung, The University of Queensland

Box 17

Application of the coral cover BBN tool on the GBR – Reef Bags at Bait Reef

The coral_cover_benefits.neta BBN was applied to a representative site at Bait Reef where Reef Bags were deployed (refer to the section on **Reef Bags** and **Box 6** for further details). The BBN was used to predict coral cover at the site over time, and its predictions were compared with monitoring data.

To reflect the environmental conditions at the site, states were chosen that represent a **shallow (≤5 m), sheltered lagoon environment with a flat to gentle slope and large rubble pieces** (**Figure 169**). Current strength varies across the site, so expected coral cover outcomes were tested for both weak and moderate to strong current conditions.

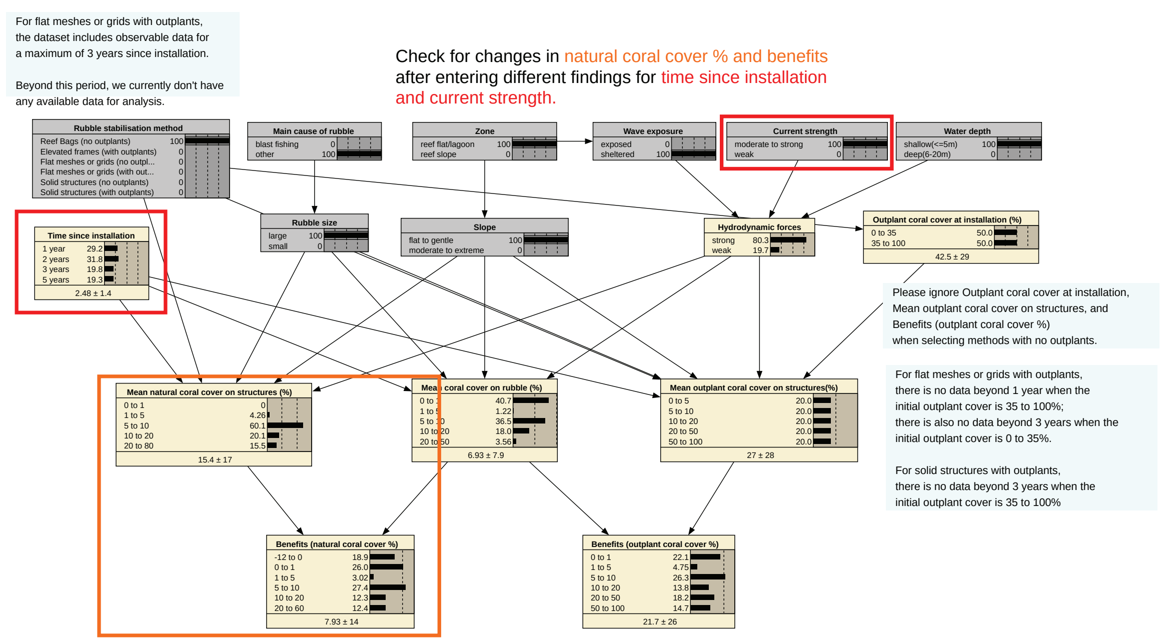


Figure 169.
Screenshot of coral_cover_benefits.neta with environment conditions for a Reef Bags site at Bait Reef entered. The nodes **Mean natural coral cover on structures (%)** and **Benefits (natural coral cover %)** provide insights on restoration outcomes over time when selecting different states for Time since installation.

Source: Shu Kiu Leung, The University of Queensland

	Survey data		BBN Predictions					
			Weak currents			Moderate to strong currents		
Time since installation (years)	Natural coral cover on structures (%)	Benefits (natural coral cover %)	Natural coral cover on structures (%)	Most likely outcome for coral cover on structures (probability of outcome)	Benefits (natural coral cover %)	Natural coral cover on structures (%)	Most likely outcome for coral cover on structures (probability of outcome)	Benefits (natural coral cover %)
1	5	0	7.1±1.9	5-10% (90.7%)	0.4±5.4	7.2±1.8	5-10% (93.1%)	0.4±5.4
2	10	5	8.8±4.1	5-10% (66.8%)	3.0±6.7	8.7±3.8	5-10% (73.1%)	2.9±6.6
3	15	10	11.4±4.4	10-20% (52.1%)	6.9±7.2	11.8±4.4	10-20% (57.0%)	7.3±7.1
5	20	15	40.0±2 2.0	20-80% (73.4%)	25.9±20	42.6±2 2.0	20-80% (80.3%)	28.2±19.0

Table 23. Predictions of natural coral cover and benefits over time at the Bait Reef site when Reef Bags were deployed.

Predicted natural coral cover on structures and benefits was shown to increase over time, with a substantial increase between years 3 and 5 with high uncertainty (**Table 23**). Minimal differences in coral cover and benefits were predicted between weak and moderate to strong current strength. Overall, results aligned well with monitoring data

More info.
For further information on how to use Netica and advanced features, please consult Netica's Help System: **https://www.norsys.com/WebHelp/NETICA.htm.**

Limitations

It is important to note that the data primarily reflects expert beliefs and current practices in the field and may not equally represent all environments or stabilisation methods (**Table 24**).

There is an inherent bias towards environments where restoration is more likely to succeed. Experts typically avoid undertaking restoration projects where they believe it will not succeed, which may have resulted in an overrepresentation of environments that are more likely to see successful results, such as sheltered sites, compared to less favourable environments like highly exposed sites. Additionally, some methods are more represented than others, such as elevated frames, which are popular due to their versatility.

The outputs of the BBN tend to have higher uncertainty the longer it has been since installation due to a lack of monitoring data, as most projects are conducted for short periods, typically only 1 to 2 years (**Table 24**). This, again, underscores the critical need for long-term monitoring to accurately assess the effectiveness of rubble stabilisation efforts over time (see section **Monitoring and evaluating project success**).

While the outplant coral cover and associated benefits tend to level off or decrease over time when initial outplant cover is between 35-100%, this **does not mean** we advise against starting with high coral cover. Survey results indicate that mortality of outplanted corals is expected within the first few years, potentially due to density-dependent effects. At higher densities, corals may compete against each other for space and resources (Boström-Einarsson et al., 2018; Goergen & Gilliam, 2018; Rinkevich, 2014), and corallivores may find it easier to feed on corals due to the increased availability of prey (Moerland et al., 2016; Morton & Blackmore, 2009; Roff et al., 2011). This is consistent with observations of predation by *Drupella* snails reported by some survey respondents. Additionally, mortality may simply be more noticeable when coral cover is initially high. While we expect some early losses, corals generally recover over time, though this is not reflected in the Bayesian network due to temporally limited data, so we cannot guarantee whether coral cover will rebound. Therefore, we recommend that when outplanting, be prepared for potential declines in cover, and acknowledge that long-term outcomes remain uncertain.

	Frequency of measurement	Major Caveats and advice	
Method	**Number of unique environments where the method is applied**	**Natural coral cover / benefits**	**Outplant coral cover / benefits**
Reef Bags (with outplants)	3	The BBN has data for variable combinations involving **flat to gentle slopes** and **large rubble**. Predictions are more reliable for these conditions over time periods of **1 to 3 years**. Data for 5-year projections carries higher uncertainty and should be interpreted with caution.	Not applicable
Elevated frames (no outplants)	15	The BBN has data for all combinations involving **flat to gentle slopes**. Predictions are more reliable for these conditions over all time points. Some data is available for combinations with **moderate to extreme slopes**, mostly under **strong hydrodynamic forces**. There is limited data for moderate to extreme slopes with weak forces.	The BBN has data primarily for combinations with **flat to gentle slopes**, or with **strong hydrodynamic forces** at **lower outplant coral cover (0-35%) at the time of installation**. Predictions are most reliable for these conditions over all time points.
Flat mesh or grids (no outplants)	3	The BBN has data for various combinations of slope, hydrodynamic forces, and rubble sizes over time periods of 1, 3, and 5 years. There are some gaps for the 2-year mark, particularly for **moderate to extreme slopes**, **strong hydrodynamic forces** and **small rubble size**.	Not applicable
Flat mesh or grids (with outplants)	8	The BBN has data mainly for **large rubble** across various slopes and hydrodynamic forces. The model can provide reliable predictions only up to the **3-year mark**.	The BBN can only provide estimates up to **3 years when outplant coral cover at installation is 0-35%** and up to **1 year when cover is 35-100%** due to a lack of data. Within the available data, predictions are most reliable for combinations with **large rubble** or **weak hydrodynamic forces**.
Solid structures (no outplants)	6	The BBN can reasonably predict outcomes particularly at the **2-year** and **5-year** time points. While there is also data for **1-** and **3-yea**r post-installation, there are significant gaps for combinations with **moderate to extreme slopes**, or **flat to gentle slopes** with **strong hydrodynamic forces**.	Not applicable
Solid structures (with outplants)	10	The BBN has data for all combinations involving **flat to gentle slopes**, except for one scenario: **flat to gentle slopes** with **weak hydrodynamic forces** and **large rubble** at **5 years since installation**. Data for combinations involving **moderate to extreme slopes** are generally limited, except when it involves **large rubble** on these slopes.	The BBN can only provide estimates up to **3 years when outplant coral cover at installation is 35-100%** due to the lack of data. Within the available data, predictions are more reliable for combinations with **flat to gentle slopes.**

Table 24. Major caveats and advice for using the coral_cover_benefits.neta BBN by methods and environments

Although the BBNs are based on survey data, there are still gaps in the conditional probability tables that require expert input to fill. Much of the data used to train the BBNs is derived from experts' opinions as well, which can be highly subjective. Different experts might have varying views on what certain conditions mean. For example, some experts might classify current speeds of 1 m/s as weak, while others consider anything above 0.5 m/s to be moderate to strong. To address these discrepancies, we manually reclassified the information where possible, to ensure that the inputs are consistent despite the variability in expert opinion.

The BBNs also do not account for *all* factors that may influence coral cover; including only the most significant factors identified in the survey (Appendix C). This is due to limitations of network complexity; adding too many variables would reduce the model's predictive power. For example, sediment levels, larval supply and corallivory rates, which can all greatly impact coral cover, are not considered in the BBN. Additionally, while decreases in coral cover over time are often reported due to factors such as macroalgal overgrowth, predation by *Drupella*, and other local disturbances, these are not captured by the Bayesian network. As a result, the underlying causes of some of the changes in coral cover may not be fully represented by the included variables.

Moreover, in BBNs, discretisation is required even though many environmental variables have continuous characteristics. Manual discretisation of continuous variables, particularly those pertaining to coral cover, may have led to information loss and approximation errors. Due to sample size limitations, coral cover was discretised into broad categories that include a wide range of values (e.g., 20 to 80%), which can obscure variability within the categories and lead to inaccuracies. Also, most environmental variables were categorized into just two groups. For example, rubble smaller than 10 cm was classified as small, with no separate category for very small rubble (-5 cm). Where rubble is not stabilised sufficiently, coral cover outcomes may be even lower than predicted for very small rubble (-5 cm) in high energy systems - particularly if unbranched - due to the higher risk of rubble mobilisation (Kenyon et al., 2023b). This nuance may not be fully reflected in the BBN predictions.

Glossary of Terms and Acronyms

Adaptive management
Implementing management while learning about which management actions are most effective at achieving specified objectives. Structured 'learning by doing', incorporating management actions into experiments, to compare the effectiveness of alternative management actions.

Artificial reefs
Artificial structures that are intentionally deployed underwater that serve different purposes, such as coastal protection, fish aggregation, and reef restoration. Artificial reefs can be created from a wide range of natural and man-made materials.

Baseline (survey/data)
A reference point used for comparisons against which changes in the ecosystem conditions are assessed.

Bathymetry
The study of the seafloor. It involves measurement of water depths and underwater terrain features such as ridges and trenches.

Biodiversity
The variability among living organisms from all sources (including terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part). It includes diversity within species and between species, and diversity of ecosystems.

Biofilm
A thin layer of microorganisms (such as cyanobacteria and algae) that adhere to a surface and form a complex community. Biofilms create a foundation for corals and other sessile organisms to settle.

Biological triage
A process to prioritise resources following acute disturbances, used to determine which reef component need to be "rescued" first when resources are limited.

Blast fishing
Also known as fish bombing or dynamite fishing. A destructive and illegal fishing practice that uses explosives to stun or kill fish. This practice is prevalent in developing countries due to rapid population growth and economic expansion. The explosives can destroy the skeletons of corals, resulting in vast amounts of rubble.

(Coral) Bommies
A large outcrop of coral reef.

Carbonate budget
A measure of the net rate of calcium carbonate production in a reef environment, accounting for both construction and erosion processes, typically quantified in kg m^{-2} per year. It offers key insights into reef framework development and is significantly influenced by climate change, as increased atmospheric CO_2 levels cause ocean acidification, reducing the carbonate production capabilities of calcifying organisms like corals, thereby impacting reef health and sustainability.

CCA
Crustose coralline algae. CCA are rock-hard calcareous red algae that fulfil two key functional roles in coral reef ecosystems: they contribute significantly to reef calcification and cementation, and they induce larval settlement of many benthic organisms (such as corals and sponges).

(Rubble) Cementation
A process that occurs after the preliminary stabilisation and binding of rubble pieces. This involves the precipitation of calcium carbonate ($CaCO_3$) from seawater and results in the formation of cements that bind the rubble pieces more rigidly.

Coral bleaching
Occurs when the microscopic algae (*Symbiodinium spp.*, also known as zooxanthellae) living within coral tissues are expelled due to a change in water chemistry (temperature, salinity, pH) leaving the coral skeleton looking bleached. If the zooxanthellae do not return within a month, and they will only do so under optimum conditions, the coral dies.

Coral cover
The average area covered by hard corals, recorded as a percentage. The measurement is often used to assess the health of reefs. The amount of coral cover is influenced by rates of reproduction, growth and mortality. When corals reproduce less, grow more slowly or die more frequently, coral cover declines.

Coral density
The number of corals colonies per unit area.

Coral disease
Coral disease has significantly affected coral reefs in the Caribbean and poses a growing threat to Australia's reefs. To date, more than seven coral diseases have been identified on Australian reefs (including white syndrome, black band, and brown band disease).

Coral outplanting
Planting nursery-grown coral fragments onto reef habitats. Used interchangeably with coral transplantation.

Coral recruitment
The process of new juvenile corals joining the reef community through a three-stage process:

1) the arrival of juveniles from spawning events or brooding
2) the settlement of juveniles; and
3) the growth of settled juveniles to a visible size.

Coral spawning
The synchronised release of eggs and sperms by corals into the water. This coordinated event helps increase the chance of fertilisation. The fertilized eggs then develop into larvae that settle on a hard surface to form new coral colonies.

Corallivore
Organisms that eat corals.

Corals of opportunity
Detached coral fragments found on reefs, which, unless reattached, have a low survival rate.

CoTS
Crown-of-thorns starfish. They are coral eating starfish with the potential for population outbreaks which destroy vast areas of coral reefs.

Cumulative impact
The compounded impact on the environment resulting from one or more pressures, their interactions, and the additive influence of past, present, and reasonably foreseeable future pressures.

(Reef) Degradation
The overall decline in coral reef habitats, coral cover, and structural complexity.

Disturbances
Events like storms, cyclones, and marine heatwaves that causes significant changes to the impacted area.

Ecosystem
A dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit.

Ecosystem function
The physical, chemical, and biological processes that take place within the ecosystem that may directly or indirectly contribute to ecosystem services.

Ecosystem services
Actions or attributes of ecosystems of benefit to humans, including regulation of the atmosphere, maintenance of soil fertility, food production, regulation of water flows, filtration of water, pest control and waste disposal. It also includes social and cultural services, such as the opportunity for people to experience nature.

Feasibility
The feasibility of success of an intervention as defined by its ability to be logistically feasible, at a scale sufficient to have the required impact on ecological function and affordable to deploy across entire reef scapes. The degree of success is dependent on funding, stakeholder and Traditional Owner support, regulatory capacity building, collaboration of key agencies and research providers, inclusion of private sector capability in the effort, and global action on climate change.

GBR
Great Barrier Reef.

GBRMP
Great Barrier Reef Marine Park.

GBRMPA
Great Barrier Reef Marine Park Authority.

Genetic diversity
The variety of genes among individuals of the same species, enabling it to adapt and thrive in different environments, especially in the face of climate change.

Genetic repository
A collection of genetic samples, preserving essential local genotypes of different species for future restoration activities. Also known as a "gene bank".

Habitat
The environment occupied by an organism or groups of organisms.

Habitat heterogeneity
The number of different habitats in an ecosystem. Increasing habitat heterogeneity can influence species diversity and community functions.

Habitat structure
The physical complexity of reef habitats. Reef environments with reduced habitat complexity will support only a fraction of the species and individuals found in complex flourishing reef habitats. High levels of habitat structure are a fundamental attribute of resilient coral reefs.

Herbivory
The process where organisms feed on plant material, predominantly algae, that grow on coral reefs. Herbivorous fishes and invertebrates are essential for maintaining the ecosystem's resilience. They prevent macroalgae from overgrowing and taking over the space and resources that corals need to thrive.

Hydrodynamic forces
The forces exerted by water motion, such as waves and currents, on objects immersed in water.

(Coral) Larvae
The initial stage in the life cycle of a coral (also see **planula**). Originating from eggs that are fertilised during spawning events, these larvae develop into a free-swimming form. This stage is crucial for the dispersal and subsequent settlement of corals.

Larval supply
The amount of larvae a coral population can successfully produce so that natural recruitment is sufficient for maintaining a population.

Materials of opportunity
Objects that were originally intended for other purposes, such as sunken ships, vehicles, and tyres, but were then repurposed as artificial reefs.

Microhabitat
A small, localized habitat within a larger ecosystem.

Near-bed wave orbital velocity
The speed and direction of water movement close to the seabed due to the influence of waves. Water particles move in an orbital path, with the orbits becoming flatter near the bottom, hence orbital.

Phase-shift
A shift in stable, alternately states of the community composition in an ecosystem. For example, a reef can shift from a coral-dominated state to an algal-dominated state when perturbed.

Pilot study
A small-scale feasibility study of methods conducted before a large-scale implementation.

(Coral) Planula
The stage of a coral's life cycle when it exists as a free-swimming larva, before it settles onto a substrate.

Reef accretion
The process of coral reef growth, both vertically and horizontally, due to the balance between calcium carbonate production and erosion.

Remote sensing
The acquisition of information about an object or phenomenon without making physical contact with the object. Examples include satellite imagery and LiDAR technology.

Resilience
The ability of a system to absorb changes, have reduced exposure to risk, and persist in the face of disturbances, or better yet, bounce back from any type of hazards. Hazards on the reef include bleaching events, floods, cyclones, crown-of-thorns outbreaks and long-term decreases in ocean pH. Understanding and promoting resilience-enhancing processes, such as coral recruitment, are critical for the conservation and management of coral reefs, especially in the context of climate change.

Restoration
An activity undertaken that helps to recover a degraded ecosystem. It can be classified into two types – active and passive restoration. **Active restoration** involves direct human intervention, such as deploying artificial structures to stabilise loose rubble beds. On the other hand, **passive restoration** relies on natural processes to recover, often achieved by simply removing the sources of degradation and allowing the ecosystem to heal itself. One example of passive restoration is establishing no-take zones in a Marine Protected Area.

RRAP
Reef Restoration and Adaptation Program. The program aims to develop effective interventions to help the Reef resist, adapt to, and recover from the impacts of climate change. It is funded by the partnership between the Australian Government's Reef Trust and the Great Barrier Reef Foundation.

Rubble
An umbrella term for fragments of dead coral or reef rock produced through a variety of biological, physical, and chemical processes that cause abrasion and weakening of the reef framework. The size of rubble pieces can range from just slightly larger than sand (over 2 mm) to large boulders (over 1 m).

Rubble binding
The process where rubble pieces are bound together by organisms such as sponges, macroalgae, and coralline algae.

Sedimentation
The process where water action leads to the deposition and accumulation of marine sediment, including both organic materials and minerals.

Species composition
The identity and proportion of different species in a particular area. Usually expressed as a percentage, with all species components adding up to 100%.

Species diversity
The number and relative abundance of different species in a particular area. It also accounts for how evenly the individuals are distributed among those species. A high species diversity means many different species are present, and no single species dominates the population.

Species richness
The number of species present in a particular area.

Spill-over effects
The net movement of fish from restored sites to adjacent areas. This happens when fish populations in restored sites grow and overflow into nearby regions

Stakeholders
Any person or party with an interest in rubble stabilisation efforts on the Great Barrier Reef. This usually includes reef communities or reef-dependent industries; and, with Indigenous Traditional Owners as rights-holders in, and custodians of, the Reef.

Stressor
A factor that causes stress and induce changes in an ecosystem. Examples include pollution, and diseases that affect the overall health of the ecosystem.

Structural complexity
The 3D structure of an ecosystem, which is largely shaped by the variety of organisms and geological features. This complexity plays a significant role in the health of coral reefs. Coral reefs that exhibit a higher degree of structural complexity are able to offer a more diverse range of microhabitats for different organisms and provide ecosystem services such as coastal protection.

Substrate
The materials that make up the seafloor, such as rubble, sand, or hard bottom surfaces.

Wave attenuation
The reduction of wave energy as it propagates through water. Large structures designed to break waves can reflect and dissipate wave energy, contributing to wave attenuation.

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Appendices

APPENDIX A – Rapid Rubble Bed Assessment – 3 pages

Reef:	Site:	Surveyor:	Reef zone (circle): Reef flat / lagoon | Patch reef | Reef Slope | Reef Crest	Date:

How much area have you covered?

- ☐ I stayed within one area (about ~10 m wide)
- ☐ I swam for 10-30 minutes
- ☐ I swam for >30 minutes

Are you snorkelling or scuba diving?

- ☐ Snorkelling
- ☐ SCUBA diving

Did the reef seem to be mostly coral or mostly rubble?

- ☐ Mostly coral
- ☐ Mostly rubble

When & what was the last major disturbance?

....

....

- ☐ I don't know

Looks like 'A' or 'C', in area 'G' ⟶ Leave it be - intervention difficult on slope

Looks like 'A', in area 'E' or 'F' ⟶ Consider intervention
(If bed is very thin & sandy like 'I'/'K', &/or competition high, e.g., macroalgae, soft corals, stabilisation alone not sufficient. Stabilise and add vertical relief)

Looks like 'B' ⟶ Leave it be but monitor
(Rubble vulnerable to movement. If thin & sandy ('I'/'K') corals vulnerable to burial/smothering)

Looks like 'C', in area 'E' or 'F' ⟶ Consider intervention
(Rubble fairly stable but other issue limiting recruitment, e.g., competition. Add vertical relief)

Looks like 'D' ⟶ Leave it be - least concern
(If bed is very thin and sandy like 'I'/'K', stabilisation alone not sufficient. Add vertical relief)

In area 'H' ⟶ Leave it be - natural

Bed size: Sml beds more likely to recover if surrounding coral cover is high. Lge beds - intervene.
Rubble movement: The more rubble moves when wafted, the more stabilisation is warranted.

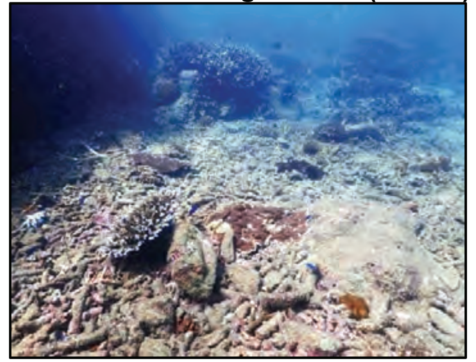
Rubble Bed #	What does the rubble bed look like? Photo A, B, C, D (& see N, O)	What kind of area is the rubble bed in? Photo E, F, G, H	How thick is the rubble bed? a: 1 or 2 layers b: Thicker than that (Photo I, J)	What is the substrate underneath the rubble? a: Sand b: Hard reef c: Can't see (too thick) (Photo K, L, M)	How wide is the rubble bed? a: < 10 m b: 10-20 m c: 20 m or more	When you waft the rubble in the bed, did it move? a: Yes b: No
1						
2						
3						
4						
5						
6						

What does the rubble bed look like? (*Tip: Larger rubble is more likely to be stable and more likely to be bound)

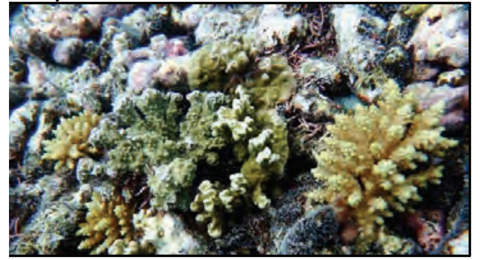
A: Sml pieces (<~10cm), few branches, NO medium-large corals (>10cm)

P Mumby

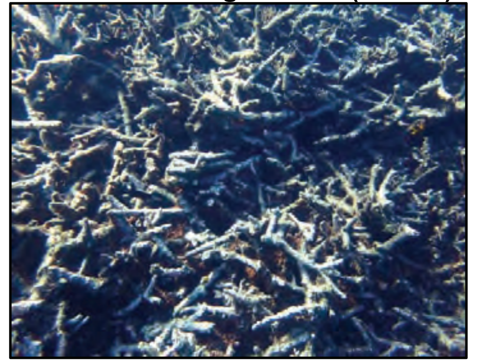
B: Small pieces, few branches, WITH medium-large corals (>10cm)



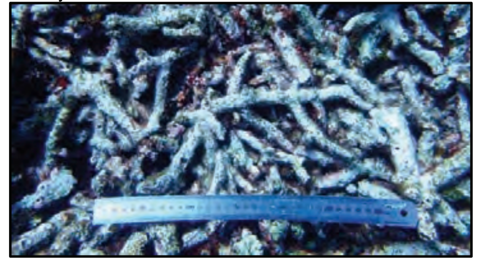
T Kenyon



C: Large pieces, very branchy, NO medium-large corals (>10cm)



T Kenyon

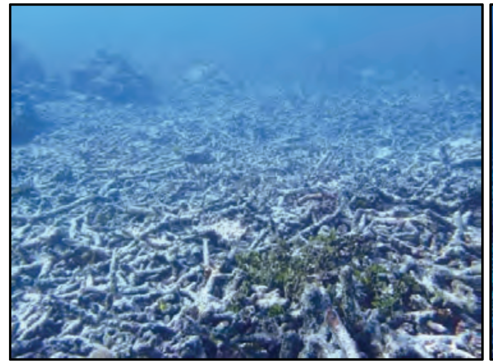


D: Large pieces, very branchy, WITH medium-large corals (>10cm)

T Kenyon

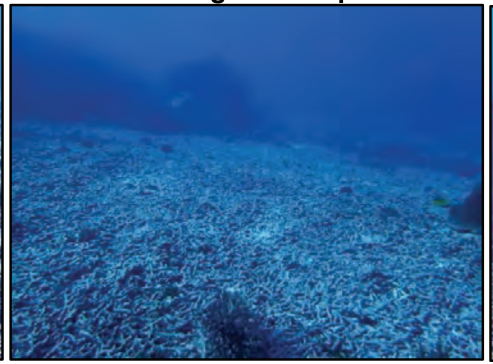
What kind of area is the rubble bed in? (*Tip: Rubble on slopes is more likely to be unstable, and rubble in depositional areas is natural)

E: On a flat area



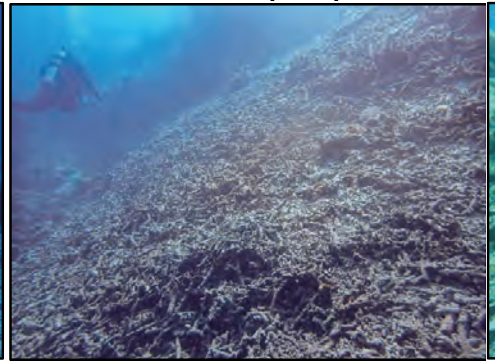
T Kenyon

F: On a gentle slope



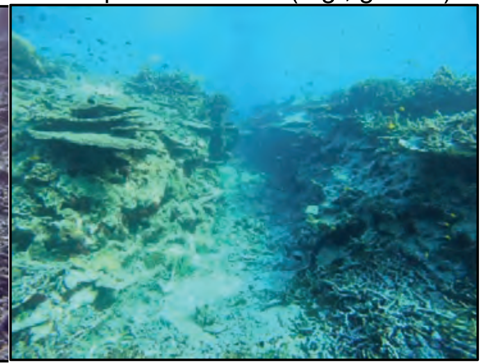
T Kenyon

G: On a steep slope



T Dodgen

H: Depositional area (e.g., groove)



T Kenyon

How thick is the rubble bed? (*Tip: Thicker beds are generally more stable & bound)

For more accuracy, you can poke a stick or ruler into the bed to gauge depth
Black void space between rubble indicates a thicker bed

I: Thinner bed (<~10cm)

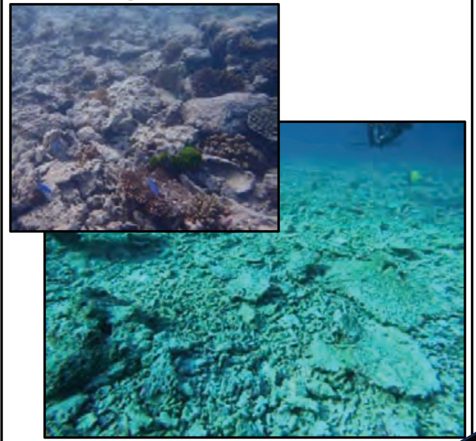
T Kenyon

J: Thicker bed

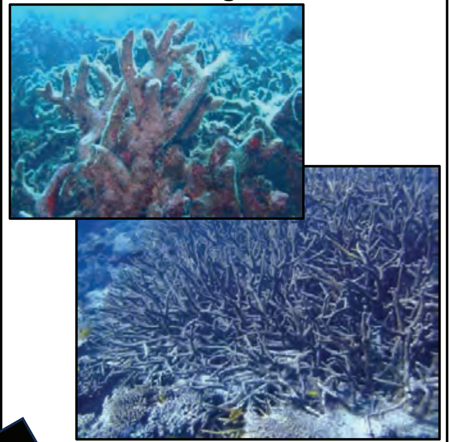
T Kenyon

Some things to keep in mind…

N: Plating rubble bed

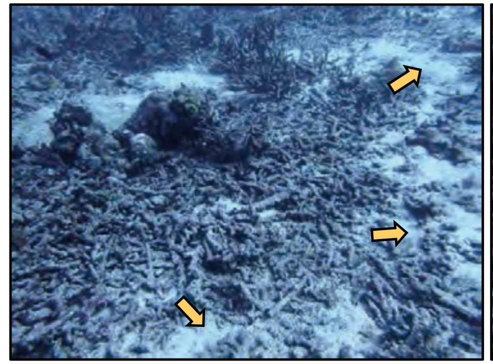


O: Dead standing coral



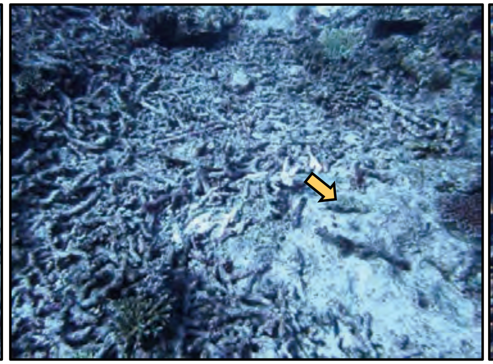
What is the substrate underneath the rubble? (*Tip: Sandy rubble is less likely to be bound & support coral)

K: Sand



T Kenyon

L: Hard carbonate reef



T Kenyon

M: Can't see (means that bed is likely thicker)

T Dodgen

The rubble shown in Photos A-D is mostly branching. Depositional areas commonly have plating rubble (Photo N). If a plating bed is NOT a depositional area, and there are no medium-large corals, the rubble may be mobile and/or there is another recruitment issue.

Note that dead standing coral (Photo O) is not yet rubble, but will break down into rubble over time – keep an eye on it!

Appendix B: Detailed Rubble Assessment

Rubble Bed Assessment – PART B) DETAILED ADD-ON

Surveyor name: **Date:** **Reef zone (circle):** reef slope / reef flat or lagoon / reef crest / groove
Reef: **Site:** **Transect #:** **Rubble bed length:** **Rubble bed width:**

Quad-rat	Photos (1 whole & 9 close-up) Tick	Total coral count (& size of each)	Slope angle Flat Gentle Steep	Rubble piece #	Stable? 0: very loose 1: movement but impeded 2: ~nil movement (And describe)	Binding present Y / N	To how many other rubble pieces?	What is the dominant binder (thing that seems to be doing most of the binding)? Describe, e.g., hard, soft, gooey, colour & take 1 photo pointing to rubble piece # on datasheet & 2nd photo of binding organism (close-up).	Widest span (cm)	Morphology Unbranched Branching Corymbose Plate Foliose Massive Unknown	How many branches	# of recruits <5 cm on rubble piece	Photo of piece top & underside with ruler for scale	Rubble bed thick-ness
				1.1										
1				1.2										
				1.3										
				2.1										
2				2.2										
				2.3										
				3.3										
3				3.4										
				3.5										
				4.1										
4				4.2										
				4.3										
				5.1										
5				5.2										
				5.3										

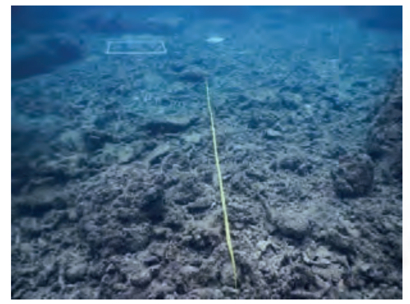
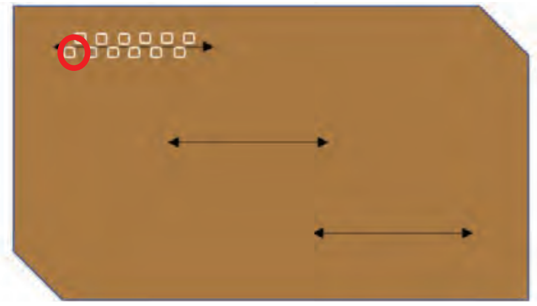
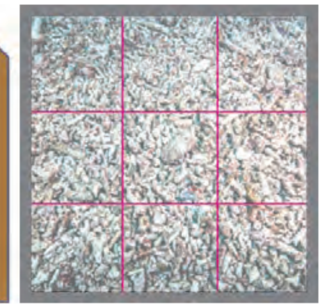
Surveyor name: Date: Reef zone (circle): reef slope / reef flat or lagoon / reef crest / groove
Reef: Site: Transect #: Rubble bed length: Rubble bed width:

Quad-rat	Photos (1 whole & 9 close-up) Tick	Total coral count (& size of each)	Slope angle Flat Gentle Steep	Rubble piece #	Stable? 0: very loose 1: movement but impeded 2: ~nil movement (And describe)	Binding present Y / N	To how many other rubble pieces?	What is the dominant binder (thing that seems to be doing most of the binding)? Describe, e.g., hard, soft, gooey, colour & take 1 photo pointing to rubble piece # on datasheet & 2nd photo of binding organism (close-up).	Widest span (cm)	Morphology Unbranched Branching Corymbose Plate Foliose Massive Unknown	How many branches	# of recruits <5 cm on rubble piece	Photo of piece top & underside with ruler for scale	Rubble bed thick-ness
				6.1										
6				6.2										
				6.3										
				7.1										
7				7.2										
				7.3										
				8.1										
8				8.2										
				8.3										
				9.1										
9				9.2										
				9.3										
				10.1										
10				10.2										
				10.3										

APPENDIX B – Detailed add-on to the Rapid Rubble Bed Assessment – Methods Guide – 2 pages

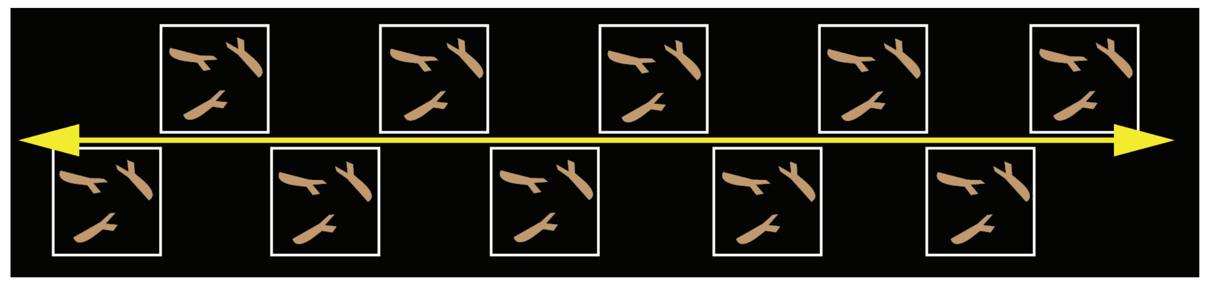
In each rubble bed (if it's large enough)

- Lay 3, 10-m transect tapes (each transect tape = datasheet Part B pg1 and 2 above)
- Place the first quadrat at 0 m (circled below), then place the next quadrat at 1 m on the opposite side, the next at 2 m, and so on until the end of the transect.

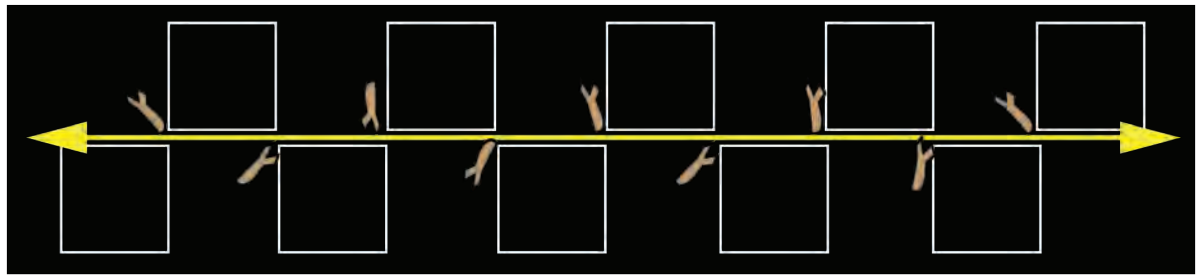
For each quadrat:

- Take a photo (to determine % cover later of coral & other benthic categories). Take 9 closer-up photos of the quadrat too to improve resolution.
- Count and measure all corals in the quadrat (no touching rubble, just look from above and sides). This gives better resolution than just % coral cover and means you know coral abundance across all sizes as well as % coral cover.
- Record the quadrat slope.
- Pick 3 rubble pieces at random to record: stability, binding, widest span, morphology, # of branches, # of recruits (on all sides of piece), and photo of each piece. Total = 30 rubble pieces per transect.
  - Stability: Considered a '0' if piece came away from substrate without any interference, i.e., being interlocked with another piece, or half buried in sand/rubble. If there is interference that requires manoeuvring the rubble piece to lift it away from the substrate, it's a '1'. If interference means rubble piece is hardly moving or needs to be broken to be removed, it's a '2'.
  - Binding: A bind is defined as where an organism is attached to one rubble piece and bridges to a second piece. A sampled rubble piece can be bound, for example, to multiple other rubble pieces each by one bind, or it can be bound only to one other rubble piece, but by multiple binds.
  - Widest span: Measured as the widest span in any direction.
  - Branches: Number of branches > 1 cm are counted.
- Lastly, measure the rubble bed thickness within the quadrat. Insert a thin (~6 mm diameter) stainless-steel rod into the rubble until it will go no further. Seek gaps where possible and 'jiggle' the rod to ensure it doesn't hit a buried rubble piece and underestimate thickness.



Using the above methods, 3 transects and 30 rubble pieces per transect might take 2-3 dives with a buddy team. If you don't have enough time for this, cutting out the following should reduce it to 1 dive with a buddy team.

- Cut out the counting and measuring of ALL corals in the quadrat, and instead count only those <5 cm (recruit abundance only), or even more simply, only get % coral cover from photo.
- Cut out the photos of each rubble piece, and cut out column "To how many other rubble pieces?"
- Rather than take 3 rubble pieces from each quadrat, take 1 rubble piece at 1m, 1 piece at 2m, and so on, at the top of the quadrat. Total = 10 rubble pieces per transect. Only fill in data for rubble pieces 1.1, 2.1, 3.1, 4.1, 5.1, 6.1, 7.1, 8.1, 9.1 and 10.1 on the datasheet, if using this method.



Appendix C: Workshop Survey Questions

Workshop Survey

1. **Which of the following methods* have you used before?** (Multiple choice)
2. **How familiar^ are you with the methods?** (Multiple choice)
3. **How many restoration sites have you worked on for each method?**
4. **What are the reasons for not implementing these methods at your sites#?** (Multiple choice)
5. **Tell us about your experience with different stabilisation method**s, including the method details, the restoration site's location and environment conditions, any past disturbances, and costs of installation and maintenance. (Multiple choice and text entry in a table)

Question type	Method details	Site's location and environment conditions	Disturbance history	Costs
Questions	• Method type* • Structural material • Length (m) • Width (m) • Height (m) • Grid cell size (for structures like meshes) • Length of whole installation (m) • Width of whole installation (m) • Number of units in whole installation	• Site name • Type of environment^^ • Country • Latitude (decimal degrees) • Longitude (decimal degrees) • Average wave height (m) • Average current speed (m/s) • Current Strength category • Maximum safe wind speed for boating • What percentage of the year is boating not possible due to high winds? (%) • Depth (m) • Steepness • Deposited sediment load • Median rubble piece size • Rubble piece morphology • Rubble bed length (m) • Rubble bed width (m) • Rubble bed thickness (m) • Dominant cover on rubble prior to installation (e.g., bare, CCA, turf, sessile invertebrates, soft coral, hard coral) • Were corals outplanted? • Larval supply (low, medium, high, or unknown?) • Underlying substrate - e.g., if the rubble bed is thin, can you see sand, hard carbonate, or consolidated rubble?	• Main type of disturbance that caused rubble • Other sources of disturbances that caused rubble • Major disturbances that have occurred since installation (list) • Number of years from the disturbance event to the installation • Number of years from the installation to the last monitoring • Suspected key issues affecting coral recovery (in order etc...)	• Material cost per unit (USD) • Cost of labour required for manufacturing per unit (USD) • Overall cost per unit • Cost of installation (USD) • Number of people required for installation • Minimum number of people required for installation • What are the tasks involved in maintenance? • Interval between routine maintenance (months) • Maintenance Cost (USD) per trip • Number of people required for each maintenance visit • How much time is typically spent on each maintenance visit? • Interval between routine monitoring (months) • Monitoring Cost (USD) per trip • Number of people required for each monitoring visit

6. **Please describe the coral metrics for natural corals at each site over time****. Questions include: (Multiple choice and text entry in a table)
    - Was rubble movement under or in vicinity of structures impeded compared to surrounding rubble?
    - What is the average percentage of juveniles, subadults, and adults you observe that are in each size category (%) under/on structures and on surrounding rubble?
    - What is the average natural coral cover under/on structures and on surrounding rubble? (%)
    - What is the average density of juveniles/total natural corals under/on structures, on settlement tiles, and on surrounding rubble per square metre?
    - What is the dominant coral type under/on structures and on surrounding rubble?
    - Assemblage## of natural coral under/on structures and on surrounding rubble (%)
    - How did you determine the answers (survey data or best guess)?

7. **Please describe the coral metrics for outplanted corals (if applicable) at each site over time****. Questions include: (Multiple choice and text entry in a table)
    - What is the average percentage of juveniles, subadults, and adults you observe that are in each size category (%) under/on structures?
    - What is the average outplanted coral cover under/on structures? (%)
    - What is the average density of juveniles/total natural corals under/on structures per square metre?
    - What is the average size of coral outplants?
    - What is the dominant coral type under/on structures?
    - Assemblage## of natural coral under/on structures (%)
    - How did you determine the answers (survey data or best guess)?

8. **Have you tried applying the methods in these types of environments^?** (Multiple choice) Choices include:
    - Yes, outcomes described above
    - No, but would expect some success
    - No, because I don't think it would work

9. **Why do you think the following method(s) won't work in these environments^^?** (Text entry)

*Method choices

- Rock piles
- Reef stars
- A-frame structure
- Pyramid structure (open bottom)
- Rebar webs (not peaked)
- Framed reef modules
- Turtle(-shaped) frame
- Reef balls
- Concrete/cement blocks (square/rectangular)
- Step reef units
- EcoReef modules
- Flat mesh (plastic)
- Flat mesh (coir)
- Flat mesh (metal)
- Barrier fencing
- Rubble removal
- Reef bags
- Bio-adhesives
- Other (please specify): ________

^Levels of familiarity

- **Very familiar**
  I have used or monitored this method multiple times and/or as part of an in-depth, long-term study.
- **Familiar**
  I have used or monitored this method at least once, but not necessarily as part of an in-depth, long-term study
- **Somewhat familiar**
  I haven't used or monitored it personally, but I've learnt about outcomes through my colleagues/friends/papers
- **Not familiar**
  I have never used or monitored it and/or don't know much about outcomes

#Reasons for not implementing a particular method

- I think it would work but I haven't had the chance to
- I didn't think it would achieve my conservation goals
- I haven't heard of it
- It wasn't applicable at the sites I worked on (e.g., Barrier Fencing and Step reef units applicable to sloped sites only)
- It was too expensive to implement
- It was too logistically challenging to implement
- It was already present at the site
- I didn't think it would fit aesthetically at the site
- Other (please specify): ________

**Time categories

- Pre-installation
- At the time of installation
- After 1 year
- After 2 years
- After 3 years
- After 5 years
- After 10 years
- After 20 years

^^Environment types

- Reef flat
- Lagoon
- Patch reef
- Reef slope (shallow and exposed)
- Reef slope (shallow and intermediate exposure)
- Reef slope (shallow and sheltered)
- Reef slope (deep and exposed)
- Reef slope (deep and intermediate exposure)
- Reef slope (deep and sheltered)
- Other (please specify): ________

Coral types (assemblage)

- Branching Acropora
- Table/plate
- Massive
- Encrusting
- Other corals (please specify): ________

REEF RESTORATION & ADAPTATION PROGRAM
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QUT
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