Coral Conservation

Global evidence for the effects of actions

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Cover image: Healthy coral reef. Photograph by Oleksandr Sushko at Unsplash, https://unsplash.com/photos/an-underwater-view-of-a-coral-reef-with-fish-7AmBaTymwJg.

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12. Habitat restoration and creation

Background

Habitat destruction is the greatest threat to biodiversity worldwide and habitat protection remains one of the most important and frequently used conservation actions. However, in many parts of the world, restoring damaged habitats, improving habitats through altering management regimes, or creating new habitat may also be possible. The role of restoration ecology in conservation is well established (Dobson *et al*. 1997), and there is a growing movement within the more specific field of coral reef restoration (Vardi *et al*. 2021), with a rapidly developing evidence base (Boström-Einarsson *et al*. 2020).

Habitat restoration for corals includes actions aimed at stabilizing damaged reefs and the use of natural materials or unnatural materials and structures to restore, repair or create habitat for natural coral settlement. This includes the use of settlement tiles and the repurposing and modification of existing and obsolete man-made offshore structures.

For studies describing attempts to restore habitats indirectly through the designation of legal or other protections, see *Habitat protection*, and for those restoring habitats through cultivating or transplanting of corals see *Species management*.

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Here, descriptive studies of biodiversity on or around man-made structures already in place, such as oil rigs and wind farms, are not included, unless they were specifically deployed or modified to enhance local coral diversity or left in place following decommissioning, to act as artificial reefs.

Boström-Einarsson L., Babcock R.C., Bayraktarov E., Ceccarelli D., Cook N., Ferse S.C., Hancock B., Harrison P., Hein M., Shaver E., Smith A., Suggett D., Stewart-Sinclair P.J., Vardi T. & Mcleod I.M. (2020) Coral restoration – A systematic review of current methods, successes, failures and future directions. *PloS One*, 15, e0226631. https://doi.org/10.1371/journal.pone.0226631

Dobson A.P., Bradshaw A.D. & Baker A.J. (1997) Hopes for the future: restoration ecology and conservation biology. *Science*, 277, 515–522. https://www.science.org/doi/10.1126/science.277.5325.515

Vardi T., Hoot W.C., Levy J., Shaver E., Winters R.S., Banaszak A.T., Baums I.B., Chamberland V.F., Cook N., Gulko D., Hein M.Y., Kaufman L., Loewe M., Lundgren P., Lustic C., MacGowan P., Matz M.V., McGonigle M., McLeod I., Moore J., Moore T., Pivard S., Joseph Pollock F., Rinkevich B., Suggett D.J., Suleiman S., Shay Viehman T., Villalobos T., Weis V.M., Wolke C. & Montoya-Maya, P.H. (2021) Six priorities to advance the science and practice of coral reef restoration worldwide. *Restoration Ecology*, 29, e13498. https://doi.org/10.1111/rec.13498

Natural habitat restoration/creation

12.1 Use natural materials to restore/repair/create habitat for corals to encourage natural coral settlement

https://www.conservationevidence.com/actions/3987

- **Four studies** evaluated the effects of restoring / repairing / creating habitat for corals using natural material to encourage coral settlement. Two were in Indonesia[2a,b] and one study was in each of Israel[1] and Australia[3].

COMMUNITY RESPONSE (1 STUDY)

- **Richness/diversity (1 study)**: One site comparison study in Israel[1] found that large rocks placed in an orderly pattern had a lower diversity of coral species than natural reef patches.

POPULATION RESPONSE (2 STUDIES)

- **Abundance/Cover (4 studies)**: Three of four studies (two replicated including one controlled, and one site comparison) in Israel[1], Indonesia[2a,b], and Australia[3] found that using piles of rocks to create reefs led to higher numbers of corals colonizing when rocks were randomly aggregated compared to orderly[1], in different patterns[2b] or bare rubble[2a,b]. The fourth study[3] found that repositioned coral columns ('bommies') retained live coral tissue and were colonized by other coral species.

Background

Man-made reefs provide a solution to the pressure of human activity by expanding the available habitat on which corals can naturally settle and colonize (Abelson & Schlesinger 2002). Using natural material to restore or create habitat for corals to settle on can provide a more sustainable option than using unnatural materials. Natural materials can be coral rock/rubble, limestone rock, or calcium carbonate substrate such as giant clam *Hippopus* and *Tridacna* shells (Neo *et al*. 2015). They can also be 'living' materials such as coral outcrops (sometimes known as 'bommies'), comprising habitat-forming species of coral (e.g., *Porites* spp.) that can provide a substrate for other corals to colonize. Using natural material to construct reefs can enable corals to settle, particularly if the material being used is similar to nearby substrate. In addition, natural materials can offer an opportunity to design a reef which closely resembles the natural surroundings.

Here we focus on the creation of reef structures using natural materials to encourage subsequent settlement by wild coral from existing populations in the vicinity. Other similar actions include *Use structures made from unnatural materials to restore/repair/create habitat for corals to encourage natural coral settlement; Stabilize damaged or broken coral reef substrate*. Actions relating to transplanting or cultivating coral species on natural substrates are covered in *Transplant nursery-grown corals onto natural substrate; Transplant wild-grown corals onto natural substrate; Cultivate coral fragments in an artificial nursery located in a natural habitat*; and *Cultivate coral larvae in an artificial nursery located in a natural habitat*.

Abelson A. & Shlesinger Y. (2002) Comparison of the development of coral and fish communities on rock-aggregated artificial reefs in Eilat, Red Sea. *ICES Journal of Marine Science*, 59, S122–S126. https://doi.org/10.1006/jmsc.2002.1210

Neo M.L., Eckman W., Vicentuan K., Teo S.L.-M. & Todd P.A. (2015) The ecological significance of Giant Clams in coral reef ecosystems. *Biological Conservation*, 181, 111–123. https://doi.org/10.1016/j.biocon.2014.11.004

A site comparison study in 1989–1998 of two man-made reefs in the Gulf of Aqaba, near Eilat, Israel (1), found that a reef comprising randomly aggregated piles of smaller rocks had a greater number of coral species than one comprising orderly aggregated piles of larger rocks, and the orderly aggregated reef had a lower number of coral species than the nearby natural reef. Species richness was higher on a reef with randomly aggregated piles of small rocks (33 species) than one with orderly aggregated piles of larger rocks (25 species) after 8.3 years. The average number of coral species and number of individuals were significantly lower on the orderly aggregated reef (8 species, 17 individuals) compared to a natural reef located 100 m away (18 species, 58 individuals) after seven years. Two artificial reefs, constructed using limestone rocks to imitate the substrate on the nearby natural reef, were deployed in December 1989, one hundred meters south of a Coral Reserve. One reef comprised randomly aggregated piles of rocks (area: 4.9 m^2, average rock diameter 18.9 cm) and the other orderly aggregated piles of rocks (area: 12 m^2, average rock diameter 49.5 cm). Coral species were visually recorded on the two artificial reefs every 4–6 months for four years and eight months, then with a single survey eight years and four months after deployment. Comparison between the orderly aggregated and natural reef was made during a single transect survey in 1996.

A replicated, controlled study in 2000–2003 at nine coral rubble sites in the Komodo National Park, Indonesia (2a) found that using rock piles to create reefs led to higher numbers of stony coral recruits and greater area covered by coral than sites left as bare rubble. The average number of stony corals increased during the study period from 1–21/m^2 (six months after rock pile installation) to 1–42/m^2 (three years after installation) (data not statistically tested). The average area covered by corals increased from 0–19 cm^2/m^2 (six months after installation) to 14–1262 cm^2/m^2 (three years after installation). There was no detectable increase in coral numbers or coverage on the bare rubble control site. In spring 2000, piles of limestone and lithic sandstone rocks (0.5–2.0 m^3) were placed inside three or four 10 m^2 areas of coral rubble substrate at each of nine sites. Rock piles were 70–90 cm high and placed 2–4 m apart. Surveys were carried out every 6 months until May 2002 then a final survey in March 2003. Coral recruits were counted, and area covered by coral was measured using 1 m^2 quadrats.

A study in 2002–2003 at four coral rubble sites in the Komodo National Park, Indonesia (2b), reported that stony corals settled on rocks piled in different patterns whereas none settled on areas of bare rubble. Six–twelve months after rock piles were installed, average coral numbers were 7/m^2 (4–14/m^2) and the average size of corals was 8 cm^2 (3–11 cm^2). Data were not statistically tested. In March–September 2002, rock piles each ~140 m^3 and comprising limestone and lithic sandstone were installed in different patterns at four sites with >1000 m^2 of coral rubble substrate. Site 1: rocks completely covered the site ~75 cm high; site 2: rock piles 1–2 m^3 were placed every 2–3 m; site 3: spurs ~75 cm high, 2 m wide were placed every 2–3 m parallel to the prevailing current; site 4: spurs ~75 cm high, 2 m wide were placed every 2–3 m perpendicular to the prevailing current. Sites were surveyed once in March 2003 (6–12 months after rocks were installed). Coral recruits were counted and measured using 1 m^2 quadrats. An area of bare rubble adjacent to each site was surveyed for comparison.

A replicated study in 2017–2018 off Whitsunday Island, Great Barrier Reef, Australia (3) found that following the repositioning of displaced column-shaped coral outcrops ('bommies') of stony coral *Porites* spp. colonies, some live tissue was retained, and other coral species colonized them. Sixteen months after bommies were repositioned, coverage of original live tissue ranged from 0–20% (average 6%) with 16 of the 22 bommies surveyed still retaining some live tissue. Thirteen of the 22 bommies were colonized by other corals including species of *Pocillopora, Cyphastrea, Favia, Favites, Goniastrea, Psammocora* and *Hydnophora*). Eight bommies had at least one coral recruit, four had at least two, and one had six. Recruits ranged from 3–15 cm in diameter. In March 2017, a cyclone dislodged bommies of *Porites* spp. colonies (1–3 m diameter) and deposited them on the intertidal zone. In June 2017 heavy machinery was used to roll the bommies back into the subtidal region along with 100 m^3 of dead coral rubble. Divers surveyed coral bommies in October 2018, recording live tissue coverage (%) and identifying coral species recruited onto the bommie. **Costs (AUS$)**: The costs (reported in 2019) to reposition dead coral rubble were ~AUS$30,000 (it is not reported whether this included the bommie repositioning).

(1) Abelson A. & Shlesinger Y. (2002) Comparison of the development of coral and fish communities on rock-aggregated artificial reefs in Eilat, Red Sea. *ICES Journal of Marine Science*, 59, S122–S126. https://doi.org/10.1006/jmsc.2002.1210

(2) Fox H.E., Mous P.J., Pet J.S., Muljadi A.H. & Caldwell R.L. (2005) Experimental assessment of coral reef rehabilitation following blast fishing. *Conservation Biology*, 19, 98–107. https://doi.org/10.1111/j.1523-1739.2005.00261.x

(3) McLeod I.M., Williamson D.H., Taylor S., Srinivasan M., Read M., Boxer C., Mattocks N. & Ceccarelli D.M. (2019) Bommies away! Logistics and early effects of repositioning 400 tonnes of displaced coral colonies following cyclone impacts on the Great Barrier Reef. *Ecological Management and Restoration*, 20, 262–265. https://doi.org/10.1111/emr.12381

12.2 Stabilize damaged or broken coral reef substrate or remove unconsolidated rubble

https://www.conservationevidence.com/actions/3988

- **Six studies** examined the effects of stabilizing damaged or broken coral reef substrate or removing unconsolidated rubble on coral colonies. Three studies were in Indonesia[2,3,6], and one was in each of the Maldives[1], the Phillipines[4,] and Puerto Rico[5].

COMMUNITY RESPONSE (0 STUDIES)

POPULATION RESPONSE (4 STUDIES)

- **Abundance/Cover (5 studies)**: Five studies (three replicated, including two controlled) in the Maldives[1], Indonesia[2,3,6], and the Philippines[4] reported that in areas where degraded coral reefs were stabilized, coral numbers[1,2,3] and coverage[1,3,4,6] increased compared to those with unstablized coral rubble. One of the studies[3] found that coral numbers and coverage varied between reefs stabilized with rock piles compared to other materials, another study[6] found density varied with different configurations of rock piles and one study[1] found more corals on structures designed to provide a high level of stability.
- **Survival (1 studies)**: One controlled study in the Philippines[4] found that on areas where coral reef was stabilized stony coral survived and survival was higher than in unstabilized areas.
- **Condition (1 study)**: A study in Puerto Rico[5] reported that stabilizing a patch of damaged coral reef, as well as transplanting wild-grown and nursery-grown fragments of staghorn coral, led to the patch of restored reef more than doubling in size, whereas no growth was reported on an unstabilized patch.

Background

Historically, coral ‘rock’ has been extracted from reefs for use in construction. The practice involves removing the top 0.5 m of the coral structure (Clark & Edwards, 1999). The remaining reef comprises broken/loose coral and coral ‘rubble’ (Clark & Edwards, 1999). Other actions, such as ‘blast fishing’ (the use of dynamite to bring fish to the surface) have a similarly devastating effect on coral reefs (Raymundo *et al*. 2007). Stabilizing damaged or degraded coral reefs using natural or unnatural materials can provide a stable substrate enabling coral colonies to re-establish. Stabilized reefs are likely to be more resilient to the impact of storms (Raymundo *et al*. 2007).

This action is specifically related to the effectiveness of ‘stabilizing’ an existing coral reef/rubble substrate. Actions relating to the restoration or creation of reefs using natural or unnatural materials are summarized in sections *Use natural materials to* restore*/repair/create habitat to encourage coral settlement; Use structures made from unnatural materials to* restore*/repair/create habitat to encourage coral settlement*. Coral settlement happens by natural colonization from existing wild colonies in the vicinity. Actions relating to cultivating or transplanting corals onto stabilized reefs are covered in *Cultivate coral fragments in an artificial nursery located in a natural habitat; Cultivate coral larvae in an artificial nursery located in a natural habitat; Transplant nursery-grown corals onto natural substrate; Transplant nursery-grown corals onto artificial substrate; Transplant wild-grown corals onto natural substrate; Transplant wild-grown corals onto artificial substrate; Change transplant attachment method*.

Clark S. & Edwards A.J. (1999) An evaluation of artificial reef structures as tools for marine habitat rehabilitation in the Maldives. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 9, 5–21. https://doi.org/10.1002/(SICI)1099-0755(199901/02)9:1<5::AID-AQC330>3.0.CO;2-U

Raymundo L.J., Maypa A.P., Gomez E.D., Cadiz P. (2007) Can dynamite-blasted reefs recover? A novel, low-tech approach to stimulating natural recovery in fish and coral populations. *Marine Pollution Bulletin*, 54, 1009–1019. https://doi.org/10.1016/j.marpolbul.2007.02.006

A study in 1990–1993 at an area of degraded coral reef in Galu Falhu, Maldives (1) reported that using artificial structures to provide greater stability to coral rubble substrate led to an increase in the number of coral colonies. After 3.5 years, approximately 500 coral colonies (average density 13/m^2) were recorded on structurally complex concrete/PVC blocks that provided high substrate stability. After 3.5 years, average density on concrete mats that provided medium stability was 3 recruits/m^2 but 18/m^2 on the edges. After 3.5 years, some corals were observed attached to chain link fencing designed to provide low stability (numbers not reported). After 2.5 years, coral coverage on the unstabilized rubble had declined from 0.8% to 0.19%. In 1990–1991, four 10 × 5 m areas of previously mined coral rubble substrate at four sites each received one of three artificial substrate-stabilizing structures or were left unstabilized. Structures comprised complex concrete/PVC blocks (providing high stability), concrete mats (medium stability), or chain-link fencing (low stability) (see paper for design). Structures were deployed 0.5–1.8 m deep and were either sufficiently heavy to prevent movement by wave action or, for the concrete mats and chain-link fencing, weighted down using paving slabs. Monitoring took place at 8–12 month intervals for 2.5–3.5 years. **Costs (UK£)** (presented in 1999): concrete/PVC blocks £210/m^2; concrete mats £66/m^2; chain-link fencing £26/m^2.

A replicated study in 2000 at a degraded coral reef in Komodo National Park, eastern Indonesia (2) reported that stabilizing damaged coral substrate using piles of quarried rocks led to an increase in stony coral numbers compared to unstabilized coral rubble. Results were not tested for statistical significance. After six months, stony coral numbers on the stabilized reef ranged from 1–20/m^2 and after 12 months 1–36/m^2 compared to no observed increase in coral numbers on the unstabilized areas (data not reported). In April 2000, three or more 0.5–2.0 m^3 rock piles were installed at each of nine sites with coral-rubble substrate (comprising dead coral fragments) across Komodo National Park. Sites were surveyed for stony coral recruits in October 2000 and April 2001 using six 1 m^2 quadrats/site. **Costs (US$)**: US$ 5–10/m^2 (reported in 2001).

A replicated, controlled study in 1998–2001 at nine coral rubble sites in the Komodo National Park, Indonesia (3) found that stabilizing coral rubble using piles of rocks led to a higher number and coverage of coral recruits compared to rubble stabilized using cement blocks, or netting, or unstabilized rubble. After three years, the average number of corals was highest on rock piles (13/plot) followed by cement blocks (11/plot) and netting (7/plot) and lowest on unstabilized rubble (5/plot). Average area (cm^2/plot) covered by coral recruits was highest on rock piles (476 cm^2), followed by cement blocks (270 cm^2), and netting (253 cm^2), and lowest on unstabilized rubble (188 cm^2). In October and November 1998, two–four 1 m^2 plots were placed at each site with either rock piles (20–40 cm high, rocks 20–30 cm diameter), cement blocks, or netting (~5 cm mesh) pinned to the substrate. An additional four plots/sites were left as unstabilized rubble. The number of coral recruits and area covered was recorded every six months for three years. Plots began to degrade after 2.5 years due to strong currents.

A controlled study in 2003–2006 on a platform/patch coral reef in Negros Oriental, Philippines (4) found that in plots where rubble was stabilized with plastic mesh carpets and stone piles, new stony corals settled and had greater survival and cover than corals on unstabilized rubble. On stabilized plots established in the spawning season, corals settled within three months and reached 1–8 individuals/m^2 after 36 months. On plots established after spawning, they settled within a year and reached 4–7 individuals/m^2 after 32 months. Over a 10-month period after settlement, coral survival and colony size was greater on stabilized plots (survival: 63%, diameter: 6 cm) than unstabilized rubble (survival: 6%, diameter: 2–4 cm). Two years after establishment, stabilized plots had a higher average coverage of corals (19%) than unstabilized rubble (8%), but lower than adjacent healthy reef (44%). Five 17.5 m^2 plots were established, three in June 2003 (coral spawning season) and two in October 2003 (before storm season). Plots were at the edge of a 2,400 m^2 rubble field created by dynamite fishing, within a platform/patch reef in the Calagcalag Marine Protected Area. In the plots and the areas in between, plastic mesh carpets (2 cm mesh) were anchored to the rubble with metal stakes (with holes cut to accommodate existing coral), and rock piles (1 pile/0.5 m^2, 1 m high) were placed on top of the mesh. Corals in plots and in transects through untreated rubble and adjacent healthy reef were counted 1–4 times/year for three years. In May 2004, ten to twelve coral recruits from each plot established in June 2003 (total 30 recruits) and 25 recruits from the rubble field were tagged and monitored for growth and survival for 10 months.

A study in 2006–2014 at a damaged coral reef site in Tallaboa, Puerto Rico (5) reported that stabilizing the substrate along with transplanting wild-grown and nursery-grown fragments of staghorn coral *Acropora cervicornis*, led to the area of restored reef increasing. After eight years, the area of restored reef had grown from 70 m^2 to 180 m^2. Coral colonies in unrestored areas in the vicinity, with loose rubble and damaged substrate, showed no signs of recovery during the same period. It was not possible to determine from the study how much of the recovery was attributable to stabilizing the substrate, transplanting loose fragments, or transplanting nursery-grown fragments. In 2006, following the destruction of a coral reef by a ship grounding, wire cages and metal stakes were used to stabilize a 70 m^2 area of damaged reef. Approximately 227 (10–20 cm) loose fragments of staghorn coral were collected from nearby reefs and attached to the substrate using cement puddles. In 2009–2011, approximately 400 (20–40 cm) fragments of staghorn coral were collected from a nursery and attached to the substrate using masonry nails, cable ties and/or epoxy. Coral recovery was measured using aerial imagery in 2014. No other methods are reported.

A replicated, controlled, before-and-after study in 2002–2016 at four sites in Komodo National Park, eastern Indonesia (6) found that using piles of quarried rocks to stabilize coral rubble substrate resulted in an increase in coral density compared to unstabilized rubble, and coral cover varied on different rock configurations. Average stony coral cover on the rock piles increased over time and reached 45% after 14 years compared to 3% on the adjacent unstabilized coral rubble site. Coral cover varied between rock configurations (range: single rock: 3–68%; small piles: 20–61%; parallel: 24–83%; perpendicular: 39–68%). In 2002, over 6,000 m^2 of quarried rock (20–30 cm diameter) was placed 6–10 m deep at four sites within the Komodo National Park (Gillawadarat, Karang Makassar, Padar, and Papagarang). Rocks were placed in different configurations: single rock pile; small piles 1–2 m^3; parallel to the prevailing current;

and perpendicular to the prevailing current. Rock piles were surveyed in 2004, 2008 and 2016 using five–eight 1 m^2 quadrats that the authors selectively placed to capture the range and type of cover.

(1) Clark S. & Edwards A.J. (1999) An evaluation of artificial reef structures as tools for marine habitat rehabilitation in the Maldives. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 9, 5–21. https://doi.org/10.1002/(SICI)1099-0755(199901/02)9:1<5::AID-AQC330>3.0.CO;2-U

(2) Fox H.E. & Pet J.S. (2001) Pilot study suggests viable options for reef restoration in Komodo National Park. *Coral Reefs*, 20, 219–220. https://doi.org/10.1007/s003380100175

(3) Fox H.E., Mous P.J., Pet J.S., Muljadi A.H. & Caldwell R.L. (2005) Experimental assessment of coral reef rehabilitation following blast fishing. *Conservation Biology*, 19, 98–107. https://doi.org/10.1111/j.1523-1739.2005.00261.x

(4) Raymundo L.J., Maypa A.P., Gomez E.D., Cadiz P. (2007) Can dynamite-blasted reefs recover? A novel, low-tech approach to stimulating natural recovery in fish and coral populations. *Marine Pollution Bulletin*, 54(7), 1009–1019. https://doi.org/10.1016/j.marpolbul.2007.02.006

(5) Griffin S.P., Nemeth M.I. Moore T.D. & Gintert B. (2015). Restoration using *Acropora cervicornis* at the T/V MARGARA grounding site. *Coral Reefs*, 34, 885–885. https://doi.org/10.1007/s00338-015-1310-2

(6) Fox H.E., Harris J.L., Darling E.S., Ahmadia G.N., Estradivari & Razak T.B. (2019) Rebuilding coral reefs: success (and failure) 16 years after low-cost, low-tech restoration. *Restoration Ecology*, 27, 862–869. https://doi.org/10.1111/rec.12935

Artificial habitat creation

12.3 Use structures made from unnatural materials to restore/repair /create habitat for corals to encourage natural coral settlement

https://www.conservationevidence.com/actions/3989

- **Ten studies** examined the effects of using unnatural materials to create habitat to encourage coral settlement. Five studies were in the USA[1,3,5,6,10], two in Singapore[4,9] and one in each of Hong Kong[2], Indonesia[7], and Japan[8].

COMMUNITY RESPONSE (2 STUDIES)

- **Richness/diversity (2 studies)**: One site comparison study in the USA[3] found that diversity of corals settled on concrete or limerock was similar to a natural reef. Another site comparison study in Japan[8] found that diversity of corals settled on ropes was higher than on some natural reefs.

POPULATION RESPONSE (10 STUDIES)

- **Abundance/Cover (10 studies)**: Ten studies (five replicated, including one controlled, and one randomized, controlled) in the USA[1,3,5,6,10], Hong Kong[2], Singapore[4,9], Indonesia[7], and Japan[8] found that coral settled on unnatural materials. Two of the studies[1,2] found that the number of corals settling depended on settlement substrate material. Two studies[4,10,] found that coral settlement was higher on fibreglass/sand/calcium carbonate[4], and concrete[10] substrate than on the surrounding natural reef. Three studies[3,5,6,] found that coral cover[5,6,] and density[3,5,] on concrete and/or limerock[3,5,] and concrete/limestone[6] substrate became similar to the natural reef. One study[7] found that the number of coral recruits was similar whether concrete structures were next to or away from transplanted adult colonies.
- **Survival (1 study)**: One replicated, controlled study in the USA[10] found that soft coral settled on concrete slabs had lower survival than on a natural reef.
- **Condition (3 studies)**: Two of three studies (one replicated, one site comparison) in the USA[3], Singapore[4] and Japan[8] found that coral that settled on concrete or limerock[3], or fibreglass/sand/calcium carbonate[4] structures were smaller than coral on the surrounding natural reef. The third, replicated, study[8] found that corals settled on ropes experienced less bleaching but higher levels of disease than on a natural reef.

Background

The use of unnatural materials, (materials not typically encountered by corals such as concrete, or PVC), to create reefs specifically designed to encourage settlement by coral is a widely-used method that aims to rapidly expand available habitat and encourage corals to settle. However, there is also the potential for negative consequences within the coral ecosystem through pollution or contamination caused by the degradation of unnatural reef materials (such as concrete or PVC) (McManus *et al*. 2018).

Here we focus on the creation of artificial reef structures using unnatural materials to encourage subsequent settlement by wild coral. Other similar actions include *Use natural materials to restore/repair/create habitat for corals to encourage natural coral settlement; Stabilize damaged or broken coral reef substrate; Repurpose obsolete offshore structures to act as structures for restoring coral reefs* (where a man-made structure is no longer being used for its original purpose and has been repurposed as an artificial reef); *Modify existing man-made structures to create artificial reefs* (where a structure was created for another purpose but has been modified to allow colonization by coral or has been colonized in its original state); and *Use settlement tiles to encourage natural coral settlement* (where tiles made from various materials are placed on the substrate). Actions relating to cultivating or transplanting corals onto artificial substrates are covered in *Cultivate coral fragments in an artificial nursery located in a natural habitat; Cultivate coral larvae in an artificial nursery located in a natural habitat; Transplant nursery-grown corals onto artificial substrate*; and *Transplant wild-grown corals onto artificial substrate*.

McManus R.S., Archibald N., Comber S., Knights A.M., Thompson R.C. & Firth L.B. (2018) Partial replacement of cement for waste aggregates in concrete coastal and marine infrastructure: a foundation for ecological enhancement? *Ecological Engineering*, 120, 655–667. https://doi.org/10.1016/j.ecoleng.2017.06.062

A study in 1995–1998 in two artificial reefs in Florida, USA (1) found that three years after concrete blocks embedded with limerock were used to create habitat, stony corals, hydrocorals and octocorals had established on the unnatural substrates. At one site, three years after a ship grounding crater was filled with concrete blocks embedded with limerocks, seven types (species or genera) of coral were found at a density of 3 corals/m^2. *Porites astreoides* was the most abundant (>15% of corals) at the site. Sixty percent of corals had settled on the embedded limerocks (25% of the structure), rather than the surrounding concrete (75%). At the other site, three years after a grounding crater was filled with limerock boulders, 11 types of coral were found, at a density of 4 corals/m^2. *Porites astreoides, Favia fragum* and *Agaricia* sp. Were the most abundant, each constituting >15% of corals at the site. In October and November 1989, two ships grounded on reefs 6.5 km apart in the northern Florida Keys National Marine Sanctuary, leaving craters. In June–August 1995, at the 2.5 m-deep site, 40 concrete blocks embedded with limerocks were used to fill the crater and sealed with cement. At the other 10 m-deep site large limerock boulders were used to fill the crater. In summer 1998, three years after installation, juvenile coral recruits were mapped and measured on 17 concrete blocks and 17 limerock boulders. The proportion of corals on the embedded limerocks compared to surrounding concrete was measured on nine of the concrete blocks.

A replicated study in 1993–1995 at an artificial reef in Hoi Ha Wan, Hong Kong (2) found that after pulverised fly-ash/cement blocks were used to create habitats, the number of stony coral recruits settling onto the blocks varied according to time immersed, block orientation, composition and species. A total of 387 *Oulastrea crispata* were recorded during the 24-month monitoring period (0–65/m^2). More recruits settled on the top and reef-facing sides of the block compared to the sea-facing or bottom sides (data not reported). There was no difference in *Oulastrea crispata* recruitment on blocks comprising different pulverised fly-ash:cement mixes. Thirty *Culicia japonica* recruits were recorded during the monitoring period, with the density fluctuating (range 0–6/m^2) and peaking after 24 months. More recruits were recorded on the reef-facing, top and bottom sides compared to the sea-facing (data not reported). More *Culicia japonica* settled on blocks comprising 3:1 pulverised fly-ash:cement mix (numbers not reported). In December 1993, a total of 176 smooth-sided cube blocks (0.15 m^3) were randomly placed on top of an existing artificial reef 7 m deep. Blocks comprised different ratios of pulverised fly-ash:cement (0:1, 1:3, 1:1, 3:1). Coral recruits were counted approximately every three months for 24 months.

A site comparison study in 1995, and 1998–2001 at two damaged coral reefs in the Florida Keys National Marine Sanctuary, USA (3) found that using concrete armor or limerock boulders to repair the reefs led to natural settlement by corals with 70–80% of species the same as on nearby natural reefs, but the diameter of stony coral *Porites asteroides* colonies was lower, and density did not differ between restored and natural reefs. Six years after the artificial structures were installed, 80% of species recorded on concrete armor and 70% of species on limerock boulders were also found on the adjacent natural reefs. Average colony diameter of *P. asteroides* increased from 14 mm (concrete armor) and 18 mm (limerock boulder) in 1998 to 22 mm (concrete) and 23 mm (limerock) in 2001, but was smaller in 2001 than colonies on the adjacent natural reefs (adjacent to concrete 85 mm; adjacent to limerock: 34 mm). Average density of *P. asteroids* increased on the concrete armor reef from 2.1 colonies/m^2 in 1998 to 4.5/m^2 in 2001 whereas average density was unchanged on limerock boulders (1.4/m^2 both years). Average density was not significantly different between either concrete armor or limerock boulders and their adjacent natural reefs (concrete armor: 4.5, adjacent reef: 5.4 colonies/m^2; limerock boulders: 1.4; adjacent reef 0.9 colonies/m^2). In 1995, six years after two ships (M/V Maitland and M/V Elpis) ran aground, artificial structures comprising 12 concrete armor blocks (Maitland site) and 16 limerock boulders (Elpis site) were installed to repair the damaged reef. The artificial reefs were monitored to record natural settlement by coral species. Density and diameter of *P. asteroides* were recorded in 1998 and 2001 and compared, in 2001, to *P. asteroides* colonies on natural reefs approximately 25 m away.

A replicated study in 2001–2004 at three artificial reefs in Singapore (4) found that after fibreglass/sand/calcium carbonate structures were used to create habitat, stony coral recruits settled, and at one site at a higher density compared to natural coral rubble substrate, although recruits were smaller. After 24–26 months, the average density of coral recruits across all sites ranged from 0.1 recruits/m^2 to 4.8/m^2. At one site after 23–31 months, coral density was higher (range: 6–11 recruits/m^2) than the adjacent natural coral rubble (range: 4–10 recruits/m^2). Although at that site the average size of recruits on the artificial structures grew between month 26 (1.0–1.5 cm) and 31 (2.0–2.5 cm), these were smaller than recruits on the natural substrate (2.5–3.0 cm for both months). *Pocillopora damicornis* was the dominant species at each site (50%, 79%, 100%) with species from six other families also recorded (see paper for list). In October 2001, ninety-six 70 cm diameter 50 cm tall structures, comprising fibreglass mixed with sand and calcium carbonate, were installed at three sites. Structures were fixed to the seabed using 40 cm or 70 cm stakes. A random sample of 10 structures were monitored every 2–3 months for 24–26 months. In addition, from 23–31 months after installation, coral density and growth on five structures at one of the sites were compared to five 1 m^2 plots on adjacent natural coral rubble. **Costs (US$)**: Each substrate structure cost US$130 (in 2006) and US$23 for six 40 cm stakes.

A site comparison study in 1999–2004 at an artificial and natural coral reef site in Bal Harbour, Florida, USA (5) found that corals settled on an artificial reef made from concrete and limerock and, over time, the coral community more closely resembled the adjacent natural reef and stony coral coverage and density increased. The coral community on the artificial reef became more similar to the natural reefs during the first 3.5 years after the artificial reef was installed and then stabilized to a similarity of 45–58% (data presented as a Bray Curtis Index). Average cover of stony coral increased on the artificial reef to 1.35% after five years and was reported as similar to one of the natural reefs (0.70%). Density of stony corals increased from 0.21/m^2 in year one to 25.29/m^2 after five years. In May 1999, an artificial reef comprising a 46 × 23 m rectangle of 8,000 t of 0.9–1.5 m diameter limerock boulders surrounded by 179 prefabricated concrete and limerock modules (see paper for details). These modules were installed between two natural reefs, 3.1 km offshore, 20 m deep. Reefs were monitored every six months for five years from October 1999 using quadrats to record coral diversity and density.

A study in 2007 on artificial and natural reefs in Florida Keys National Marine Sanctuary, Florida, USA (6) reported that hard coral cover was similar on two older concrete and limestone artificial reefs compared to natural reefs but lower on two newer reefs. Percentage of hard coral cover on 12-year-old artificial reefs was similar to adjacent natural reference reefs (Maitland artificial: 5%, natural: 3%; Elpis artificial: 5%, natural: 4%) but newer reefs had lower hard coral cover than natural reefs (Iselin eight-year-old artificial: 2%, natural: 5%; Wellwood five-year-old artificial: 2%, natural: 8%). Results presented as a similarity index including all species recorded. The hard coral community on the 12-year-old artificial reefs was dominated by *Porites asteroides*. In 2007, four 10 metre long line transect surveys were carried out on four concrete and limestone artificial reefs (two 12-, one eight-, and one five-years-old) and adjacent natural reefs. The percentage of hard coral cover was recorded.

A replicated, randomized, controlled study in 2005–2007 at three degraded coral reefs in northern Sulawesi, Indonesia (7) found that concrete structures placed close to transplanted stony coral fragments had similar numbers of stony coral recruits to structures placed further away. The number of coral recruits was similar on concrete structures placed next to transplanted corals compared to structures placed away from corals in eight of nine comparisons (next to transplants: 0.02–0.28 corals/100 cm^2, away from transplants: 0.03–0.26 corals/100 cm^2), and higher in the ninth comparison (next to transplants: 0.58 corals/100 cm^2, away from transplants: 0.36 corals/100 cm^2). For limestone plates placed next to, or distant from, transplanted corals there were a similar number of recruits in 15 of 18 comparisons, more recruits in two comparisons, and fewer in one comparison (see paper for data). In July 2005–March 2006, six-thousand-one-hundred-and-sixty-four stony coral fragments (*Acropora yongei, Pocillopora verrucosa, Acropora muricata, Isopora brueggemanni*) were collected from donor colonies near three transplant sites. Two plots (10 × 10 m) at each of three sites, with each plot randomly assigned to either: concrete structures (25/plot) alternating in a 'chessboard' design with transplanted stony coral fragments attached to bamboo frames; or concrete structures only (25/plot). At all plots, six groups of three limestone settlement plates were also installed on metal frames. Coral recruits that settled on concrete structures were counted after 14–24 months. Recruits on limestone plates were counted every three months for 14–24 months. Plates were replaced every three months.

A site comparison study in 1997 and 2009–2010 at a fish farm and adjacent coral reefs in Setouchi Channel, Japan (8), found that corals that settled and began growing on suspended ropes had lower rates of bleaching but higher instances of infection than corals on natural reefs, and the community differed between the ropes and natural reefs. Three months after monitoring began, the percentage partial bleaching on rope-growing corals was lower (12%) than on corals growing on one of the disturbed reefs (46%), but similar to corals growing on the other disturbed (18%) and protected (12%) reefs. Rates of infection by flatworm *Waminoa* spp. were higher after nine months in rope-growing corals (4%) compared to corals growing on disturbed (0%, 1%) and protected (0%) reefs. Diversity of coral communities on the ropes was significantly higher than communities on the two disturbed sites, and either equaled or was higher than on the protected site (results presented as multivariate analyses, see paper for full species list). Coral responses to other threats (e.g. algae and sponge overgrowth) were not significantly different between rope-growing or naturally growing corals. In 1997, a tuna fish farm was established using floating cages suspended by rope 3 m deep, ~50 m above the seabed. In May and August 2009 and February 2010, surveys were carried out on the ropes and three adjacent coral reefs (two disturbed by outbreaks of crown-of-thorns starfish; one protected through management of crown-of-thorns starfish). Photographs were used to monitor diversity, bleaching, infection, and other threats.

A replicated, site comparison study in 2004 and 2014 at seven artificial reefs off Singapore (9) found that corals settled on fibreglass reefs, and the percentage of organisms that were stony corals increased over 10 years. Stony corals represented on average <1% of organisms on artificial reefs in 2004 and 2–42% (11% average) 10 years later. In 2014, stony coral colonies on average covered <1–32% of artificial reef surfaces and at three of seven sites 25–58% of corals were recorded with eggs (no eggs were recorded at the remaining sites). In the early 2000s, fibreglass artificial reefs were fixed with iron stakes to areas of sand and rubble at seven sites off Singapore's southern offshore islands. The communities on the outer surfaces of all 84 artificial reefs were surveyed in 2004 and the 44 that remained in 2014. Thirty-five were surveyed in both years. In 2014, three fragments were taken from every adult coral colony ≥12 cm to look for eggs (to determine if the corals were reproductive).

A replicated, controlled study in 2004–2009 at a reef in the South Atlantic Bight, Georgia, USA (10) found that using concrete paving slabs led to higher recruitment of temperate stony coral *Oculina arbuscula* but a higher mortality rate than the natural reef substrate. After almost five years, the average number of coral recruits was higher on concrete paving slabs (17/plot) than on the natural reef (2/plot). The maximum number recorded during one survey was 85 (concrete) and 3 (natural)/plot. Mortality (deaths/plot) was higher at the end of the study for recruits on the concrete paving slabs (5) than on the natural reef (0.25). In June 2004, twenty 30 × 30 cm plots were marked on a hard-bottom reef comprising relict scallop shells on rocky substrate, 20 m deep. Concrete paving slabs (30 × 30 × 5 cm) were placed, unsecured, into 10 plot areas. The remaining plots were left as natural substrate. Twenty surveys were carried out periodically from June 2004–June 2009 to record coral recruitment and mortality using photographs.

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12.4 Use settlement tiles made from unnatural materials to encourage natural coral settlement

https://www.conservationevidence.com/actions/3990

- **Sixteen studies** examined the use of settlement tiles to encourage natural coral settlement. Three studies were in Australia[1a,b,11], two in each of the Philippines[2,8c], Israel[6a,b], and the United Arab Emirates[7,12], and one in each of Japan[3], Italy[4], Italy and Spain[5], the US Virgin Islands[8a], Taiwan[8b], Belize[9], and Palau[10].

COMMUNITY RESPONSE (0 STUDIES)

POPULATION RESPONSE (16 STUDIES)

- **Abundance/Cover (16 studies)**: Sixteen replicated studies (including two randomized, one controlled, one site comparison and one paired) in Australia[1a,b,11], the Phillipines[2,8c], Japan[3], Italy[4], Italy and Spain[5], Israel[6a,b], the United Arab Emirates[7,12], the US Virgin Islands[8a], Taiwan[8b], Belize[9], and Palau[10], found that coral naturally settled on settlement tiles. Four of the studies[2,6a,7,11] found that the number of corals settling depended on settlement tile material. Two studies[2,3] found that coral settlement numbers were higher on tiles within a coral reef[2] or near existing adult colonies[3]. Two studies[11,12] found that coral settlement tended to be higher on the underside of settlement tiles, whereas three studies[8a-c] found that more corals settled on the upper tile surface with refuge holes than without.
- **Survival (2 studies)**: One replicated study[4] found that average survival was similar on tiles at different depths. One replicated, site-comparison study[5] found that survival one year after settlement varied on the site.
- **Condition (1 study)**: A replicated study in Italy[4] found settled coral growth and the number of new polyps increased with age.

Background

The use of settlement tiles comprising materials not typically encountered by corals such as marble, concrete, terracotta, acrylic, or PVC are used to encourage natural settlement by coral larvae. Tiles with settled corals can be removed to be cultivated in ex-situ or in-situ nurseries or left on site to create additional habitat. However, there is also the potential for negative consequences within the coral ecosystem through pollution or contamination caused by the degradation of unnatural reef materials (such as concrete or PVC) (McManus *et al*. 2018) or the material itself being less suitable than a natural reef thus reducing settlement by larvae (Natanzi *et al*. 2021).

Here we focus on the use of settlement tiles to encourage natural settlement by wild coral. Other similar actions include *Use natural materials to restore/repair/create habitat for corals to encourage natural coral settlement; Use structures made from unnatural materials to restore/repair/create habitat for corals to encourage natural coral settlement; Repurpose obsolete offshore structures to act as structures for restoring coral reefs* (where a man-made structure is no longer being used for its original purpose and has been repurposed as an artificial reef); and *Modify existing man-made structures to create artificial reefs* (where a structure was created for another purpose but has been modified to allow colonization by coral or has been colonized in its original state). Actions relating to cultivating or transplanting corals onto artificial substrates are covered in *Cultivate coral fragments in an artificial nursery located in a natural habitat; Cultivate coral larvae in an artificial nursery located in a natural habitat; Transplant nursery-grown corals onto artificial substrate*; and *Transplant wild-grown corals onto artificial substrate*.

McManus R.S., Archibald N., Comber S., Knights A.M., Thompson R.C. & Firth L.B. (2018) Partial replacement of cement for waste aggregates in concrete coastal and marine infrastructure: a foundation for ecological enhancement? *Ecological Engineering*, 120, 655–667. https://doi.org/10.1016/j.ecoleng.2017.06.062

Natanzi A.S., Thompson B.J., Brooks P.R., Crowe T.P. & McNally C. (2021) Influence of concrete properties on the initial biological colonization of marine artificial structures. *Ecological Engineering*, 159,106104. https://doi.org/10.1016/j.ecoleng.2020.106104

A replicated study in 1994–1995 at two reef sites at Heron Reef, Great Barrier Reef, Australia (1a) found that attaching artificial settlement tiles directly to the substrate did not result in higher natural coral recruitment than tiles attached in pairs or singly to wire mesh racks. Five months after tiles were installed, there was no significant difference between the number of coral recruits on tiles attached to the substrate (Site 1: 1.4, Site 2: 1.2/100 cm^2), pairs of tiles on wire racks (Site 1: 1.3, Site 2: 1.4/100 cm^2) or single tiles on racks (Site 1: 1.3, Site 2: 1.5/100 cm^2). In September 1994, forty unglazed terracotta settlement tiles (110 × 110 × 10 mm) with numerous pits and grooves (<1 × 1 mm) were taken to each of two reef sites 500 m apart. Tiles (10/site) were screwed to a stainless-steel baseplate (100 × 50 × 0.6 mm) and attached to the substrate 1–2 m apart using two screws. Wire mesh, A-frame racks (five/site) were anchored to the substrate 2–3 m apart, 9 m deep using steel pegs. One pair of tiles (one on top of the other) and one single tile were screwed to each side of the A-frame (30 tiles/site). Plates and racks were retrieved in February 1995 and the number of coral recruits was counted using a microscope.

A replicated study in 1994–1995 at two reef sites at Heron Reef, Great Barrier Reef, Australia (1b) reported that attaching artificial settlement tiles to the substrate on different natural substrate features, depths, and at different angles led to natural coral settlement. Five months after tiles were installed, the number of acroporid coral recruits ranged from 0–4/tile at both sites, and pocilloporid coral recruits ranged from 0–16/tile at Site 1 and 0–11/tile at Site 2 (data reported as statistical model results). In September 1994, unglazed terracotta settlement tiles (110 × 110 × 10 mm) with numerous pits and grooves (<1 × 1 mm) were attached to stainless steel base plates and screwed to the substrate at two reef sites (site 1: 228 tiles; site 2: 206 tiles). Tiles were attached on different topographic features categorized as ‘level’ (flat substrate);

'protected' (located in a depression >5 cm below surrounding substrate); 'raised' (on mound >10 cm above substrate); 'stepped' (located on a series of ledges). Tiles were placed at different angles (0–90° and depths (2.5–8.7 m). Tiles were collected after five months, and the number of coral recruits was counted and identified.

A randomized, replicated study in 1998 on sandy substrate at a coral reef at Danjugan Island, Sulu Sea, central Philippines (2), found that a higher number of stony coral larvae settled on tiles made from consolidated coral rubble or concrete than rubber, and more coral larvae settled on tiles placed within compared to outside an existing reef. After 4.5 months, the average number of stony coral larvae/tile was higher on coral rubble (within reef: 7.7; outside reef: 2.9) and concrete (within reef: 6.9; outside reef: 2.3) than rubber (within reef: 0.45; outside reef: 0.35) tiles and higher on tiles within the existing reef than outside. Almost all settled larvae were from two families (Pocilloporids: 87% within, 88% outside; Acroporids: 11% within, 12% outside). In February 1998, forty-eight 10 × 10 cm tiles comprising 16 each of coral-rubble-cement, concrete, and rubber were randomly arranged on 16 frames (one of each type/frame) and attached using wire ties. Eight frames were placed within an existing coral reef <0.25 m from live coral, and eight placed outside the reef area >5 m from live coral. Frames were placed 12 m deep, 30 cm above the sandy seabed. Frames were retrieved after 4.5 months and larvae were counted and identified under a microscope.

A replicated, site comparison study in 1997–1999 at two coral reef sites in Amakusa, Japan (3) found that placing artificial settlement tiles adjacent to adult stony coral *Pocillopora damicornis* colonies led to higher recruitment than tiles placed 8–10 m away. Three months after larvae were released by the adult colonies, 70 recruits had settled on tiles in July–October 1997 and 65 in July–October 1998 but no recruits settled NovemberJune in 1998 or 1999. The study reports that there were significantly more recruits on tiles placed adjacent to adult *P. damicornis* colonies than on tiles placed 8–10 m away but numbers are not reported. In July 1997, fifteen concrete blocks (40 × 20 × 10 cm) were placed on the substrate, adjacent (5–10 cm) to existing *Pocillopora damicornis* colonies, and a further 15 blocks were placed 8–10 m away from the nearest colony. Six ceramic settlement tiles (10 × 10 × 2 cm) were bolted to each concrete block. Tiles were retrieved after three months and new plates were attached and retrieved in June 1998. The process was repeated from July 1998–June 1999. *P. damicornis* recruits were identified and counted under a microscope.

A replicated study in 1998–2002 on rocky substrate in Leghorn, Italy (4) found that marble settlement tiles were settled on by Mediterranean red coral *Corallium rubrum* larvae and some survived and grew, with survival similar between depths. Overall, 388 new coral colonies settled on tiles during the four-year study (244 on tiles 25 m deep and 144 at 35 m). After four years, coral density was 19 (at 25 m) and 10 (at 35 m) settlers/10 cm^2. Average annual survival of cohorts (survival rate between two consecutive years) was similar across the study period and between depths (76% at 25 m; 75% at 35 m). After four years, 34% (25 m) and 31% (35 m) of the first cohorts (settled in 1998) had survived. Average diameter increased with coral age (1 year old: 0.6; 4 years old: 2.5 mm), height also increased with age (2 years old: 2 mm; 4 years old: 7 mm). The average number of polyps was significantly higher for four-year-old corals (38) than two (9) and one (5) year old. In June 1998 (approximately three weeks before red coral spawning), 20 white marble tiles (90 × 120 mm) were fixed with a steel screw into crevices at 25 m and 35 m depth (10/depth). Tiles were monitored every three months from October 1998–October 2002 when they were removed and red coral settlers counted and measured.

A replicated, site comparison study in 2003–2004 at two sites in Italy and one in Spain (5) found that using marble settlement tiles resulted in recruitment of red coral *Corallium rubrum* with settlement rates, recruitment density and mortality rates varying depending on site. Four months after tiles were installed, there was no significant difference in overall settlement rate between sites (Calafuria: 67%; Elba: 50%; Medes: 50%). Average settler recruitment density varied between sites (Calafuria: 2.8; Elba: 1.1; Medes 1.6 recruits/cm^2). One year after installation, average mortality rates varied between sites with 72% (21/29) mortality at Mendes, 14% (7/50) mortality at Calafuria, and 10% (2/20) mortality at Elba. In June 2003, fifty-four marble tiles (9 × 12 cm) were secured using a single central screw to rocky crevices on vertical cliffs 25–35 m deep. Nine tiles were placed at each of two locations in three sites in the Mediterranean (Calafuria and Elba, Italy; Mendes, Spain). Settlement by red coral recruits was photographed and analysed after four months (October 2003) and mortality rate measured after a year (June 2004).

A replicated study in 1999–2001 at a shallow reef in Eilat, Israel (6a) found that using unglazed ceramic settlement tiles resulted in a higher number of naturally settled hard coral spat (settled larvae) compared to brick tiles but only during the third survey period and no difference in the number of naturally settled soft coral spat. Four months after the third deployment of tiles, there were 255 hard coral and 153 soft coral spat on 66 tiles. Numbers of naturally settled hard coral spat were higher on ceramic tiles (4–10/100 cm^2) compared to brick tiles (3–4/100 cm^2). There was no difference for soft coral spat (ceramic: 1–2/100 cm^2; brick: 1–2/100 cm^2). There were 34 hard and 81 soft coral spat recorded four months after the second deployment of tiles but no difference between ceramic or brick tiles. No coral spat was recorded during the first survey period. In November 1999, June 2000, and March 2001, nine unglazed ceramic (100 × 100 × 5 mm) and nine fired brick (115 × 115 × 25 mm) settlement tiles were fixed to the substrate using masonry plugs, and nine of each type attached to one of three wire racks. Tiles were placed 10–20 mm (masonry plug) or 200–400 mm (wire rack), above the substrate, 5 m deep. Tiles were recovered and replaced four months after each deployment. Coral spat were counted and species groups recorded using a dissecting microscope.

A replicated study in 1999–2001 at a shallow reef in Eilat, Israel (6b) found that settlement tiles attached to wire racks had a higher number of naturally settled hard coral spat (settled larvae) compared to tiles attached to the substrate but only during the third survey period and no difference in the number of naturally settled soft coral spat. Four months after the third deployment of tiles, there were 255 hard coral and 153 soft coral spat on 66 tiles. Numbers of naturally settled coral spat were higher on tiles attached to a wire rack (4–10/100 cm^2) compared to tiles attached directly to the substrate (3–4/100 cm^2). There was no difference for soft coral spat (wire rack: 1–2; substrate: 1–2/100 cm^2). There were 34 hard and 81 soft coral spat recorded four months after the second deployment of tiles but no difference between tiles on the rack or the substrate. No coral spat was recorded during the first survey period. In November 1999, June 2000, and March 2001, eighteen settlement tiles (nine 100 × 100 × 5 mm unglazed ceramic; nine 115 × 115 × 25 mm fired brick) were attached using cable ties to one of three wire racks fixed 200–400 mm above the substrate at a

45° angle, 5 m deep. Eighteen tiles were attached to the substrate 5 m deep using masonry plugs leaving a gap of 10–20 mm. Tiles were recovered and replaced after four months. Coral spat were counted and species groups recorded using a dissecting microscope.

A replicated, randomized, controlled study in 2007–2008 on two artificial reefs and two rocky reefs off Dubai, United Arab Emirates (7) found that sandstone, terracotta, granite, gabbro, and concrete settlement tiles had similar densities of settled corals at three of four sites. At one of four sites, juvenile corals were more abundant on gabbro (8 corals/100 cm^2) than sandstone (3 corals/100 cm^2) and concrete (3 corals/100 cm^2) tiles, and more abundant on terracotta (7 corals/100 cm^2) than sandstone, with other comparisons showing no differences (granite: 5 corals/100 cm^2). At the other sites, few corals were recorded with no significant differences between materials (<1 coral/100 cm^2 at all). Settlement tiles (100 × 100 × 15 mm) were made from sandstone, terracotta, granite, gabbro and concrete. Twenty-five of each were randomly arranged horizontally 10–15 mm above the substrate at 4 m depth on each of two breakwaters and two rocky reefs in April 2007 (before May–October spawning season). After 12 months, tiles were brought to the laboratory, immersed in bleach for 24 h to remove organic matter, and juvenile corals on the bottom of each tile were counted. Twenty-five tiles went missing during the experiment.

A replicated study in 2010–2012 on five fringing reefs off St John, US Virgin Islands (8a) found that the upper surfaces of unglazed terracotta or acrylic settlement tiles were colonized by stony corals when they had refuge holes, but not when they were smooth. No corals settled on upper surfaces of tiles without refuge holes during the study. On tiles deployed August 2010–June 2011 coral density did not differ between upper surfaces with refuge holes (0.97 corals/100 cm^2) and lower surfaces (1.08 corals/100 cm^2), but on tiles deployed June 2011–August 2012 there was lower density on upper surfaces with refuge holes (0.14 corals/100 cm^2) than lower surfaces (1.31 corals/100 cm^2). See paper for preferences of different coral species. At five sites off St John (<500 m apart), a cluster of 15 unglazed terracotta or acrylic settlement tiles was attached at 45° to horizontal at 5 m depth, 1 cm above the substrate, using stainless steel studs and a spacer which were attached to rocks with epoxy putty. Tiles were deployed August 2010–June 2011, then replaced and left until August 2012. When retrieved, tiles were cleaned, dried and inspected with a microscope for corals. For each sampling period, authors inspected the lower surface of seventy-five terracotta tiles (15 × 15 × 1 cm) and the upper surface of 20 terracotta tiles topped with acrylic tiles (15 × 15 × 0.6 cm) which had been drilled with holes on the top surface only, and 20 undrilled acrylic-only tiles.

A replicated study in 2010–2012 on three reefs off Lyudao, Lanyu and Kenting islands, Taiwan (8b) found that the upper surfaces of unglazed terracotta or acrylic settlement tiles with refuge holes were colonized by a higher density of stony corals than upper tile surfaces with no holes. Four weeks after deployment, upper surfaces of tiles with refuge holes had a higher density of settled corals (1.6–7.9 corals/100 cm^2) than upper surfaces without holes (0.3–1.9 corals/100 cm^2) and lower surfaces (0.3–4.7 corals/100 cm^2, data is not separated for lower surfaces with or without refuge holes). See paper for preferences of different coral species. Pairs of unglazed terracotta or acrylic tiles (10 × 10 × 1 cm) with a smooth and a grooved surface were stuck together, either with both grooved surfaces facing outwards (refuges) or both smooth surfaces facing outwards (smooth). Off three islands (70–105 km apart), 15–18 pairs of refuge and smooth tiles were fixed a few cm above the substrate at 45° to horizontal using stainless steel bolts at a depth of 5 m. Tile pairs were deployed in March–April (2–3 weeks before coral spawning), off Lyudao in 2010 and off Lyudao, Lanyu and Kenting in 2012, retrieved four weeks later, cleaned, dried and inspected with a microscope for corals.

A replicated study in 2010–2012 on three reefs off Caniogan, Cangaluyan and Lucero islands, Philippines (8c) found that upper surfaces of fibre-cement settlement tiles with refuge holes were colonized by a higher density of stony corals than upper surfaces without holes. Five months after deployment, upper tile surfaces with refuge holes had a higher density of settled corals (1.9–11.4 corals/100 cm^2) than smooth upper surfaces (0–1.7 corals/100 cm^2) and lower surfaces (0.4–2.8 corals/100 cm^2, data is not separated for lower surfaces with or without refuge holes). See paper for settlement surfaces of different coral species. Fifteen fibre-cement tiles (10 × 10 × 1.2 cm) with refuges (drilled with sixty-four 0.5 cm radius holes on each side) and 15 without refuges (smooth) were fixed 1 cm above the substrate at 45° to horizontal using concrete nails at a depth of 5 m on fore-reefs at Caniogan, Cangaluyan and Lucero (11–24 km apart). Refuge and smooth tiles were installed 30 cm apart in February 2012 and retrieved in July 2012. Peak coral spawning was March–May. Retrieved tiles were cleaned, dried and inspected with a microscope for corals.

A replicated, controlled study in 2007–2008 at two coral reefs at Glovers Reef and Carrie Bow Cay, Belize (9), found that using exclusion devices on settlement tiles to deter herbivorous parrot fish led to a reduction in settlement by coral spat (settled larvae) and an increase in nuisance algae compared to tiles without devices. One year after exclusion devices were installed, the number of coral spat was lower on tiles with exclusion devices (0.3–0.6/tile) compared to tiles with just frames (1.3–1.5/tile) and bare tiles (0.9–1.7/tile). Coverage by nuisance macroalgae was also higher on tiles inside exclusion devices (38–68%) compared to tiles with wire (22–33%) and bare tiles (24–30%). Coral species were mainly *Agaricia* spp. and *Porites* spp. although there were no *Porites* spp. settled on any of the exclusion tiles. In March 2007, parrot-fish exclusion devices were placed around 24 terracotta settlement tiles (10 × 10 × 1 cm). Devices comprised a 20 cm diameter wire star-shaped frame with 15.2 cm vertical stainless-steel bolts attached at 4 cm intervals to resemble a 'cage'. Frames only were attached to 24 tiles and a further 24 were left bare. Twenty-four groups of three tiles (one/treatment) were screwed to the substrate at each of Glovers Reef and Carrie Bow Cay. Coral settlement and algal growth were recorded after one year.

A replicated, paired study in 2008 at Iou Lukes reef, Palau (10), found that settlement tiles allowed to 'biologically condition' for three months had a higher density of artificially enhanced or naturally settled stony coral spat (settled larvae) compared to tiles conditioned for one week, and density was higher on tiles with artificially enhanced coral larvae supply. One week or five weeks after nearby wild-growing stony coral spawned or larvae were artificially introduced to the tiles, density of coral spat was higher on tiles conditioned for three months (natural: 50; artificial: 205/0.1 m^2) compared to tiles conditioned for one week (natural: 4; artificial 29/0.1 m^2). Density was significantly higher on one-week conditioned and three-month conditioned tiles where larvae supply had been enhanced compared to the natural tiles. In January 2008 and April 2008, four fibre-cement settlement tiles (10 × 10 × 0.6 cm) were attached to each of 28 concrete/limestone 'pallet-balls' (1.2 × 0.9 m) placed 3–5 m apart, 5–8 m deep on the seafloor adjacent to a natural reef. Tiles were allowed to 'condition' (develop biofilm) for three months (January 2008) or one week (April 2008) before coral spawning. In April 2008, seven randomly selected pallet-balls were 'seeded' with nursery-cultivated stony coral *Acropora digitata* larvae (see paper for methods), and corals on the natural reef spawned. Tiles were retrieved either one or five weeks after wild-growing coral colonies had spawned and the number of coral spat was counted.

A replicated study in 2012–2015 at coral reef patches ('microatolls') off One Tree Island, Great Barrier Reef, Australia (11) found that PVC pipes and the top of ceramic settlement tiles were colonized by a lower number of small stony coral recruits than the underside of ceramic tiles but there was no difference for larger coral colonies or overall coral cover. After 34 months, no coral recruits (<1 cm) were attached to PVC pipes or the top of ceramic tiles, compared to an average of 0.2 (range 0–2) on the underside of ceramic tiles. There was no difference in the average number of coral colonies (>1 cm) attached to PVC pipes (0.7, range 0–8) or the underside (0.6, range 0–7) or topside (0.2, range 0–3) of ceramic tiles. There was no difference in total coral cover (recruits and colonies) between settlement materials (data presented as a figure). In May 2012, thirty PVC pipes and 61 unglazed ceramic tiles were each fixed, horizontally, to a PVC frame attached to the substrate using cable ties. Ceramic tiles were placed in pairs with one tile facing upwards (30 tiles) and one facing down (31 tiles). PVC frames were placed randomly within three microtolls at 1–2 m deep. Corals were counted and measured in March 2015.

A replicated study in 2019 at a reef at Sir Abu Nu'Ayr Island off the United Arab Emirates (12) found that terracotta settlement tiles were naturally settled by stony corals (including *Acropora* spp. and *Porites* spp.). An average of three corals settled/tile, and all but two recruits settled on the grooved underside of the tiles. *Acropora* spp. made up 30% of settled corals, and *Porites* spp. made up 10%. In April 2019, thirty-one terracotta tiles (10 × 10 × 1 cm) were attached to the reef substrate (5 m deep, 2 m apart) using a screw and epoxy, with the grooved surface facing down. In September 2019, tiles were collected, and the number of recruits were counted, and species were identified.

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12.5. Repurpose obsolete offshore structures to act as structures for restoring coral reefs

https://www.conservationevidence.com/actions/3991

- **Two studies** evaluated the effects of repurposing obsolete offshore structures to restore coral reefs. One study was in Japan[1] and one in the Gulf of Mexico[2].

COMMUNITY RESPONSE (0 STUDIES)

POPULATION RESPONSE (2 STUDIES)

- **Abundance/Cover (2 studies)**: One study in Japan[1] found that concrete aquaculture boxes had higher coral cover than the surrounding reef. One replicated, site comparison study in the Gulf of Mexico[2] found that toppled oil rig platforms had similar overall stony coral density to rigs left standing, but density of species varied between rigs.

Background

Man-made offshore structures, such as oil rigs and aquaculture boxes, provide hard surfaces that may allow coral larvae to settle in areas where there is otherwise a lack of suitable substrate. Once these structures are no longer used for their intended commercial purpose they can be removed from the marine environment or be made into artificial reefs. If being repurposed for biodiversity, they can either be left in the same location (standing or toppled) or can be moved to a new location to increase the likelihood of natural colonization by corals and fish communities. Programmes that encourage the repurposing of obsolete structures as artificial reefs, such as 'Rigs-to-Reefs' in the Gulf of Mexico, operate under the premise that the structures will provide benefits for nature by providing new habitats and benefits for businesses by reducing the costs for decommissioning and removing obsolete equipment (Macreadie *et al*. 2011).

Other similar actions include *Use structures made from unnatural materials to create habitat to encourage coral settlement* (where a structure has specifically been made as a reef) and *Modify existing man-made structures to create habitat to encourage coral settlement* (where a structure was created for another purpose but has been modified to allow colonization by corals or has been colonized in its original state).

Macreadie P.I., Fowler A.M. & Booth D.J. (2011) Rigs-to-reefs: Will the deep sea benefit from artificial habitat? *Frontiers in Ecology and the Environment*, 9, 455–461. https://doi.org/10.1890/100112

A replicated study in 1996–2003 at an aquaculture site at Miako Island, Okinawa, Japan (1) reported that coral cover was higher inside empty aquaculture boxes compared to the surrounding reef. After seven years, coral cover inside five boxes originally designed to be used for rearing top-shell snails *Trochus niloticus* was 90% compared to 20% on the surrounding reef (data not statistically tested). By 2003, twenty-six species had colonized the base of the boxes; the dominant species being *Acropora* spp. which had grown to 40–65 cm in diameter. In 1996, five concrete aquaculture boxes (2.1 × 2.1 × 0.6 m) in shallow water (depth not specified) were left empty to enable coral to grow on the base. The box bases were made from plastic lattice reinforced with quartz sand-coated fibreglass to which the corals could attach. Monitoring frequency and other methods are not reported.

A replicated, site comparison study (years not given) on seven decommissioned oil rig platforms in the Gulf of Mexico (2) found that toppled platforms did not have greater overall density of stony corals than standing platforms, but densities of three of four stony coral species varied between toppled and standing platforms. There was no significant difference between the average density of all corals on toppled oil platforms (90 corals/10 m^2) and standing platforms (20 corals/10 m^2). However, on average, *Madracis decactis* and *Tubastraea coccinea* densities were higher on toppled (*Madracis decactis*: 0.4 corals/10 m^2; *Tubastraea coccinea*: 28 corals/10 m^2) than standing platforms (*Madracis decactis*: 0.3 corals/10 m^2; *Tubastraea coccinea*: 19 corals/10 m^2). In contrast, *Phyllangia* *americana* density was lower on toppled (1 coral/10 m^2) than standing platforms (4 corals/10 m^2). There was no difference in *Oculina diffusa* density between toppled (2 corals/10 m^2) and standing platforms (2 corals/10 m^2). Surveys for stony corals were carried out on two standing oil platforms deployed 15–30 years prior (sea level to maximum depth of 101 m and 113 m) and five obsolete oil platforms cut at the base and toppled 13–20 years prior (minimum depth: 23–30 m; maximum: 48–195 m). Monitoring was carried out using photos and videos taken by remotely operated vehicles along two to four vertical and two horizontal struts/platform (20 m to a maximum of 110 m deep).

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12.6 Modify existing man-made structures to encourage natural coral settlement

https://www.conservationevidence.com/actions/3992

- We found no studies that evaluated the effects on corals of modifying existing man-made structures to encourage natural coral settlement.

'We found no studies' means that we have not yet found any studies that have directly evaluated this action during our systematic journal and report searches. Therefore, we have no evidence to indicate whether or not the action has any desirable or harmful effects.

Background

Modifying existing man-made structures, such as sea walls, breakwaters, and renewable energy structures (e.g. wind turbines), to create substrate that encourages natural coral settlement can offer an option for establishing new coral reefs. Coral larvae can settle on many man-made substrates, including concrete (Burt *et al*. 2009), so existing structures can provide an ideal surface on which to settle and grow. These structures can be modified to encourage settlement and growth by, for example, creating crevices or drilling holes in the surface of the structure.

This action covers structures that continue to be used for their original or intended purpose but are modified in some way to encourage coral larvae to settle. Other similar actions include *Use structures made from unnatural materials to restore/repair/create habitat for corals to encourage natural coral settlement* (where a structure has specifically been made as a reef), *Repurpose obsolete offshore structures to act as structures for restoring coral reefs* (where a man-made structure is no longer being used for its original purpose and has been repurposed as an artificial reef). This action covers natural settlement by coral onto existing structures that are modified. Other studies investigating cultivating and transplanting coral onto existing structures are covered *Cultivate coral fragments in an artificial nursery located in a natural habitat; Cultivate coral larvae in an artificial nursery located in a natural habitat; Transplant nursery-grown coral fragments onto artificial substrate*; and *Transplant wild-grown coral onto artificial substrate*.

Burt J., Bartholomew A., Usseglio P., Bauman A. & Sale P.F. (2009) Are artificial reefs surrogates of natural habitats for corals and fish in Dubai, United Arab Emirates? *Coral Reefs*, 28, 663–675. https://doi.org/10.1007/s00338-009-0500-1