Improvement of the coral growth and cost-effectiveness of hybrid infrastructure by an innovative breakwater design in Naha Port, Okinawa, Japan

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**ABSTRACT**

Hybrid infrastructure combining gray and green infrastructure should be more cost-effective than gray infrastructure; however, its cost-effectiveness and cost-effective methods for its construction are not clear. Here we used pro-environment breakwaters, having the original breakwater function of wave attenuation along with the additional function of providing marine-life habitats, as a model for estimating the cost-effectiveness of hybrid infrastructure. We defined effectiveness as the area of coral cover on the breakwaters. We compared coral areas between a normal (control) breakwater, and pro-environment breakwaters (PBs) with artificial tide pools (ATPs) at shallow depth (PBshallow) or ATPs at deeper depth (PBdeep). The coral area increased by ~10% on PBshallow and ~20% on PBdeep compared to the control. PBdeep had the largest increase in coral area, resulting from the installation of ATPs, which accounted for ~40% of the increase in coral area. PBdeep with greater breakwater surface area and ATPs at depths more appropriate for corals than PBshallow increased the cost-effectiveness by ~10% compared to the control. Our finding that the cost-effectiveness of ATP installation is comparable to that of coral transplantation to natural reefs suggests that ATPs are cost-effective for coral habitat restoration.

1. Introduction

Green infrastructure is a concept that utilizes the various functions of nature for infrastructure construction and management. In recent years, there has been a growing interest in using green infrastructure for coastal disaster management (Sutton-Grier, Wowk, and Bamford 2015). Sutton-Grier, Wowk, and Bamford (2015) summarized the advantages and disadvantages of gray and green infrastructure, and of hybrid infrastructure that combines both types. The advantage of gray infrastructure is that it can provide a high level of disaster risk reduction immediately after construction, but it also has the disadvantages of not being able to adapt to the expected rise in sea level due to climate change, and degrading with age. Green infrastructure can provide many co-benefits such as improving water quality, fisheries and tourism resources, and carbon sequestration, as well as disaster risk reduction. Moreover, healthy ecosystems such as those associated with green infrastructure can be expected to recover from disturbances (Gilmour et al. 2013; Romero-Torres et al. 2020) and have the potential to keep up with sea-level rise (Montaggioni 2005), although recent ecosystem degradation and the predicted increase in the rate of sea-level rise threaten this latter capacity (Perry et al. 2018). There is, however, little knowledge of green infrastructure functions or cost-effectiveness, and if the green infrastructure is created by restoring an ecosystem, it can take time to demonstrate its functions (Sutton-Grier, Wowk, and Bamford 2015). Hybrid infrastructure incorporating features of both gray and green technologies can provide a variety of co-benefits that cannot be achieved by gray infrastructure alone, while also providing reliable disaster risk reduction functions. However, there is little empirical research on its effectiveness (Kuwae and Crooks Forthcoming).

The use of green infrastructure requires quantitative studies of its effectiveness and cost. In terms of infrastructure cost-effectiveness, green infrastructure tends to have high economic efficiency and low effectiveness for disaster risk reduction, whereas gray infrastructure tends to have low economic efficiency and high effectiveness for disaster risk reduction. Hybrid infrastructure is considered to be more cost-effective than gray infrastructure because it has a certain degree of secondary effects, such as food production and biodiversity, whereas its functions for disaster risk reduction and economic efficiency fall between those for gray and green infrastructure (Royal Society 2014). The
number of publications quantifying the cost-effectiveness of green infrastructure is limited; Ferrario et al. (2014) compared the disaster prevention effects (wave height reduction) of natural coral reefs and breakwaters with the cost of reef restoration and the cost of constructing or maintaining breakwaters and found that natural reefs are more cost-effective in terms of disaster risk reduction. Narayan et al. (2016) analyzed the cost-effectiveness of disaster risk reduction in terms of wave height reduction by mangroves, salt marshes, coral reefs, and seagrass beds, and the cost of restoration of these ecosystems. Both of these studies estimated the cost-effectiveness of green infrastructure alone; they are not examples of cost-effectiveness calculations for hybrid infrastructure.

A pro-environment breakwater is a structure that has the original functions of a breakwater (wave attenuation) as well as the functions of marine-life habitats, such as tidal flats, seagrass or seaweed beds, and coral reefs. Thus, it can be defined as hybrid infrastructure that combines gray and green infrastructure. Naha Port, on the coast at the cities of Naha and Urasoe, Okinawa, Japan, has pro-environment breakwaters aimed at improving coral recruitment and growth. Corals are the fundamental organisms of tropical and subtropical marine ecosystems and coral reef ecosystems are estimated to have the highest economic value of all ecosystems (De Groot et al. 2012). Therefore, the promotion of coral colonization on breakwaters improves their services, such as those benefiting tourism and fisheries (Cesar and van Beukering 2004; Grafeld et al. 2017; Spalding et al. 2017), and disaster risk reduction (wave attenuation due to increased roughness; Harris et al. 2018). However, the effect of breakwaters on the abundance of corals has not been documented.

In this study, we estimated the cost-effectiveness of hybrid infrastructure (area of coral cover / construction cost) using the pro-environment breakwater at Naha Port as a model. We also compared the cost-effectiveness of several breakwater types to determine a cost-effective method for improving the ecosystem functions of breakwaters.

2. Materials and methods

2.1. Structure of the pro-environment breakwater

Two 60-m sections of the pro-environment breakwater were appended to the eastern end of the “first Urasoe breakwater” at Naha Port, Okinawa, Japan, in 2012–2014 (Figure 1). The yearly averaged significant wave height and period off the first Urasoe breakwater during 1973–1999 were 1.00 ± 0.76 m and 6.40 ± 1.43 s, respectively (mean ± SD; Nagai 2012). In contrast to the normal breakwater (Figure 2), the pro-environment breakwater has (1) artificial tide pools (ATPs), (2) a raised mound on the inshore (port) side, (3) cutouts in caisson ends to widen the gap between adjacent caissons, and (4) 10-mm or 30-mm groove patterns processed onto the surfaces of wave-dissipating blocks, vertical walls of the caissons, armor units, and foot protection blocks (Figure 3).

Each ATP is a box-shaped structure installed on the inner side of a caisson to create a shallow area suitable for coral growth (Figure 4). The ATP is submerged when the water level is higher than the side walls but becomes a tide pool with an exposed edge during low tides (Figure 4(a)). The ATP is a structure that mimics a top-shell-snail aquaculture structure, where corals recruit very successfully (Omori et al. 2006, 2007). The top of the edge wall of the ATP is either 1.0 m above low water level (LWL +1.0 m) or at LWL +0.7 m, designed to become a tide pool for several hours during low spring tides. The inside dimensions of the box are 465 cm in the direction of the breakwater extension, 380–400 cm in the orthogonal direction, and 50–65 cm in depth (Figure 5). There are three different types of processed surfaces on the concrete caps (Figure 5), at the center of the bottom of each ATP: (1) 10-mm or 30-mm groove patterns (Figure 4(b,c,g,h)), (2) fiber reinforced plastic (FRP) grating (40-mm grid size and 8 cm thick)(Figure 4(d,f)), or (3) no surface processing (Figure 4(e)). The surface-processed area of the bottom in each ATP is ~6 m².

The raised mound (Figure 3) on the protected (port) side of the pro-environment breakwaters is designed to increase the extent of shallow areas suitable for corals. The top of the mound is raised by ~5–7 m to a height of LWL −7 to −5 m, compared to the height of the mound of a normal breakwater (LWL −11.6 m).

The cutouts at the caisson joints are intended to widen the space between adjacent caissons to facilitate seawater exchange between the inside and outside of the port. The gap at the joint between normal caissons is usually ~10 cm, but at a joint between caissons with cutouts, the gap is wider, up to ~2 m. The width of the gap from the top to about 2 m above the mound is 52–90 cm, and on the lower part, 110–173 cm (Figure 6).

The surfaces of wave-dissipating blocks, caissons, armor units, and foot protection blocks were processed to have 10-mm or 30-mm groove patterns. For the wave-dissipating blocks, there were eight processed square sections per block, with four 350 mm × 400 mm sections, two 350 mm × 280 mm sections, and two 500 mm × 500 mm sections (Figure 7). The vertical walls of the caissons were processed by attaching mortar plates with 10-mm or 30-mm groove patterns. The plates are 300 mm × 300 mm with a thickness of 40 mm for 10-mm groove patterns or 60 mm for 30-mm groove patterns (Figure 8). The 10-mm or 30-mm groove patterns were also processed onto the top surface of armor units and
foot protection blocks. There are two processed sections (500 mm × 500 mm) on each 30-ton armor unit, and two 1000 mm × 500 mm and one 1000 mm × 1000 mm processed sections on each foot protection block.

Cross-sections of the three types of the breakwater – normal (control), pro-environment breakwater with ATPs installed at shallow water depth (PB\textsubscript{shallow}), and those with ATPs installed at a deeper water depth (PB\textsubscript{deep}) – are shown in Figure 9. For PB\textsubscript{shallow}, the top of the edge wall of the ATPs is at LWL +1.0 m, the depths of the ATPs are 55 cm, the top of the raised mound is at LWL −7 m, and the depth range of the mortar plates on the vertical wall is LWL −3.5 to −6.0 m. For PB\textsubscript{deep}, the top of the edge wall of the ATPs is at LWL +0.7 m, the depths of the ATPs are 55 cm, the top of the raised mound is at LWL −5 m, and the depth range of the mortar plates on the vertical wall is LWL −1.6 to −3.9 m.

2.2. Methods for estimating coral area

2.2.1. Areas on breakwaters designated for estimating coral area

We estimated the area of coral cover on the control breakwater, PB\textsubscript{shallow} and PB\textsubscript{deep} per meter length of each breakwater type based on the results of a coral distribution survey. We estimated the coral area over the depth range from LWL to LWL −20 m; the upper depth is approximately equal to the average low tide level of the spring tide, which is generally the upper limit of the habitable depth for corals, and the deepest depth is the lower limit (toe) of the breakwaters. For the inner side of the pro-environment breakwaters, we also included the bottom, sides, and top of the ATPs in the calculation of the area covered by corals (Figure 9). The area of coral was estimated for each part of the breakwater: wave-dissipating blocks, caisson body (mainly vertical walls), armor units

Figure 1. Study site. (a, b) Location of the study site at Naha Port, Okinawa, Japan. Locations of (c) the “first Urasoe breakwater” and (d) the pro-environment breakwaters.
Figure 2. Isometric view of the normal breakwater showing a 60-m section, from low water level (LWL) +12.30 to −21.80 m in the vertical direction. Green-shaded areas are below LWL; white-shaded areas are above LWL. The breakwater is constructed by placing caissons, which are box-like structures made of reinforced concrete, on top of the foundation mound. On top of the caissons, superstructures are placed to increase the weight and height of the breakwater. The foundation mound is covered with foot protection blocks and armor units to keep the foundation rubble in place. Wave-dissipating blocks are placed on the outside of the port to attenuate wave energy.

Figure 3. Isometric view of the pro-environment breakwater showing a 60-m section, from low water level (LWL) +12.30 to −21.80 m in the vertical direction. Green-shaded areas are below LWL; white-shaded areas are above LWL. The main differences from the normal breakwater are labeled: artificial tide pools (ATPs), raised mound on the inside (port side) of the breakwater, cutouts of the caissons at caisson joints, and a groove pattern (10-mm or 30-mm) embossed on the surfaces of wave-dissipating blocks, vertical walls of the caissons, armor units, and foot protection blocks.

Figure 4. Photographs of artificial tide pools (ATPs). (a) ATPs with fiber reinforced plastic (FRP) grating (the height of the rim is low water level [LWL] +1.0 m). The ATPs become tidepools with an exposed edge during low tides. (b–e) The bottoms of the ATPs with (b) 10-mm groove patterns, (c) 30-mm groove patterns, (d) FRP grating, and (e) no surface processing. (f–h) Magnified views of (f) FRP grating, (g) 10-mm groove patterns, and (h) 30-mm groove patterns.

of coral area because the coral growth specific to these areas was not monitored. Details of the methods for estimating the area covered by corals for each part of the breakwater are in the following sections.

2.2.2. Artificial tide pools
We estimated the coral area of ATPs with FRP grating installed at LWL +1.0 or +0.7 m. We used composite images of ATP surfaces (bottom, sides, and top) to map the coral distribution on the walls and imported the mapping images into image processing software (ImageJ-Fiji; Schindelin et al. 2012) to measure the coral area. The total coral area of the four ATPs per caisson was divided by the length of the caisson (20 m) to obtain the coral area per meter of breakwater extension. Similarly, we measured the ATP wall surface area on the image processing software and divided the coral area by the wall surface area to obtain the percent coral cover (coral cover of all coral species except...
for soft corals) of the ATPs. The coral distribution survey was done four years after installation of the ATPs at LWL +1.0 m and five years after installation of the ATPs at LWL +0.7 m. This time difference might have affected the respective coral areas (please see Section 4.1.1).

2.2.3. Caisson body (mainly the vertical wall), foot protection blocks, and armor units inside the port

The coral areas of the caisson body (mainly the vertical wall), foot protection blocks, and armor units inside the port were estimated on the basis of the relationship between water depth and coral cover. We measured the coral cover in a 1 m × 1 m quadrat for every 1 m of water depth from LWL to LWL −7 m on the left and right sides of caisson joints and at the same depths at distances of 5 and 10 m from the right side of the joint on the vertical walls. To evaluate the effect of mortar plates with groove patterns, we also measured the coral cover on mortar plates installed between LWL −4 and −5 m on PBshallow and between LWL −2 and −3 m on PBdeep. For comparison, we measured the coral cover on the unprocessed vertical wall over the same depth ranges.

For the control, we calculated the coral area using the average of coral cover at each depth of the unprocessed vertical wall of the normal breakwater. For the zones of PBshallow and PBdeep without processed surfaces (LWL to LWL −3.5 m and LWL −6 to −7 m for PBshallow and LWL to LWL −1.6 m and LWL −3.9 to −5 m for PBdeep), the coral area was calculated using the

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Figure 5. (a) Plan view and (b) cross-sectional view of artificial tide pools (ATPs). The dimensions are in millimeters and the depths are in meters relative to low spring tides (LWL). The plan view shows the area of fiber reinforced plastic (FRP) grating. The numbers outside and inside of the parentheses indicate the dimensions and water depths for PBdeep and PBshallow, respectively.

Figure 6. Photograph showing the cutout at the caisson joint inside the port from the top of the edge wall of the ATP (LWL +0.7 m) to the top of the raised mound (LWL −5 m). In this photograph, the gap is 73 cm wide at the upper part of the joint and 173 cm wide at the lower part.
average of coral cover at each depth of the unprocessed vertical wall of pro-environment breakwaters. For the surface-processed zones of PB\textsubscript{shallow} and PB\textsubscript{deep} (LWL −3.5 to −6 m for PB\textsubscript{shallow} and LWL −1.6 to −3.9 m for PB\textsubscript{deep}), we used the average coral cover of the surface-processed zones at each depth. The coral cover of the foot protection blocks and armor units was estimated using the coral cover of vertical walls of the normal breakwater. For all breakwaters, the coral cover at depths below LWL −7 m was assumed to be the same as the average coral cover at LWL −7 m for the unprocessed vertical wall of the normal breakwater. The surface areas of vertical walls, armor units, and foot protection blocks were calculated for each meter extension of each breakwater type as the surface area exposed to seawater and available for coral colonization. For this calculation, we used the top surface dimensions derived from the cross-sections of the respective breakwater extensions (Figure 9).

2.2.4. Wave-dissipating blocks and armor units outside the port

We estimated the coral area on wave-dissipating blocks from the coral cover of wave-dissipating blocks on the outside of the first Urasoe breakwater. For the control, none of the wave-dissipating blocks had surface processing, and the coral area was estimated using the relationship between water depth and mean coral cover at LWL −1 to −12 m for unprocessed wave-dissipating blocks on the normal breakwater. For depths at which coral cover data were not available, we interpolated from the mean cover of the depths above and below the target depth. The coral cover between LWL and LWL −1 m was assumed to be the same as the mean coral cover at LWL −1 m. The coral cover below LWL −12 m was assumed to be the same as that at LWL −12 m (8.15% ± 7.71% [mean ± SD, n = 36]). At the first Urasoe breakwater, coral cover decreases with depth from
LWL −1 to −12 m, thus the coral cover at WLW −12 m, which is the deepest observed, was used to estimate the coral area below that depth. This assumption may overestimate the coral cover at depths below WLW −12 m. However, we observed a coral cover of 12.28% ± 13.89% (mean ± SD, n = 9; T. Tanaya, unpublished data) at WLW −19 m at the first Shinko breakwater near the first Urasoe breakwater, and it is reasonable to expect the same coral cover below WLW −12 m at the first Urasoe breakwater.

For PBshallow and PBdeep, wave-dissipating blocks with groove patterns were installed as the top layer of the blocks from WLW to WLW −12 m. The coral area of the surface-processed blocks was determined by adding the increase in coral area due to the surface processing to the coral area of the unprocessed blocks as follows:

\[
A_{\text{coral}} = A_{\text{block processed}} \times \%C_{\text{processed}} \\
+ (A_{\text{block total}} - A_{\text{block processed}}) \times \%C_{\text{unprocessed}}
\]

Figure 8. Mortar plates with (a) 10-mm or (b) 30-mm groove patterns. Dimensions are in mm. (c) Photograph of plates with 10-mm pattern attached to the vertical wall of a caisson.

Here, \(A_{\text{coral}}\) is the coral area of the surface-processed blocks per meter depth and per meter extension, \(A_{\text{block processed}}\) is the processed area of wave-dissipating blocks per meter depth and per meter extension, \(\%C_{\text{processed}}\) is the average coral cover of the processed area of wave-dissipating blocks on the pro-environment breakwater at each depth, \(A_{\text{block total}}\) is the total
surface area of wave-dissipating blocks per meter depth and per meter extension, and $\%C_{\text{unprocessed}}$ is the average coral cover of unprocessed wave-dissipating blocks on the normal breakwater at each depth. $A_{\text{block total}}$ was estimated by multiplying the top surface area of the zone of wave-dissipating blocks by the rugosity of natural coral-reef topography ($=1.40$, i.e. the mean value for coral reefs in the Indo-Pacific region; Graham and Nash 2013) to take into account the roughness of the wave-dissipating blocks. The top surface area of the zone of wave-dissipating blocks was calculated from the slope and length of that part of the breakwater cross-section (dark blue lines in Figure 9). $A_{\text{block processed}}$ was determined by multiplying the number of blocks with exposed surfaces per meter depth and extension (0.0729 blocks) and the processed area.
per block (1.256 m²). The number of blocks with exposed surfaces was obtained from a simple scale model of a breakwater with approximately scaled wave-dissipating blocks. \( \%C_{\text{processed}} \) was estimated by multiplying \( \%C_{\text{unprocessed}} \) by the ratio of the mean coral cover of the processed areas with 10-mm groove patterns to that of the unprocessed areas for LWL to LWL –6 m (2.40). The coral cover deeper than LWL –12 m was estimated in the same way as for the control.

2.3. Calculation of cost and cost-effectiveness

The construction costs of the control breakwater, \( \text{PB}_{\text{shallow}} \) and \( \text{PB}_{\text{deep}} \) per 1-m extension were estimated based on the cost of materials such as rubble and blocks required for each part of the breakwater and that of the construction work, including manufacturing, loading, and installation of materials. The cost of the foundation rubble is based on the unit cost for the year 2019. The cost-effectiveness was estimated by dividing the coral area by the construction cost.

3. Results

3.1. Coral area, construction cost, and cost-effectiveness of breakwaters

The coral area per meter of breakwater extension was 10.15 m² on the control, 11.53 m² on \( \text{PB}_{\text{shallow}} \) (14% higher), and 12.41 m² on \( \text{PB}_{\text{deep}} \) (22% higher) (Table 1). This increase in coral area is because \( \text{PB}_{\text{shallow}} \) and \( \text{PB}_{\text{deep}} \) have 11% and 13% more surface area that can be colonized by corals, respectively, compared to the control, and slightly higher coral cover (11.08% and 11.67%, respectively), than the control (10.83%). The construction costs per meter of breakwater extension were 25,406,000 yen, 27,632,000 yen, and 28,016,000 yen for the control, \( \text{PB}_{\text{shallow}} \) and \( \text{PB}_{\text{deep}} \), respectively (Table 1).

The cost-effectiveness (coral area/construction cost) of the breakwaters was 4.00, 4.17, and 4.43 cm² (1000 yen)⁻¹ for the control, \( \text{PB}_{\text{shallow}} \) and \( \text{PB}_{\text{deep}} \), respectively, indicating that the pro-environment breakwaters were more cost-effective in terms of coral area than the normal breakwater (Table 1). The cost-effectiveness of \( \text{PB}_{\text{shallow}} \) and \( \text{PB}_{\text{deep}} \) increased by 4% and 11% relative to the control, respectively, with \( \text{PB}_{\text{deep}} \) being the most cost-effective.

3.2. Breakdown of coral area for each breakwater type

The coral areas of the control, \( \text{PB}_{\text{shallow}} \), and \( \text{PB}_{\text{deep}} \) per meter of breakwater extension were 8.84, 9.23, and 9.23 m² for the side of the breakwater on the outside of the port, respectively, and 1.31, 2.30, and 3.18 m² for the inner side, respectively. Compared to the control, the coral area on pro-environment breakwaters increased by 0.39 m² per meter of breakwater outside the port and 0.99–1.87 m² inside the port (Figure 10).

The coral area per meter of breakwater for each part of the control breakwater was 7.86 m² for wave-dissipating blocks, 0.98 m² for armor units outside the port, 0.61 m² for vertical walls, and 0.70 m² for armor units and associated components (i.e. armor units, caisson body, and foot protection blocks) inside the port (Figure 10).

The coral area per meter of breakwater for each part of \( \text{PB}_{\text{shallow}} \) was 8.25 m² for wave-dissipating blocks, 0.98 m² for armor units outside the port, 0.35 m² for the ATPs, 1.04 m² for vertical walls, and 0.91 m² for armor units and associated components inside the port (Figure 10). Compared to the control, the coral area of the wave-dissipating blocks, ATPs, vertical walls, and armor units, and associated components inside the port increased by 0.39 m², 0.35 m², 0.43 m², and 0.21 m², respectively.

The coral area per meter of breakwater for each part of \( \text{PB}_{\text{deep}} \) was 8.25 m² for wave-dissipating blocks, 0.98 m² for armor units outside the port, 0.95 m² for the ATPs, 1.05 m² for vertical walls, and 1.18 m² armor units and associated components inside the port (Figure 10). Compared to the control, the coral area of the wave-dissipating blocks, ATPs, vertical walls, and armor units, and associated components inside the port increased by 0.39 m², 0.95 m², 0.44 m², and 0.48 m², respectively. The largest increase in coral area was due to the installation of the ATPs. The effect of the ATPs and the installation of the raised mound in increasing coral area was greater in \( \text{PB}_{\text{deep}} \) than in \( \text{PB}_{\text{shallow}} \). The coral area for each part of breakwater type for each depth is shown in Table S1.

3.3. Breakdown of construction costs for each breakwater type

The construction costs per meter of breakwater extension for \( \text{PB}_{\text{shallow}} \) and \( \text{PB}_{\text{deep}} \) were 2,226,000

| Breakwater type* | Surface area (m²) | Coral cover (%) | Coral area (m²) | Construction cost (yen, thousands) | Cost-effectiveness (coral area/cost) (1000 yen)⁻¹ |
|------------------|------------------|----------------|----------------|-------------------------------|-----------------------------------|
| Control          | 93.68            | 10.83          | 10.15          | 25,406                        | 4.00                              |
| \( \text{PB}_{\text{shallow}} \) | 104.05           | 11.08          | 11.53          | 27,632                        | 4.17                              |
| \( \text{PB}_{\text{deep}} \) | 106.30           | 11.67          | 12.41          | 28,016                        | 4.43                              |

*\( \text{PB}_{\text{shallow}} \) pro-environment breakwater with artificial tide pools (ATPs) at shallow depths; \( \text{PB}_{\text{deep}} \) pro-environment breakwater with ATPs at deeper depths.
yen and 2,610,000 yen higher than that of the control, respectively (Table 2). The cost breakdown shows that the increase in construction cost on the inner (port) side alone was 2,012,000 yen for PBshallow and 2,563,000 yen for PBdeep; the cost of constructing the raised mound accounted for most of the increased cost. On the other hand, the cost of ATP installation was 383,000 yen, much less than the raised mound. However, the net increase in construction cost for ATP installation on PBshallow after including the savings from the lower cost of the superstructure (225,000 yen), caisson body (46,000 yen), and rubble foundation under the caisson (26,000 yen) was 86,000 yen compared to the control. This is because the volume of the superstructure in PBshallow is partially reduced by the installation of ATPs, and the caisson volume and the volume of foundation rubble are also lower than in the control breakwater. For PBdeep, there was a net decrease in construction cost of 70,000 yen compared to the control for ATP installation, after including the lower costs for the superstructure and the caisson body, and the higher cost of the rubble foundation under the caisson (Table 2) because the caisson body of PBdeep is smaller than that of the control because of the shallower installation depth of the caisson. The increased cost for the surface processing of wave-dissipating blocks was 67,000 yen, and the cost for mortar plates with surface processing was 61,000 yen. A breakdown of the costs of ATP installation and surface processing is shown in Table S2.

Table 2. Construction costs for each breakwater type per 1-m extension. Values in parentheses are the differences from the control (normal) breakwater. Construction costs (yen [thousands] per meter).

|                  | Control   | PBshallow | PBdeep  |
|------------------|-----------|-----------|---------|
| Inside the port  |           |           |         |
| Foundation mound | 2,036     | 1,841 (+195) | 2,109 (+73) |
| Armor layer      | 944       | 1,287 (+343) | 1,516 (+572) |
| Foot protection blocks | 111       | 111 (0)     | 128 (+17)    |
| Raised mound     | 0         | 1,864 (+1,864) | 1,901 (+1,901) |
| Sub-total        | 3,091     | 5,103 (+2,012) | 5,654 (+2,563) |
| Outside the port |           |           |         |
| Foundation mound | 2,892     | 2,892 (0)  | 2,906 (+14)  |
| Armor layer      | 1,446     | 1,446 (0)  | 1,446 (0)   |
| Wave-dissipating blocks | 3,458     | 3,458 (0)  | 3,401 (+57) |
| Surface treatment of wave-dissipating blocks | 0         | 67 (+67)   | 67 (+67)   |
| Foot protection blocks | 223       | 223 (0)    | 255 (+32)  |
| Sub-total        | 8,019     | 8,086 (+67) | 8,075 (+56) |
| Other            |           |           |         |
| Foundation mound (under caisson) | 2,640     | 2,614 (+26) | 2,786 (+146) |
| Caisson          | 9,433     | 9,387 (+46) | 9,078 (+355) |
| Surface treatment of caisson | 0        | 61 (+61)   | 61 (+61)   |
| FRP grating (ATPs) | 0         | 383 (+383) | 383 (+383) |
| Superstructure   | 2223      | 1,998 (+225) | 1,979 (+244) |
| Sub-total        | 14,296    | 14,443 (+147) | 1,4287 (+9) |
| Total            | 25,406    | 27,632 (+2,226) | 28,016 (+2,610) |

*PBshallow* pro-environment breakwater with artificial tide pools (ATPs) at shallow depths; *PBdeep* pro-environment breakwater with ATPs at deeper depths; *FRP*, fiber reinforced plastic.

Figure 10. Coral areas of the normal (control) breakwater and pro-environment breakwaters (PBshallow and PBdeep) per meter of extension. Dark blue indicates the coral area of wave-dissipating blocks, light blue indicates armor units outside of the port, orange indicates armor units and associated components inside the port (i.e. armor units, foot protection blocks, and the caisson body other than the vertical wall), yellow indicates the vertical wall of the caisson, and green indicates the ATPs.
4. Discussion

4.1. Effects of the pro-environment breakwater on coral growth

4.1.1. Effect of ATPs on coral growth

The coral area inside and outside the port was higher on both types of pro-environment breakwater compared to the normal breakwater (Figure 10). On PB_{deep}, with the greatest coral area, ATPs increased the coral area by 0.95 m² per meter of breakwater, the greatest increase in the coral area of all breakwater components compared to the control. Note that the coral area of the ATPs on pro-environment breakwaters was evaluated on the basis of the coral cover surveyed 4–5 years after the construction of the breakwaters. The coral cover of the original breakwater at Naha Port increased until 6–8 years after its construction and then stabilized (Yamamoto et al. 2002), suggesting that coral cover may also increase on the pro-environment breakwaters with coral growth in the next few years, if there is no disturbance threatening coral survival. The ATP design was based on structures used for top-shell-snail aquaculture (Omori et al. 2007), and as in those structures, there were many three-dimensional corals, mainly Acropora spp., on the FRP grating on the bottom of some ATPs (personal observation). Given the high level of ecosystem function of Acropora spp. such as rapid growth rates (Pratchett et al. 2015) and the creation of complex, three-dimensional (structural) skeletal shapes that can provide shelter for fish and can help to increase fish populations (Agudo-Adriani et al. 2016; Graham and Nash 2013), the benefits of ATPs are expected to be particularly high.

The reasons for the high effectiveness of the ATPs for coral growth might be explained by (1) the expansion of shallow area suitable for coral growth, (2) the effect of the bottom surface processing of the ATPs, and (3) the existence of stagnant periods at low tides after mass spawning events of Acropora spp. corals. The ATPs successfully increased the shallow area with high coral cover. The ATP surface area per meter of breakwater extension was 6.24 m² for PB_{shallow} and 6.01 m² for PB_{deep} (Table S1). For corals dependent on the photosynthetic products of symbiotic zooxanthellae, the light intensity is the primary environmental factor affecting coral growth rates (Chalker 1981). The attenuation of light intensity with increasing water depth reduces coral growth rates (Pratchett et al. 2015), which might be one reason for higher coral cover at shallower depths. In particular, the inner side of the breakwater where ATPs were installed is considered to be a relatively turbid environment due to the effects of river inflow and enclosure, and in such an environment, the light intensity may limit coral distribution (Morgan et al. 2016).

The surface processing on the bottom of the ATPs may also have a positive effect on coral settlement and growth. The FRP grating increases the surface area per unit bottom surface, thereby increasing the area where corals can settle. FRP grating may also enhance coral recruitment and subsequent growth by providing a substrate above the bottom, making the corals less susceptible to sedimentation, which have adverse effects on coral growth. In particular, smothering by sediments and sediment-trapping algae is a major factor affecting coral larval recruitment and juvenile coral survival, and coral settlement is close to zero on sediment-covered surfaces (Fabricius 2005). Survival and settlement of coral larvae decrease at higher concentrations of suspended matter (Gilmour 1999), and growth rates decrease with increasing suspended matter concentrations in coral species with low sediment tolerance (Rogers 1990).

The grid structure of FRP grates may also prevent fish from feeding on juvenile corals (Suzuki et al. 2011). Even on natural coral reefs, juvenile corals are abundant in microtopography (crevices), suggesting that these areas provide effective refuges from herbivorous fish (Brandl, Hoey, and Bellwood 2014). Because the area of FRP grating on the existing pro-environment breakwaters accounts for only 34% of the bottom area of the ATPs, the positive effect on coral growth by ATPs would be enhanced by expanding the areas with surface processing. It is also possible that the box structure of the ATPs may trap coral larvae during low tides after the mass spawns of Acropora spp. corals (Omori et al. 2007).

The average coral cover of ATPs with FRP grating (mean ± SD) was significantly higher in ATPs installed at deeper depth (15.89% ± 0.31%, n = 4) than in ATPs installed at shallow depth (5.66% ± 0.66%, n = 4) (Welch’s t-test, t = −28.06, degrees of freedom = 6, P < 0.001), which resulted in the substantial difference in coral area on ATPs per meter of breakwater: PB_{shallow} 0.35 m²; PB_{deep} 0.95 m² (Figure 10). Although this difference in coral cover may partly be due to the fact that the ATPs with FRP grating installed at shallow depth were installed 10 months later than the ATPs with FRP grating installed at deeper depth, there was still a difference in coral cover between the other ATPs, which were installed at the same time but at different depths (personal observation). Thus, the difference in coral cover between ATPs installed at shallow depth and those installed at deeper depth cannot be explained by the difference in installation time alone.

Our results suggest that to increase the coral area of a breakwater, it is important to construct portions of the breakwater structure at a depth suitable for coral growth. The installation depth of ATPs on PB_{shallow} is LWL ±1.0 m, 30 cm shallower than the installation depth on PB_{deep} and therefore the frequency of
disturbances such as exposure to waves, higher water temperature, and lower salinities during rainfall may be higher than on PB_{deep}. In the ATPs of PB_{shallow} algae (mainly turf algae) occupy a larger area of the ATP wall than on PB_{deep}. Fast-growing and rapidly colonizing turf algae likely dominate newly available substrata, possibly due to the physical damage to corals under high wave-energy conditions (Williams et al. 2013) or coral bleaching at high water temperatures (Diaz-Pulido and McCook 2002), having an advantage over corals in competition for substrata in a highly disturbed environment.

4.1.3. Effects of surface-processed mortar plates, the gap at caisson joints, and the raised mound, on coral growth

The coral area of the vertical wall of PB_{shallow} and PB_{deep} increased by 0.43 m² and 0.44 m², respectively, per meter of extension compared to the control. One plausible reason for this is that the cutouts at the caisson joints increased the coral cover (Table S1). Around the caisson joints, coral cover and water flow tended to increase with increasing width of the gap at the joints up to around 1 m (Tanaya et al. 2019). Higher water flow through caisson joints likely enhances the coral growth because coral growth is enhanced in environments with moderate currents (Nakamura 2010).

The effect of surface processing on coral growth on the vertical wall varied with depth, with coral cover higher at LWL −2.5 m compared to the unprocessed section but lower than that of the unprocessed section below LWL −3.5 m. (The mean coral covers of processed and unprocessed sections were 26.25% and 17.18% for LWL −2.5 m, 12.00% and 13.67% for LWL −3.5 m, 8.41% and 18.53% for LWL −4.5 m, and 2.12% and 16.16% for LWL −5.5 m, respectively). For PB_{shallow} where the mortar plates with surface processing were installed below LWL −3.5 m (Figure 9), the light intensity at the surface-processed area of the vertical wall may be low, particularly in the grooves of the processed surface and in gaps between plates, thereby inhibiting coral growth there.

The coral area of armor units and associated components inside the port on PB_{shallow} increased by 0.21 m² and on PB_{deep} by 0.48 m² per meter of extension compared to the control (Figure 10). The increase was greater on PB_{deep} than on PB_{shallow}; the surface area was greater on PB_{deep} and coral cover was higher, probably because of the shallower installation depth of the raised mound.

4.2. Cost-effectiveness of pro-environment breakwaters

The cost-effectiveness of PB_{deep} compared to the control was increased by 11%, and the coral area was increased by 22% (Table 1), with the largest increase due to the installation of ATPs, which accounted for 42% of the increase in coral area (Figure 10). A breakdown of construction costs for the pro-environment breakwaters showed that the cost of creating a raised mound on the port side of the breakwater accounted for most of the increase in cost, with a small increase in construction costs associated with the installation of ATPs (Table 2). Thus, the installation of ATPs is a cost-effective method for improving the coral growth on breakwaters.

Here, as a hypothetical breakwater, we consider “Control + ATP”, in which ATPs with the top edge of ATP walls at LWL +0.7 m are installed on a normal breakwater (Figure 11). For the inner and outer parts of the breakwater, the construction cost of Control + ATP is the same as that for the control. Considering that the cost of the caisson body, superstructure, the foundation under the caisson, and the installation of ATPs is almost the same as for PB_{shallow} although the installation depth of ATPs is slightly different, the total construction cost of Control + ATP per meter extension is estimated to be 25,492,000 yen. The structure of Control + ATP is almost the same as that of the PB_{shallow} without the raised mound, although the installation depth of the ATPs is different. Control + ATP is therefore as structurally stable as PB_{shallow} because the raised mound of PB_{shallow} is designed to promote coral colonization and does not contribute to or detract from the stability of the breakwater. For Control + ATP, the cost of the installation of concrete caps, underwater concrete placement, and FRP grating increases compared to Control; however, since the superstructure and caissons are partially truncated because of the installation of the ATPs, the weight of the superstructure and caisson is reduced. As a result,
the increase in cost per meter of breakwater length can be reduced to 86,000 yen compared to Control alone. The wave-resistance performance of Control + ATP is lower than that of Control because the weight of the superstructure and caisson is lower than that of Control, but the wave resistance performance is within the allowable range as demonstrated by the successful performance of PBshallow.

The total coral area per meter extension of Control + ATP is estimated to be 11.10 m², calculated by adding the coral area of the ATPs at deeper depth (0.95 m²) to the coral area of the control (10.15 m²). Using the same method to calculate cost-effectiveness in terms of enhanced coral habitat for each breakwater type, that is, the increase in coral area divided by the increase in construction cost, the values are 6.2, 8.7, 110.5 cm² (1000 yen)⁻¹ per meter of breakwater extension for

![Figure 11. Cross-sectional view of a hypothetical "Control + ATP" breakwater. Dimensions and depths are given in meters; the numbers in parentheses are masses in tons. For Control + ATP, the tops of the edge walls of the artificial tide pools (ATPs) are at LWL +0.7 m.](image)

![Figure 12. Relationship between construction cost and coral area per meter of breakwater length. The dotted lines show the coral areas and costs for possible combinations of breakwater cross-sections, and the solid red line shows the combinations of cross-sections that provide the largest coral area for a given cost. A combination breakwater comprising varying proportions of "Control" and "Control + ATP" maximizes the coral area in the budget range of 25,406,000–25,492,000 yen, and one with a combination "Control + ATP" and "PBdeep" maximizes the coral area in the budget range of 25,492,000–28,016,000 yen.](image)
designing a cost-effective breakwater for coral growth

PB\textsubscript{deep} was the most cost-effective of the three existing breakwaters (Table 1). If there is no budget limit, then the maximum coral area can be achieved by constructing PB\textsubscript{deep} for the entire length of the breakwater. In reality, however, the budget for infrastructure development is often fixed. Under these conditions, it is important to consider a combination of breakwater types that maximizes the coral area within a defined budget (Figure 12).

Here, we consider combinations of control, PB\textsubscript{shallow}, PB\textsubscript{deep}, and the hypothetical breakwater Control + ATP described in Section 4.2. The cost effectiveness of Control + ATP is 4.35 cm\textsuperscript{2} (1000 yen)\textsuperscript{-1}, higher than Control and PB\textsubscript{shallow}, but lower than PB\textsubscript{deep}. Among these four breakwater designs, combinations of the control and Control + ATP maximize coral area in the budget range of 25,406,000 to 25,492,000 yen per meter of breakwater, and combinations of Control + ATP and PB\textsubscript{deep} maximize coral area in the budget range of 25,492,000 to 28,016,000 yen. Depending on the actual budget of the project, the proportions of each breakwater type can be adjusted to maximize the coral area while staying within the budget.

5. Conclusion

In this study, we estimated the cost-effectiveness (coral area/construction cost) of pro-environment breakwaters at Naha Port as a model for hybrid infrastructure that combines gray and green infrastructure. We also compared the cost-effectiveness of several breakwater designs to investigate cost-effective ways to improve the ecological functions of the breakwater.

The coral area increased by ~10% in the pro-environment breakwater with ATPs at shallow depth (PB\textsubscript{shallow}), and by ~20% in the pro-environment breakwater with ATPs at deeper depth (PB\textsubscript{deep}), compared to the normal breakwater (control). The construction cost of the breakwaters was higher by ~10% for PB\textsubscript{shallow} and PB\textsubscript{deep} compared to the control. The cost-effectiveness of the pro-environment breakwaters was higher than that of the normal breakwater. PB\textsubscript{deep}, which had a larger total surface area and took into account the appropriate depths for corals, was the most cost-effective, increasing the cost-effectiveness by ~10% over the control, with the largest increase in the coral area due to the installation of ATPs.

This study shows that ATPs are a cost-effective method for coral habitat creation or restoration, as the cost-effectiveness of coral spatial enhancement is comparable to that of coral habitat restoration by transplantation. By adjusting the proportions of pro-environment breakwaters to reflect the actual cost, we can develop plans to achieve maximum coral area within a budget.

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References

Agudo-Adriani, E. A., J. Cappelletto, F. Cavada-Blanco, and A. Croquer. 2016. “ Colony Geometry and Structural Complexity of the Endangered Species Acropora cervicornis Partly Explains the Structure of Their Associated Fish Assemblage.” PeerJ 4: e1861. doi:10.7717/peerj.1861.

Bayraktarov, E., M. I. Saunders, S. Abdullah, M. Mills, J. Beher, H. P. Possingham, P. J. Mumbey, and C. E. Lovelock. 2016. “The Cost and Feasibility of Marine Coastal Restoration.” Ecological Applications 26 (4): 1055–1074. doi:10.1890/15-1077.

Brandl, S. J., A. S. Hoey, and D. R. Bellwood. 2014. “ Microtopography Mediates Interactions between Corals, Algae, and Herbivorous Fishes on Coral Reefs.” Coral Reefs 33 (2): 421–430. doi:10.1007/s00338-013-1110-5.

Cesar, H. S., and P. van Beukering. 2004. “Economic Valuation of the Coral Reefs of Hawaii.” Pacific Science 58 (2): 231–242. doi:10.1353psc.2004.0014.

Chalker, B. E. 1981. “Simulating Light-saturation Curves for Photosynthesis and Calcification by Reef Building Corals.” Marine Biology 63: 135–141. doi:10.1007/BF00406821.

De Groot, R., L. Brander, S. Van Der Ploeg, R. Costanza, F. Bernard, L. Braat, M. Christie, et al. 2012. “Global Estimates of the Value of Ecosystems and Their Services in Monetary Units.” Ecosystem Services 1 (1): 50–61. doi:10.1016/j.ecoser.2012.07.005.
Montaggioni, G., Grafeld, G., Gilmour, C. C., Shepard, and L. Airoldi. 2014. "The Effectiveness of Coral Reefs for Coastal Hazard Risk Reduction and Adaptation." *Nature Communications* 5: 3794. doi:10.1038/ncomms5749.

Gilmour, J. 1999. "Experimental Investigation into the Effects of Suspended Sediment on Fertilisation, Larval Survival and Settlement in a Scleractinian Coral." *Marine Biology* 135 (3): 451–462. doi:10.1007/s00227-006-0465.

Gilmour, J. P., L. D. Smith, A. J. Heyward, A. H. Baird, and M. S. Pratchett. 2013. "Recovery of an Isolated Coral Reef System following Severe Disturbance." *Science* 340 (6128): 69–71. doi:10.1126/science.1232310.

Grafeld, S., K. L. Oleson, L. Teneva, and J. N. Kittinger. 2017. "Follow that Fish: Uncovering the Hidden Blue Economy in Coral Reef Fisheries." *PLoS One* 12 (8): e0182104. doi:10.1371/journal.pone.0182104.

Graham, N. A. J., and K. L. Nash. 2013. "The Importance of Structural Complexity in Coral Reef Ecosystems." *Coral Reefs* 32 (2): 315–326. doi:10.1007/s00338-012-0984-y.

Harris, D. L., A. Rovere, E. Casella, H. Power, R. Canavesio, A. Collin, A. Pomeroy, J. M. Webster, and V. Parravicini. 2018. "Coral Reef Structural Complexity Provides Important Coastal Protection from Waves under Rising Sea Levels." *Science Advances* 4 (2): eaaq4350. doi:10.1126/sciadv.aao4350.

Kuwe, T., and S. Crooks. Forthcoming. "Linking Climate Change Mitigation and Adaptation through Coastal Green-gray Infrastructure: A Perspective." *Coastal Engineering Journal*.

Maekouchi, N., T. Ano, M. Oogi, S. Tsuda, K. Kurita, Y. Ikeda, and H. Yamamoto. 2008. "The “Eco-block” as a Coral-friendly Contrivance in Port Construction." In *Proceedings of the 11th International Coral Reef Symposium*. Ft. Lauderdale, Florida.

Montaggioni, L. F. 2005. "History of Indo-Pacific Coral Reef Systems since the Last Glaciation: Development Patterns and Controlling Factors." *Earth-Science Reviews* 71 (1–2): 1–75. doi:10.1016/j.earscirev.2005.01.002.

Morgan, K. M., C. T. Perry, S. G. Smithers, J. A. Johnson, and J. J. Daniell. 2016. "Evidence of Extensive Reef Development and High Coral Cover in Nearshore Environments: Implications for Understanding Coral Adaptation in Turbid Settings." *Scientific Reports* 6 (1): 1–10. doi:10.1038/srep29616.

Nagai, T. 2012. "Long Term Statistics Report on Nationwide Ocean Wave Information Network for Ports and Harbours (NOWPHAS 1970-1999)." [In Japanese.] Technical note of the Port and Airport Research Institute, 1035. 1–388.

Nakamura, T. 2010. "Importance of Water-flow on the Physiological Responses of Reef-building Corals." *Galaxea* 12 (1): 1–14. doi:10.3755/galaxea.12.1.

Narayan, S., M. W. Beck, B. G. Reguero, I. J. Losada, B. Van Wesenbeeck, N. Pontee, J. N. Sanchirico, J. C. Ingram, G. Lange, and K. A. Burks-Copes. 2016. "The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-based Defences." *PLoS One* 11 (5): e0154735. doi:10.1371/journal.pone.0154735.

Omori, M., H. Kajiwara, K. Matsumoto, A. Watanuki, and H. Kubo. 2007. "Why Corals Recruit Successfully in Top-shell Snail Aquaculture Structures?" *Galaxea* 8: 83–90. doi:10.3755/jcrs.8.83.

Omori, M., H. Kubo, K. Kajiwara, H. Matsumoto, and A. Watanuki. 2006. "Rapid Recruitment of Corals on Top Shell Snail Aquaculture Structures." *Coral Reefs* 25 (2): 280–285. doi:10.1007/s00338-006-0103-z.

Perry, C. T., L. Alvarez-Filip, N. A. Graham, P. J. Mummy, S. K. Wilson, P. S. Kench, D. P. Manzello, et al. 2018. "Loss of Coral Reef Growth Capacity to Track Future Increases in Sea Level." *Nature* 558 (7710): 396–400. doi:10.1038/s41586-018-0194-z.

Pratchett, M. S., K. D. Anderson, M. O. Hoogenboom, E. Widman, A. H. Baird, J. M. Pandolfi, P. J. Edmunds, and J. M. Lough. 2015. "Spatial, Temporal and Taxonomic Variation in Coral Growth—implications for the Structure and Function of Coral Reef Ecosystems." *Oceanography and Marine Biology: An Annual Review* 53: 215–295.

Rogers, C. S. 1990. "Responses of Coral Reefs and Reef Organisms to Sedimentation." *Marine Ecology Progress Series* 62 (1): 185–202. doi:10.3354/meps062185.

Romero-Torres, M., A. Acosta, A. M. Palacio-Castro, E. A. Treml, F. A. Zapata, D. A. Paz-García, and J. W. Porter. 2020. "Coral Reef Resilience to Thermal Stress in the Eastern Tropical Pacific." *Global Change Biology* 26 (7): 3880–3890. doi:10.1111/gcb.15126.

Royal Society. 2014. "Resilience to Extreme Weather, the Royal Society Science Policy Centre Report." [https://royalsociety.org/topics-policy/projects/resilience-extreme-weather/](https://royalsociety.org/topics-policy/projects/resilience-extreme-weather/)

Schindelin, J., I. Arganda-Carreras, E. Frise, V. Kaynig, M. Longair, T. Pietzsch, S. Preibisch, et al. 2012. "Fiji: An Open-source Platform for Biological-image Analysis." *Nature Methods* 9 (7): 676–682. doi:10.1038/nmeth.2019.

Spalding, M., L. Burke, S. A. Wood, J. Ashpole, J. Hutchison, and P. Zu Ermgassen. 2017. "Mapping the Global Value and Distribution of Coral Reef Tourism." *Marine Policy* 82: 104–113. doi:10.1016/j.marpol.2017.05.014.

Sutton-Grier, A. E., K. Wowk, and H. Bamford. 2015. "Future of Our Coasts: The Potential for Natural and Hybrid Infrastructure to Enhance the Resilience of Our Coastal Communities, Economies and Ecosystems." *Environmental Science & Policy* 51: 137–148. doi:10.1016/j.envsci.2015.04.006.

Suzuki, G., S. Kai, H. Yamashita, K. Suzuki, Y. Iehisa, and T. Hayashibara. 2011. "Narrower Grid Structure of Artificial Reef Enhances Initial Survival of in Situ Settled Coral." *Marine Pollution Bulletin* 62 (12): 2803–2812. doi:10.1016/j.marpolbul.2011.08.050.

Tanaya, T., N. Kinjo, S. Iwamura, S. Aoyama, I. Hasegawa, K. Suzuki, and T. Kuwea. 2019. "Effect of Water Velocity through Caisson Joints on the Coral Distribution on Breakwaters." [In Japanese.]. *Journal of Japan Society of Civil Engineers* 75 (2): I_1147–I_1152. doi:10.2208/kaigan.75.1_1147.

Williams, G. J., J. E. Smith, E. J. Conklin, J. M. Gove, E. Sala, and S. A. Sandin. 2013. "Benthic Communities at Two Remote Pacific Coral Reefs: Effects of Reef Habitat, Depth, and Wave Energy Gradients on Spatial Patterns." *PeerJ* 1: e81. doi:10.7717/peerj.81.

Yamamoto, H., Y. Takahashi, K. Sumida, T. Hayashi, N. Sugiura, and T. Maekawa. 2002. "Analysis of the Growth Processes of the Coral Assemblages on Artificial Structures." [In Japanese.]. *Journal of Japan Society of Civil Engineers* 49: 1186–1190. doi:10.2208/proce1989.49.1186.