# Evaluation of the effectiveness of 3D-printed corals to attract coral reef fish at Tamarindo Reef, Culebra, Puerto Rico

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**SUMMARY**

The development of artificial corals using 3D-printing technology has been proposed as an alternative to aid the recovery of fish populations in degraded reefs. However, no study has empirically evaluated the potential of such artificial corals to attract fish to reef patches. We conducted an experiment to determine whether the number of fish associated with natural and 3D-printed corals differs significantly. The 3D-printed artificial corals mimicked the morphology of staghorn coral *Acropora cervicornis*, whose branches serve as habitat for many fish species. There is evidence indicating that fish abundance increases with habitat complexity, but no specific evidence relating to *A. cervicornis*. Therefore, we also investigated whether the structural complexity of both natural and artificial corals affected their effectiveness to attract fish. We found that the number of fish associated with artificial and natural corals was not significantly different. However, irrespective of coral type, fish were more abundant in corals with the highest levels of complexity. Our findings suggest that 3D-printed corals can serve as a complementary tool to improve the ecosystem function of degraded coral reefs.

## BACKGROUND

The branched morphology of the Caribbean staghorn coral *Acropora cervicornis* promotes reef biodiversity by providing a three-dimensional structure that serves as a nursery ground and refuge for many fish and invertebrate species. However, a combination of human (e.g. pollution), biological (e.g. diseases), and physical (e.g. hurricanes) disturbances have led to a drastic decline in population abundances throughout the region. Currently, *A. cervicornis* is listed as a threatened species under the US Endangered Species Act of 1973. The population collapse is considered one of the major causes for the overall reduction in the abundance, biomass and diversity of reef fish in the Caribbean (Jackson *et al.* 2014).

*A. cervicornis* has shown a poor capacity to recover naturally. Therefore, it is essential to develop conservation and management strategies aimed at retaining its ecological role. The restoration of depleted populations by outplanting nursery-reared coral fragments is perhaps the most common strategy employed by conservationists to reverse current declining trends (Hernández-Delgado *et al.* 2014). Such an approach is relatively inexpensive, and has been demonstrated to be successful at increasing local population size (Miller *et al.* 2016). However, the direct outplanting of *A. cervicornis* nursery-reared colonies may not be appropriate in areas where the coral cannot successfully grow and survive. For example, outplanting may be futile in areas of high sedimentation, high nutrient levels, strong wave surge, and deep reef zones. A proposed alternative to direct outplanting is the deployment of artificial structures that provide similar habitat functionality for marine life.

Recently, the use of 3D-printed corals has gained considerable attention. With 3D-printing technology, it is possible to recreate the precise morphology (shape and texture) of coral colonies, thus permitting the creation of artificial structures that are similar to the structures found on natural reefs (Gutierrez-Heredia *et al.* 2016). Because 3D-printed coral can mimic the structural conditions that reef species experience, it is argued that they can also serve as a suitable habitat for reef fish. Although anecdotal accounts indicate that fish can be attracted to artificial corals, there is no quantitative evidence to support this. Thus, it is not clear whether artificial coral colonies can provide a restoration alternative.

This study aimed to determine whether artificial corals that are morphologically similar to *A. cervicornis* can attract reef fish at a rate similar to that of natural colonies. Because some studies have indicated that fish abundance tends to be higher within more complex structures (Untersteggaber *et al.* 2014), we also compared the number of fish associated with both natural and artificial corals of different branching complexity. We hypothesized that 1) the number of fish associated with the two types of corals will not differ significantly, and 2) abundance of fish will be higher in the most complex corals. Our results will help coral conservationists and managers to determine whether 3D-printing technology is a feasible approach for reef restoration.

## ACTION

**Study site**: This study was conducted at Tamarindo reef in the island of Culebra, approximately 30 km east of the mainland of Puerto Rico (Figure 1). This reef has been the subject of many restoration activities specifically focused on increasing the population density of *A. cervicornis*. The restoration work, carried out by the local conservation organization Sociedad Ambiente Marino (SAM), has been successful in increasing the abundance of *A. cervicornis* and associated reef fauna (e.g. juvenile fish), which made Tamarindo reef suitable for our comparative study.

**Artificial corals**: Six natural colonies of *A. cervicornis*, with varying branch complexity, served as models for the creation of the 3D-printed artificial corals. The complexity of the selected colonies was quantified using the branching index developed by Carrillo-Mendoza *et al*. (2010) given by:

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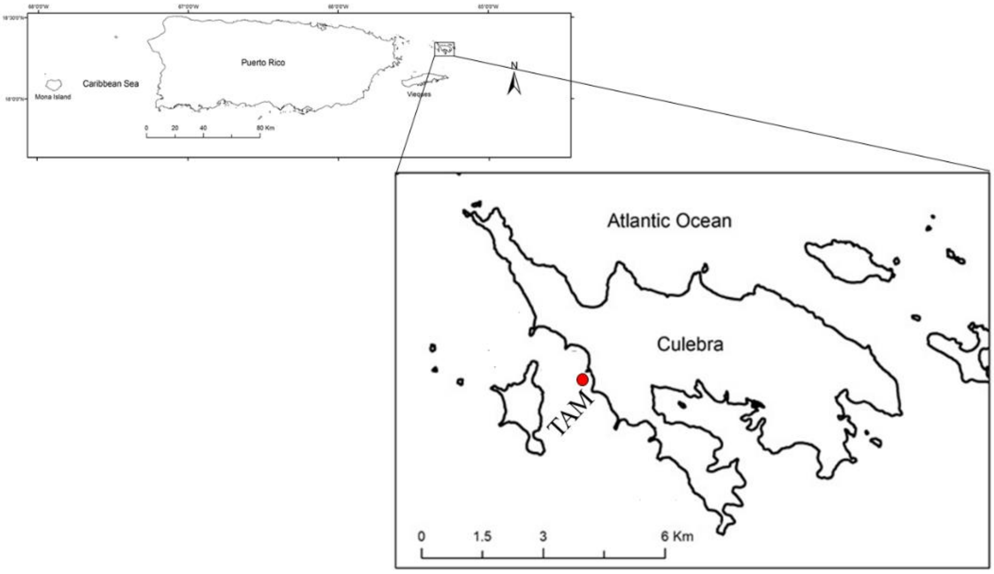


**Figure 1.** Map of the study location at Tamarindo reef (TAM), Culebra, an island to the east of Puerto Rico.

$$BI = \prod_{i=1}^{k} 2^{\left(x_i + \frac{n_j}{100}\right)}$$

In the index x = 0 and x = 1 represent, respectively, the absence and the presence of branches within any given order, n equals the number of branches within a branch order, and k is the maximum order of branching (Carrillo-Mendoza *et al.* 2010). This index has previously been applied to describe the complexity of *A. cervicornis* colonies (Mercado-Molina *et al.* 2016).

Six natural colonies were carefully detached from the nail to which they were secured during the restoration activities by SAM and located in a relatively flat reef area for photographic processing (Figure 2). A plastic hoop, 68.6 cm in diameter, was placed around each coral and three photos (base, mid, and top) were taken every ten degrees with a digital camera (GoPro Hero5) to give a total of 108 photographs. This approach allowed us to document all morphological details (e.g. spacing between branches, branch direction) of the corals. Once the photos were taken, the natural corals were returned to their original location. Coral-specific images were imported into the AgiSoft Photoscan programme. The program digitally reconstructed the morphology of each coral colony and created a 3D image. The 3D model file was imported into the design program MeshLab, which allowed us to edit the file to improve small details (e.g. image contrast and brightness) of the colonies to be printed out. Then, a 3D printer (Afinia 480) was used to convert the 3D image into a three-dimensional figure (Figure 2). The printing material was plastic filaments made of acrylonitrile-butadiene-styrene (ABS). This was used to create the 3D-printed corals because it possesses important advantages over other non-plastic materials such as plaster or cement. For instance, ABS can withstand marine environmental conditions and does not break easily; therefore, it is more stable and durable than plaster, which can erode considerably over time. At the same time, it is more manageable (i.e. lighter) and dynamic (i.e. flexible) than cement, which eases the process of creation and handling. The replicates of the natural *A. cervicornis* were printed, and were considered as low complexity (branching index < 3) or high complexity (branching index ≥ 3).

**Experimental approach**: In January 2017, the six artificial corals were placed on the reef 0.5 m away from the natural corals that served as a model for their creation. The distance that separated the wild and artificial coral was based on the average distance at which coral colonies are usually outplanted to the reef by SAM. The artificial corals were secured to the reef substrate using nails and plastic cable ties. The depth at which the study was performed varied between 3 m and 4 m.

The number of fish associated with each type of coral was estimated without the presence of humans by means of underwater video census. GoPro cameras fixed to a metal bar were positioned facing directly at both the natural and artificial corals. After deployment, the cameras were left undisturbed and allowed to record fish movement around colonies for 10 min (Tessier *et al*. 2005). We counted the number of fish that sought refuge within the branches of the corals per minute. Video censuses were carried out between 07:30 h and 08:30 h every Saturday for six weeks (22 January 2017 to 26 February 2017). At the end of the experiment, the artificial units were removed from the reef.

**Statistical analysis**: A generalized linear mixed model was used to determine whether the number of fish associated with a coral was related to the type (artificial vs. natural) or complexity (high vs. low) of the coral. Coral type and

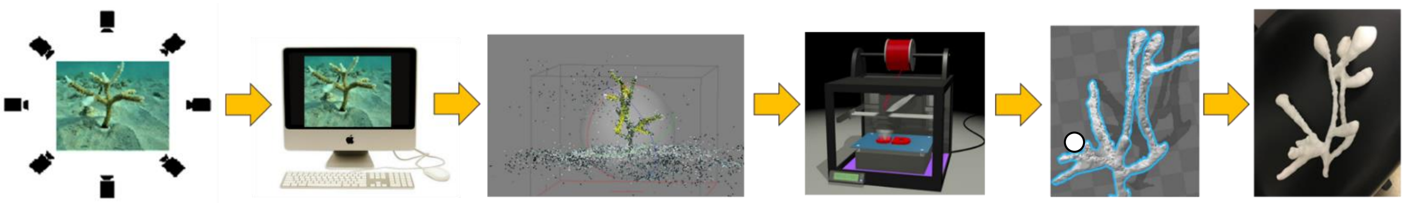

**Figure 2**. Steps followed to create artificial corals with a 3D printer.



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**Table 1.** Results of generalized mixed linear model performed to determine whether the number of fish attracted to a coral depends on coral type (artificial vs. natural) and coral complexity (high vs. low) in Tamarindo reef.

| Parameter | Estimate | S.E. | t-value | p-value |
|---|---|---|---|---|
| Intercept | 3.49 | 0.50 | 7.13 | < 0.01 |
| Coral type | 0.49 | 0.39 | 1.26 | 0.21 |
| Coral complexity | -2.93 | 0.39 | -7.56 | < 0.01 |
| Type * complexity | 0.11 | 0.55 | 0.19 | 0.85 |

complexity were treated as fixed variables, and time was treated as a random variable. Analysis was carried out using the package nlme in R (Pinheiro *et al*. 2018).

## CONSEQUENCES

The number of fish associated with corals did not differ between natural and artificial corals (Table 1). The mean number of fish/colony/minute varied between 1.12 (± 0.36 S.E.) and 4.55 (± 1.63 S.E.) in artificial corals and 1.5 (± 0.58 S.E.) and 4.00 (± 0.89 S.E.) in natural colonies (Figure 3). In contrast, fish were significantly more abundant in corals with high structural complexity (Table 1). In general, the number of fish were three (artificial corals) or four (natural corals) times higher in the most complex corals than in the simplest corals (Figure 3). There was no evidence of interaction between coral type and complexity.

We found that the same fish species were attracted to both natural and artificial coral. The most common were blue-headed wrasse *Thalassoma bifasciatum* (both juveniles and adults), yellowtail snapper *Ocyurus chrysurus* and parrotfish *Sparisoma* spp.

## DISCUSSION

Although some studies have evaluated the role of artificial structures in attracting coral reef species to degraded reef areas, research aimed at understanding or describing the efficiency of artificial corals, rather than artificial reefs, is rare. Our experiment sought to determine whether artificial corals, created with a 3D printer, could attract reef fish. We found that fish were attracted to both natural and artificial corals at similar rates. This result suggests that 3D-printed corals which are morphologically similar to *A. cervicornis* can offer the same structural habitat and protection to reef fish as natural coral colonies. This supports previous studies demonstrating that artificial structures are suitable habitats and refuges for fish in marine ecosystems (Rilov & Benayahu 2000).

Cement blocks, jetties, reef balls and shipwrecks are among the most common non-living structures employed to attract marine life to the reef and non-reef areas. However, these structures are either expensive, require extensive labour for their deployment, or are logistically complicated. Consequently, they have not been widely used by community-based environmental groups, which are usually the primary contributors to reef restoration and conservation programmes (Hernández-Delgado *et al.* 2014). Three-dimensional printed artificial corals represent an alternative tool that is easy to handle (i.e. lightweight, small size) and relatively inexpensive: in our case approximately US$ 45/ coral. Such a cost is similar to the value estimated for a coral outplant in previous large-scale restoration projects at Culebra (> 2000 coral outplants; Mercado-Molina *et al.* 2015). Creating 3D-printed corals, however, demands less time, human resources and materials than propagating corals in nursery-units. Therefore, 3D-printing technology could be incorporated into restoration and conservation programmes without significant logistical or economic constraints (Mohammed 2016). An additional advantage of 3D-printed corals over other artificial structures is size. Their small size (compared to other structures) makes it possible to place them directly within the reef framework without significant alterations to the reef environment, such as light and water movement. In contrast, and by necessity, other types of artificial structures are usually placed in sandy areas that do not provide the natural conditions that fish typically experience in the reef. The manageability of 3D-printed corals can also allow practitioners to recreate natural patterns of distribution, dispersion and abundances of the coral of interest, as well as to perform manipulative experiments to test practical conservation hypotheses.

As hypothesized, the number of fish was highest in the most complex corals. This result supports the contention that

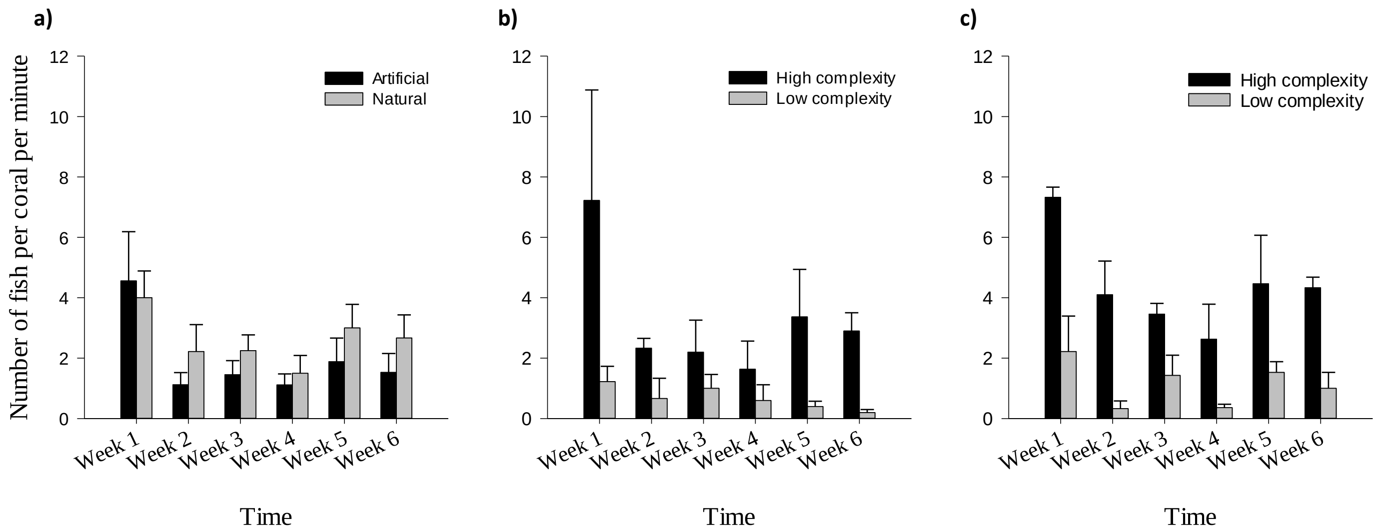


**Figure 3**. Mean number (± S.E.) of fish associated with different types of coral in each week of the study: a) artificial and natural corals (n = 6 for each treatment); b) high and low complexity artificial corals (n = 3 for each treatment); and c) high and low complexity natural corals (n = 3 for each treatment).



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structural complexity is an important factor regulating fish abundance in coral reef ecosystems (Sherman *et al.* 2002, Gratwicke & Speight 2005), probably because complex habitats reduce both competitive interactions and predation risk (Almany 2004, Grabowski 2004). In addition to enhancing the number of fish, higher coral complexity may also result in increased species richness and biomass (Rilov & Benayahu 2002). Therefore, artificial corals should be designed to be as complex as reasonable when intended for restoration and conservation projects. For example, 3D-printing technology would allow the creation of an artificial coral of *A. cervicornis* with a branching index of at least 3 in approximately five hours. Under traditional coral farming methods, this would take about 6-12 months (Hernández-Delgado *et al.* 2014). More research, however, is necessary to improve the robustness of the methodology. The Agisoft Photoscan program failed to reconstruct a 3D model based on digital images of coral colonies with a branching index greater than 3, showing an error of recognition when importing photographs of very complex colonies. This problem may be solved with more advanced technologies than those we had available. Improving the definition and resolution of the images is also desirable. Photos that capture coral structures such as. branches and polyps in more detail will produce a more realistic representation of coral.

The use of 3D-printing technology for conservation purposes is still in its infancy. As such, many questions remain to be answered. Among the most important of these is to evaluate the consequences of placing ABS plastics in the marine environment. Unfortunately, studies evaluating the effect of ABS on the biology and ecology of marine organisms are scarce. Encouragingly, however, there is evidence indicating that: 1) leachates of ABS-based products are non-toxic in the aquatic environment (Lithner *et al.* 2012); and 2) ABS does not inhibit the settlement and survival of coral larvae (Villanueva & de la Cruz 2016). It is also reasonable to question the desirability of putting more plastic deliberately into the sea. In this regard, a recent study by Villanueva and de la Cruz (2016) demonstrated that coral recruitment rates were higher in ABS-based structures than in natural substrates. Thus, artificial corals printed with ABS material would not only attract fish to the reef but could also serve as a substrate for the settlement of real corals and non-coral species.

Finally, to fully comprehend the potential of 3D-printed corals to improve the conditions of fish populations in degraded reefs, it is essential to determine whether they can also promote fish recruitment and whether the rates of fish recruitment are sufficient to support local population growth. The role of 3D-printed corals in promoting reef biodiversity should also be explored more rigorously in studies with better spatio-temporal resolution. That said, this study provides initial evidence to suggest that constructing artificial corals using 3D-printing technology may be a promising method to aid the recovery and conservation efforts of coral reefs.

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