The following document outlines the application relating to **Article 20, Paragraph 1** of the National Ordinance on Maritime Management.

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Summary of application contents:

- The **purpose of the project**, described in detail in the following application, is to install three floating artificial reef structures that will be anchored to the seabed at approximately 30 m depth offshore of Carmabi Marine Station and the Marriott Resort. These artificial reef structures will be used for research and are intended to improve the surrounding reef habitats by recruiting fish and reseeding the surrounding reef by producing and dispersing coral larvae.

- The **construction plan**, including **proposed coordinates, scaled maps,** and **working methods with accurate descriptions of anchoring and deployment strategies**, are discussed below. Anchors to the seabed will have a minimal footprint and will not negatively affect existing corals or other marine life.

- The **duration of the project** will be three years, at which point our team will be responsible for removing the structures and associated anchors from the seabed.

- A **description of the project's expected effects on existing coral populations and fish stocks** are included in this application, including **mitigating measures** that will be taken to minimize adverse effects. Following the conclusion of the project, a **comprehensive assessment of these artificial reefs** and their broader ecosystem effects will be provided to the National Ordinance on Maritime Management, as well as published in the scientific literature. In short, these artificial reef structures are designed exclusively to improve surrounding reef function and are unlikely to cause harm to Curacao's reef assemblages or seawater quality.

- Data is also provided relating to the bathymetry of Curacao, including dimensioning and positioning information to minimize the impact on traffic due to shipping and local/ commercial fishing practices.

Application summary:

Coral Arks, or "Arks," are positively buoyant, 2.5 m wide geodesic structures that are held mid-water column by a tether to the seafloor. These structures are designed to support the growth and development of compact artificial reefs in the water column. The Coral Arks project (ww.coralarks.org) is intended to create refuges of coral reef biodiversity that can persist while natural reefs become degraded, thereby serving to improve the health of surrounding reefs in future years. We propose to deploy three Arks at a depth of 10 m to serve as a "shell" onto which corals and their associated biodiversity can naturally settle. These artificial reef systems will be monitored frequently for up to 3 years as they mature to evaluate physical and biological conditions, and to conduct structural repairs as needed.

Project description:

Curacao, like much of the Caribbean, suffers from a combination of local, regional, and global stressors that have impacted their surrounding coral reef assemblages. Notable local drivers of reef decline in Curacao are over-exploitation of reef fish and land-based sources of pollution, while regional threats include Caribbean-wide phenomena such as the emergence of coral diseases, damage from hurricanes, decreased coral recruitment, and reef flattening. The Coral Arks project, described here, addresses local, regional, and global drivers of reef decline by providing corals with the biodiversity and physical conditions they need to grow and survive.

Unlike some other marine ecosystems (such as seagrass beds), coral reefs cannot easily be "planted" in a new location, because only one main component of the coral reef habitat (corals and the organisms immediately associated with those particular colonies), is moved during translocation. Corals also require a suite of other associating organisms (sponges, crabs, urchins, microbes, etc.) that provide the services to support their health. However, the current coral restoration paradigm, including on Curacao, is mostly centered on raising a single species of coral – staghorn coral – and then planting these corals back onto the reef. These approaches are cost intensive and have limited success in the long term. We would like to use Coral Arks to target whole ecosystem processes, such as enhancing grazer communities to reduce algal overgrowth, rather than simply the culturing and outplanting of corals, in order to effectively restore balance to ecosystems and the services they provide.

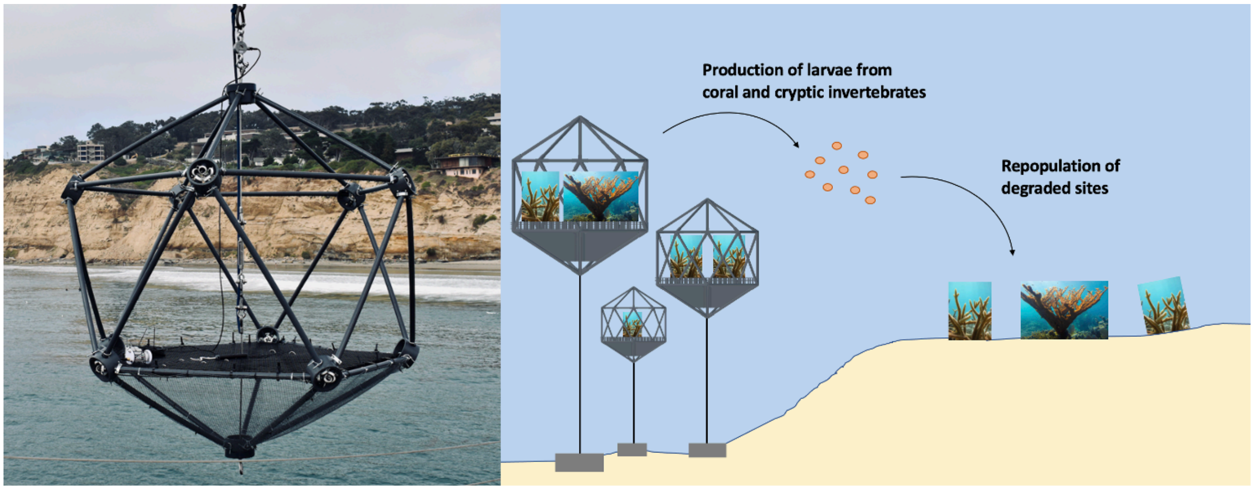

Figure 1. Coral Arks structures and expected ecological benefits.

Coral Arks are intended to be moored, 2.5 m wide, geodesic structures built to naturally recruit corals and their associated biota, creating mid-water reef ecosystems in nearshore locations. Coral reef organisms, including corals, sponges, anemones, etc. grow best in clean, clear flowing water with plenty of sunlight; all conditions that can be improved on midwater reefs. Moving corals off of the seafloor avoids the anoxia and sedimentation associated with degraded reefs and has been shown to increase coral growth, survival, and reproduction rates in coral nurseries. Further, artificial structures with larger vertical dimensions have 10-100 times higher fish production relative to structures lying on the seafloor. Fish aggregate under floating structures (fish are critical components of healthy reefs), and these structures could confine beneficial mobile organisms like urchins that further improve ecological function of the Arks systems.

We anticipate that Coral Arks will result in (1) improved survival rates for corals growing on the structures, (2) improved associated metrics of coral reef function, such as fish biomass, coral growth rates, and nearby coral recruitment, and (3) enhanced community biodiversity, compared to the traditional approach of moving corals to existing hard substrate or emplaced materials such as Reef Balls or boulders. Seafloor artificial reefs can be negatively impacted by sedimentation, scour, unstable benthos (i.e. rubble), and/or low light conditions, depending on their locations. In contrast, Arks can be located such that these impacts would not affect them.

Arks will also act as a source of coral reef biodiversity that could be used to re-populate degraded natural reef systems following catastrophic events such as storms. Larvae from broadcast-spawning organisms associated with Arks, such as corals, will be carried down-current and can help restore reefs; alternatively, Arks could act as coral nurseries, where adult corals are grown, fragmented, and purposefully re-attached elsewhere. Arks are an entirely new way to mitigate and/or restore coral reef ecosystems that can be applied anywhere reefs are found, even providing habitat for coral reef organisms in locations where ocean bottom conditions have become, or never were, conducive to coral growth (for example, in areas impacted by sedimentation or overgrowth).

We would like to deploy three of these Arks near Carmabi Marine Research Station to test this new reef recovery method in practice and improve it if necessary. We have recently found and tested new materials that corals settle on en masse (while algae don't), and will include certain natural substances in the plates that make up the Arks in order to promote the establishment and growth of corals. None of the materials that will be used will adversely affect the reef – on the contrary, we expect these structures to improve surrounding reef function.

If successful, this method will explicitly improve the surrounding coral reefs by recruiting fish and producing larvae that can help repopulate degraded areas. The Marriott owners are enthusiastic about this method and are willing to put three of these Arks on the reef slope between the Marriott and Carmabi. They would be anchored in sandy bottom or loose reef at approximately 30 m using anchoring strategies described below. The top of the Arks will be kept below 10 m, reducing hazards for navigation and boat traffic (including by fisherman).

We expect that the duration of this project will last 3 years. In the first year, we will characterize the community that recruits to and aggregates on our structures, as well as test new materials and methods for promoting the development of a coral reef separate from the seafloor. In the following years, we will focus on scaling up the methods to an ecologically relevant scale. At the conclusion of the project, our team will be responsible for removing the structures and all associated anchoring equipment from the seabed. At this point, a comprehensive assessment of these artificial reefs and their broader ecosystem effects will be provided to the National Ordinance on Maritime Management, as well as published in the scientific literature.

Construction plan:

"Arks" are midwater structures designed for coral settlement and conservation. These 2.5m diameter geodesic structures are constructed from PVC, fiberglass, and stainless steel materials, weighing 110 kg in air and 55 kg in water. Coral Arks are constructed on shore and transported by boat or by truck to the deployment site for installation on the mooring.

Coral Arks were designed based on data and models generated from ocean conditions specific to Curacao. Hydrodynamic models were developed by San Diego State University to determine the expected forces that these moored artificial reef structures will experience in Curacao's flow regimes. Detailed computational models of the currents and bathymetry generated via the General Curvilinear Coastal Ocean Model (GCCOM) for coastal regions surrounding Curacao have allowed for high resolution modeling of the Arks in natural flow scenarios. This model (Figure 2b) provides the amount of force that the system will experience at different current speeds. Our analysis of current speeds at the proposed deployment sites in Curacao (Marriott Resort and Carmabi Marine Research Station) suggests current speeds do not exceed 0.6 m/s, which corresponds to a horizontal force of 350 N (or 35 kg) on the mooring attachment point. The systems (including the structures and mooring attachments) have been designed to withstand 2 metric tonnes, which puts these expected forces well within the margin of tolerance.

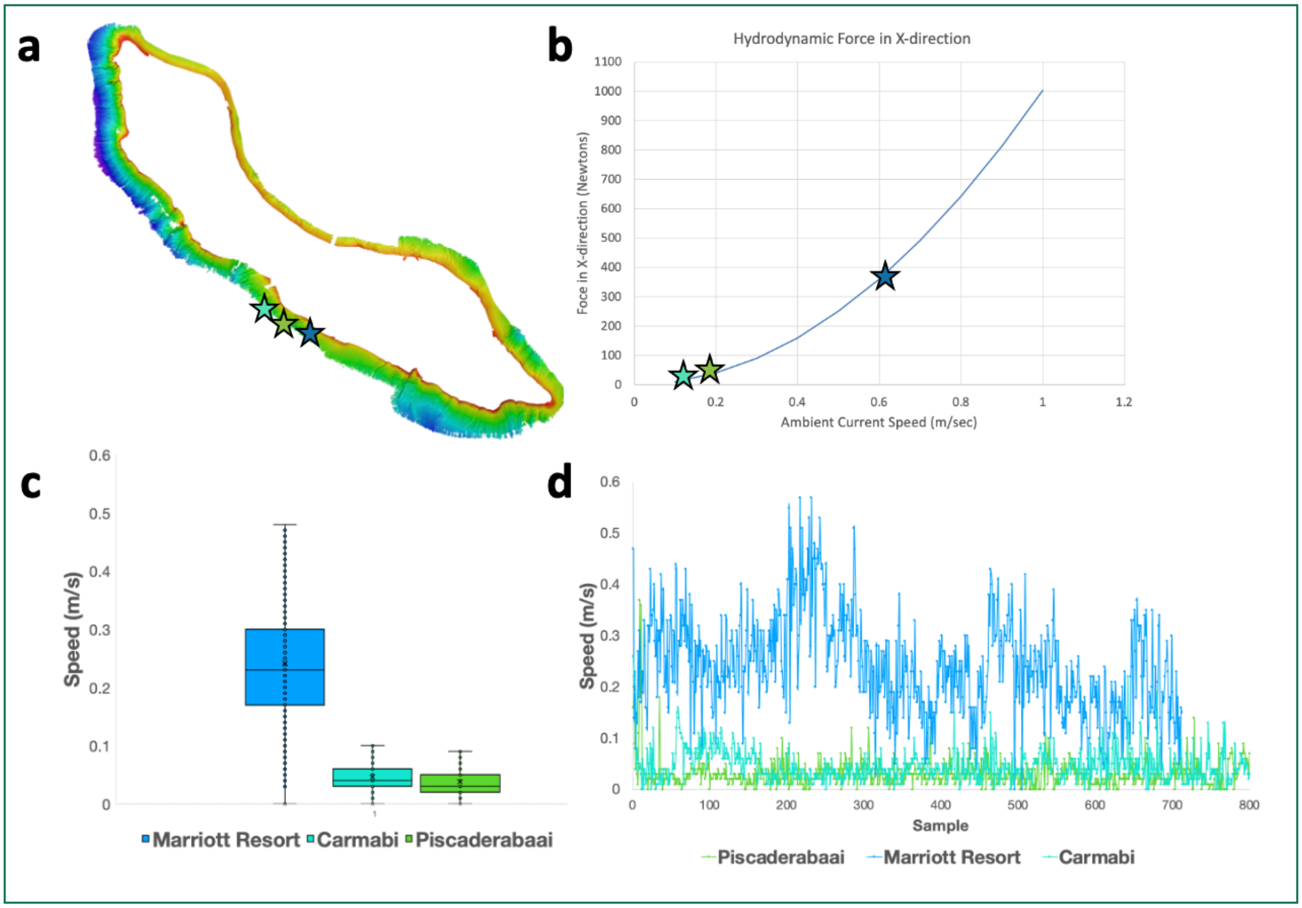

Figure 2. a) Map showing bathymetry of Curacao and planned locations (colored stars) for deployment of Arks artificial reef structures. b) Maximum expected forces on Arks artificial reef structures based hydrodynamic modeling performed using average current speeds surrounding Curacao. Stars represent the average flow speeds and expected forces at each planned deployment site. c) and d) Current speed data collected from each planned deployment site.

Ideally, Coral Arks will be moored in a location with water depths ranging between 30-40m water depth. Deeper areas experience relatively reduced storm surge conditions and allow deeper placement of Coral Arks in the water column that would reduce navigational hazards, but can be challenging for divers, with reduced bottom time available for installation and maintenance dives.

The Coral Arks system has three components: the buoyancy system, the Ark mounting framework, and the seafloor mooring system. The buoyancy system acts to keep the Arks structure suspended in the water column by providing the required buoyant force, generally accomplished by using Polyform mooring buoys. The mounting framework provides a rigid underwater structure for mounting plates to recruit corals and other organisms.

The mooring system is required to provide sufficient holding power to maintain the secure attachment of the system to the seafloor. Ideally, this will be achieved with a mooring system that either uses existing attachment points or is not so large as to require heavy equipment for installation. In general, the optimal mooring system is dependent on the seafloor material and topography, water depth, current and wave climate, and the magnitude and directional characteristics of the loading.

The system is selected to accommodate local environmental conditions such that existing habitats and ecosystems are not damaged.

Moorings for Arks installed in the Carmabi/Marriott area would ideally be constructed around debris that litters the sites from past construction projects. Numerous concrete pilings and blocks can be found at depths ranging from 5 m to 40 m, offering abundant potential locations to anchor one of these structures. This method would result in the maximum holding power for our anchoring system (these concrete blocks essentially function as mooring blocks), while carrying the least impact to surrounding coral reef assemblages. Further, anchor point locations will not contain live or dead coral and live or dead coral will not be within the swing radius of the anchor chain.

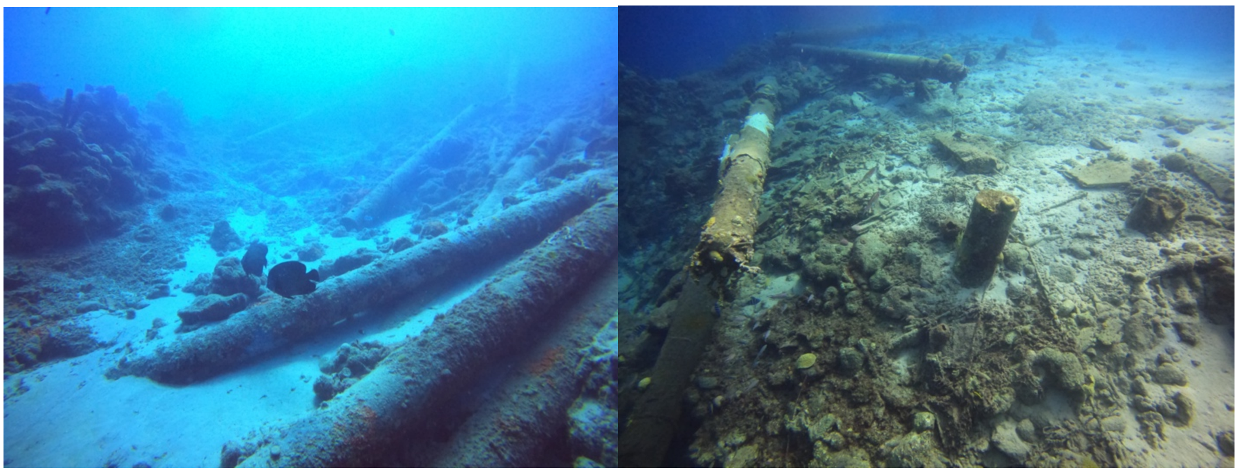

Figure 3. Examples of marine debris to serve as potential anchoring sites for Arks artificial reef structures.

In areas suitable for deployment, but with no existing debris on which to construct a mooring, the following anchoring options would be desirable:

- Helical (sand screw) and Manta Ray-type anchors, intended to support equipment such as marker buoys and other positively buoyant structures, are placed in sandy bottom or rubble areas. Helical anchors are suitable for sand substrates greater than about 2 m in depth, have a diameter of 25 cm, and have a total footprint of 0.05 m^2. Manta Ray anchors are suitable for sand or rubble depths between 1-2 m, and have a footprint of approximately 0.04 m^2.
- Pin-type anchors are designed for installation directly into hard bottom substrate, often in areas with corals. Pin-type anchors are installed by drilling or coring holes with a diameter of approximately 4 cm and then installing an approximately 22 cm-long stainless steel pin with a large eye for connecting shackles for attaching the anchor to whatever structure it is supporting. The estimated footprint disturbed by a pin anchor is 0.018 m^2.

With any of these options, multiple anchor points may be installed and connected by a bridle to increase the holding power and provide redundancy, should any one of the anchor points fail. Installation of these moorings will be accomplished by trained divers without hydraulic or heavy equipment, and will thus have limited footprint on the surrounding reef. In the case of marine debris, such as concrete pilings, galvanized steel chain (protected in a rubber sleeve) will be fasted around the concrete structures, terminating at a single attachment point above the debris. If in sand or rubble, helical sand screws will be manually installed by divers on the seafloor using an extended turning bar placed through the eye of the sand anchor. If hard substrate, such as calcium carbonate base rock (dead coral) or pavement, divers will place permanent anchors by drilling 4 cm diameter holes, 22 cm deep into the seafloor and securing eyebolt anchors into the holes with marine epoxy or Portland cement.

Once Arks are installed onto the mooring, approximately 200 kg of buoyant force (as air) is added to the mooring buoys to support the artificial reef system. Considering the weight of the structure, this works out to approximately a net 150 kg of positive buoyancy. This amount of tension is relatively low for moored structures and well within the tolerances of the components of the system (described above).

The coordinates for the proposed sites, including with maps, are included below:

Proposed site 1 – Marriott Resort - **12°07'01.2"N 68°58'02.4"W**

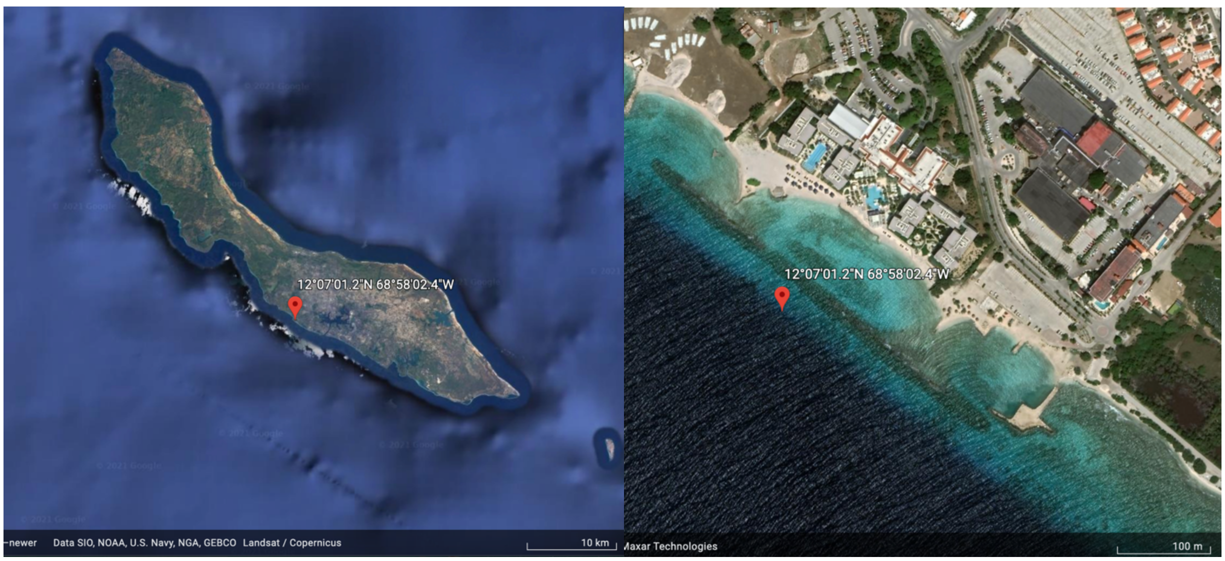

Figure 4. Proposed anchoring location offshore of Marriott Resort

Proposed site 2 – Carmabi Marine Station - **12°07'16.8"N 68°58'11.5"W**

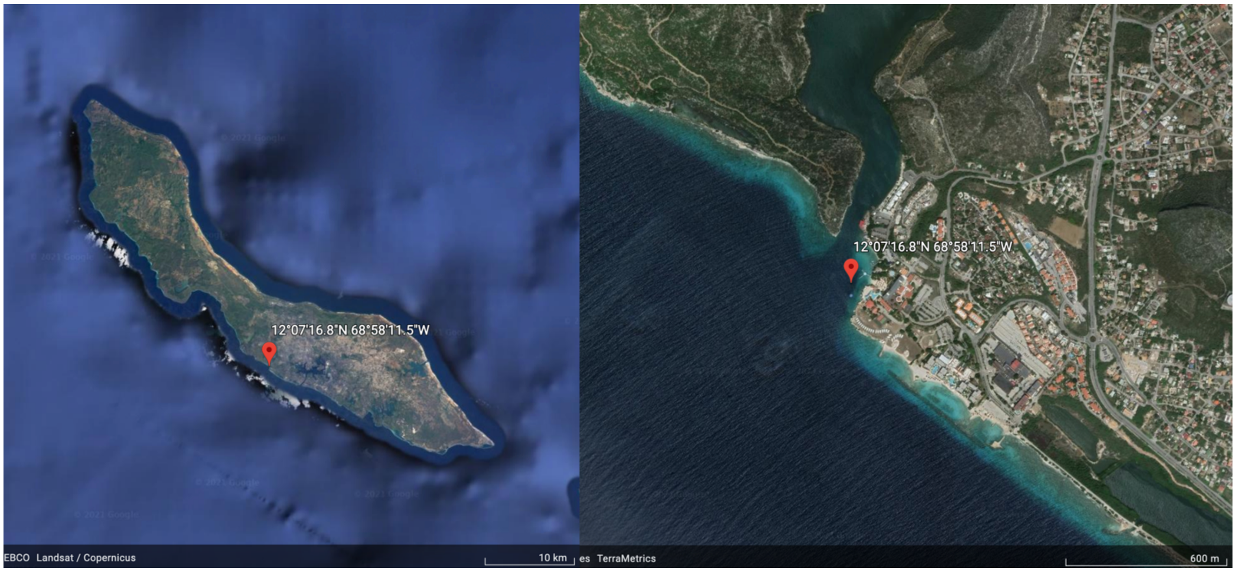

Figure 5. Proposed anchoring location offshore of Carmabi Marine Station

Risks associated with this project, as well as measures that will be taken to mitigate for these risks, are described in the following table.

Risk	Likelihood	Severity	Mitigation
Damage or detachment of Arks from mooring due to storms or vessel traffic	Low	Low	Arks systems were designed with tolerances two orders of magnitude higher than maximum expected forces from hydrodynamic models to compensate for storms and anomalous flow scenarios. Arks are positively buoyant. Thus, if they become detached, they will rise to the surface and be driven by currents to shore rather than harming surrounding reef assemblages. The tops of Arks systems will be located deeper than 10 m to avoid interference from shipping or fishing vessel traffic. Seafloor moorings will include two attachment points connected by a bridle to increase holding power.

Algal biofouling	High	Low	Arks are designed to recruit grazer communities which will reduce algal biofouling and promote coral growth and survival. Carmabi is currently conducting research on materials that can promote coral settlement while decreasing algal fouling, as well as using different organisms (such as urchins and hermit crabs) to enhance grazing. These strategies will be tested on the Arks systems in order to create a reef environment conducive to the formation of a healthy reef.
Interference from fisherman, tourists	Low	Low	Arks will be monitored consistently (weekly) by researchers at Carmabi. We expect that Arks will serve as an attraction for tourists and local divers, and are expected to promote fish populations in the area.

Preliminary data:

Coral Arks were developed to address a global need for innovative and scalable technologies to mitigate widespread coral reef degradation. Restoration efforts that target whole ecosystem processes, such as nutrient cycling and herbivory, rather than simply the culturing and outplanting of corals, are necessary to effectively restore balance to ecosystems and the services they provide.

Coral Arks were originally designed to be positively-buoyant structures anchored to the seafloor, allowing the associated reef community to benefit from improved environmental conditions in the midwater (such as increased flow/light and decreased sedimentation/scouring) relative to the benthos. Scale models and full prototypes testing in San Diego show that Coral Arks replicate the hydrodynamic environment of a healthy reef community, with high flow regimes to support calcifying organisms on the exterior, and an internal environment characterized by turbulence to support essential reef processes such as grazing and nutrient cycling.

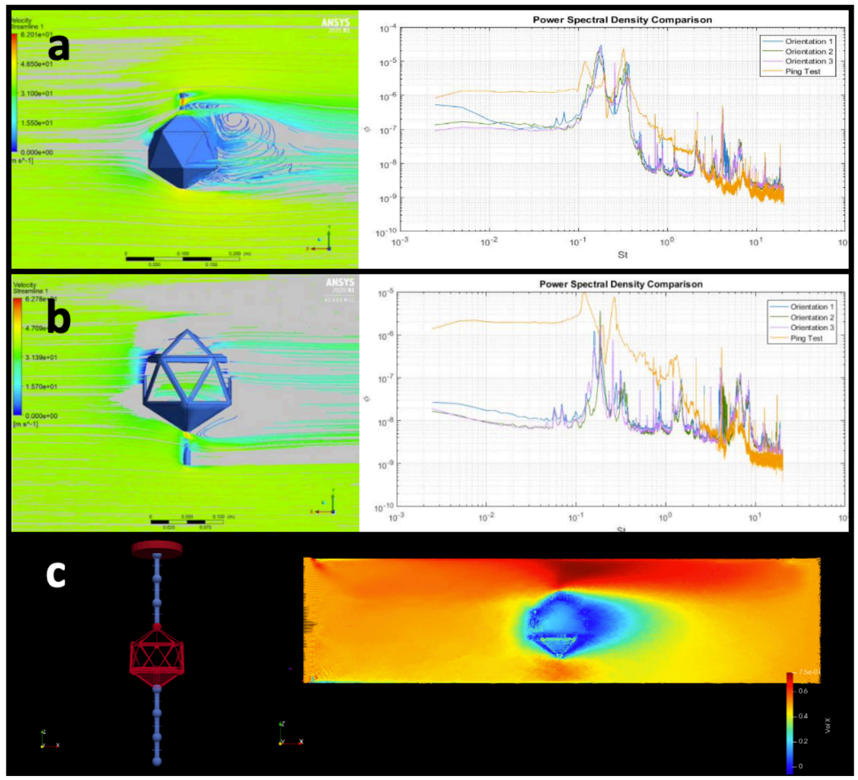

Figure 6. Wind tunnel tests were conducted to assess the hydrodynamic characteristics of (a) solid and (b) hollow scale models of Arks. Accompanying plots represent power spectral density analyses and dominant Strouhal numbers, indicating frequencies induced by flow. The hollow Ark model was then simulated using flow regimes from Curacao to predict the magnitude of reduction in current speeds as water passes through the structure (c).

Scale models of 1V frequency solid and hollow Arks structures (frequency describes the number of triangles that comprise the structure, with higher frequencies containing larger numbers of triangles) were subjected to wind tunnel tests to investigate their hydrodynamic characteristics and test their structural stability under hydrodynamic loading (Abassi et al 2021). The motion of fluid across an object creates vibrations which can compromise structural integrity over the long term. It is therefore advantageous to build a structure that does not "resonate" on its own. Solid and hollow models were subjected to a pinging test to determine natural frequencies of the structures. Both models were also tested in a wind tunnel at velocities that correspond to environmentally relevant current speeds to determine the drag coefficient of each structure as it interacts with a fluid medium. Hollow Arks models exhibited lower natural resonance and produced less drag, and thus were selected for further testing.

High resolution modeling of hollow Arks structures in natural flow scenarios was conducted using detailed computation models of the currents and bathymetry surrounding the Caribbean island of Curacao. Small-scale flow was simulated around a basic model of a hollow, 1V Arks structure at 10 cm resolution using Smooth Particle Hydrodynamics (SPH) for current speeds up to 5 m/s. These models predict a 50% reduction in flow speed in the interior of the Arks structures relative to the surrounding water.

Multiple-element hydrodynamic models were developed for both 1V and 2V frequency polyhedron structures in order to design Coral Arks systems that can withstand hydrodynamic forces expected in both typical flow conditions and extreme, hurricane-level scenarios. These models incorporated hydrodynamic forces on the Arks structure driven by currents (ambient and storm-associated), by waves (ambient and storm-associated), and forces on the mooring/anchoring system (cable stress and required strength of cables and anchor).

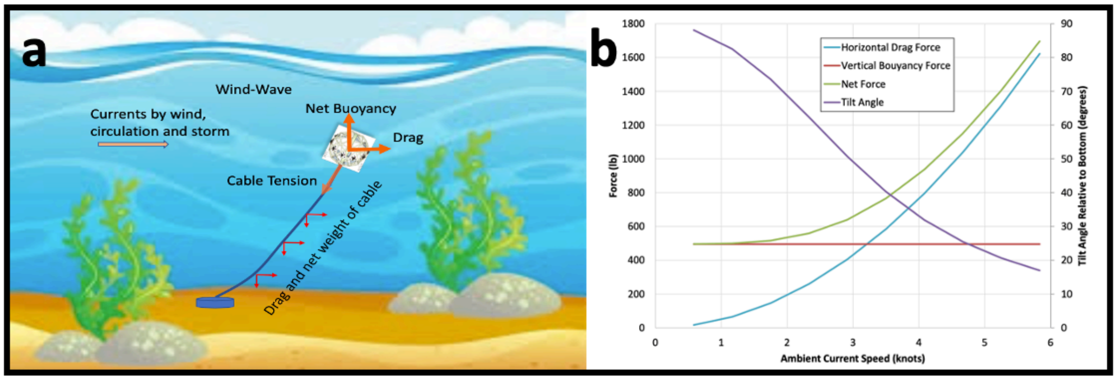

Figure 7. Hydrodynamic models were developed by project partners at NIWC Pacific for the 1V and 2V Arks structures. (a) Models integrate hydrodynamic forces due to currents, waves, and the combined effect of tension and drag forces on the mooring/anchoring system. (b) Models were developed across a range of current speeds, ranging from ambient to hurricane-level conditions.

To validate and refine criteria contained in these models, prototype 1V (1.25 m radius) and 2V (1.5 m radius) Arks structures were then constructed in San Diego for in-water testing (Figure 3). Testing consisted of three main components: 1) a crane test, 2) a towing test to simulate strong currents that a Coral Ark may experience during storm events and determine drag coefficients associated with each structure, and 3) a mooring test to determine the reduction in current strength that occurs as water passes through the structures.

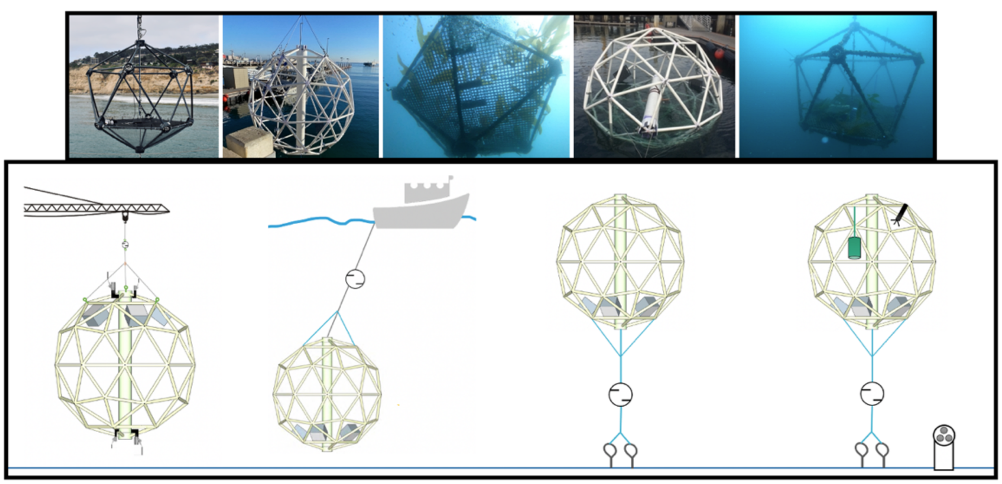

Figure 8. 1V and 2V prototype Arks structures were subjected to crane tests, towing tests, and mooring tests in San Diego to assess their performance in varying hydrodynamic conditions and for model validation.

Analysis of flow speeds on the inside and outside of Arks using acoustic dopplers demonstrated that the flow passing through the Arks becomes turbulent, resulting in a significant reduction (40-70%) in current strength within the Arks interior relative to the surrounding water. Forces on the Arks at varying current speeds measured using a custom submersible strain gauge were used to calculate drag coefficients of each structure, which scaled well with literature values assumed in the models. Overall, data collected during testing of both Arks prototypes demonstrate that our hydrodynamic models can be used to accurately simulate and predict the drag, the tension, and the tilt angles resulting from hydrodynamic forces on the structures under varying water current speeds.

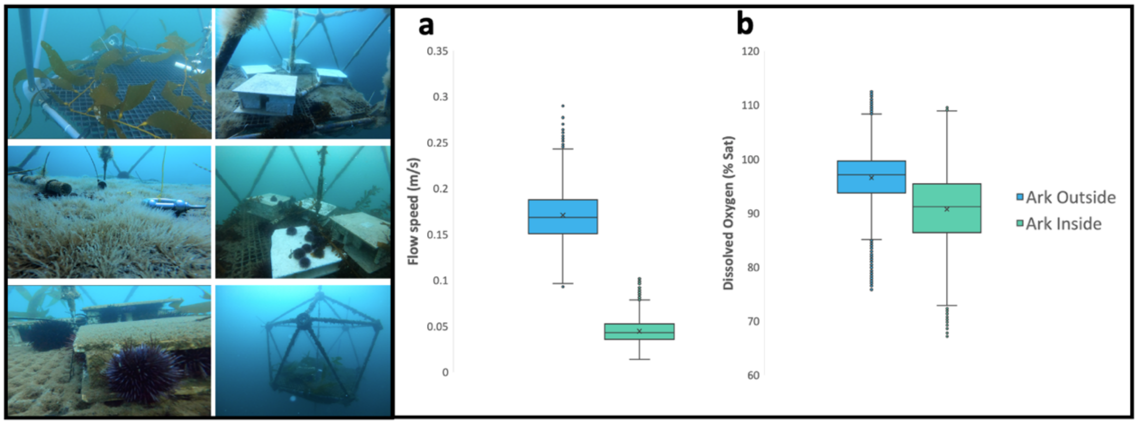

Figure 9. A 1V Coral Ark was deployed for long-term hydrodynamic and biological testing in San Diego. Measurements were taken for (a) flow speeds and (b) dissolved oxygen concentrations both inside and immediately outside the structures.

The 1V prototype structure (1.25 m radius) was deployed offshore of Scripps Institution of Oceanography for long-term submersion. Over several months, the midwater structure passively recruited a diverse biological community that represented the surrounding environment. The composition of the ecological community demonstrated classic succession, with rapidly-encrusting, colonial species like hydroids and bryozoans dominating shortly after deployment being replaced with small crustaceans, bivalves, and gastropods over the next several months. The structure also provided habitat and food for macroorganisms such as fish and urchins. Dissolved oxygen concentrations on Arks were found to be lower within the Arks interior relative to the surrounding water, indicating water retention and community respiration. Increased residence time of water within the Arks due to turbulence is expected to both dissipate energy wave energy and enhance nutrient recycling within the community.

Construction and assembly of Coral Arks

Coral Arks are polyhedral structures constructed from “struts” and “connectors,” with struts used to assemble the polyhedral frame and connectors used to secure these struts in place at each vertex. Arks can be built using various polyhedral geometries and frequencies, and can be built as a dome (half-polyhedron) or a full polyhedron (Table 1). Higher frequency polyhedrons provide more mounting locations and enhanced strength, but have a higher material cost.

Table 1. Structural components of half-dome and full polyhedrons at different frequencies

	Half-Dome Polyhedron			Full Polyhedron	
	Faces (panels)	**Vertices (connectors)**	**Anchor points**	**Faces (panels)**	**Vertices (connectors)**
1V	15	11	5	20	12
2V	36	26	10	72	52
3V	94	61	16	188	122
4V	134	92	18	268	184

Prototype structures were constructed from PVC struts and connectors, with added materials (internal platform, turnbuckle cabling system, Figure 5) made from fiberglass and stainless steel. Marine-grade stainless steel wire rope was strung through the struts and clamped at each vertex, increasing the strength considerably. Coral Arks to be deployed in Vieques will use fiberglass and stainless steel for construction.

Arks are assembled by inserting the struts into the holes in the connectors and angling the strut downwards until they “lock” in place in the connector. This process is repeated until the half-dome or full polyhedron is constructed. Assembled polyhedrons can then be transported to the deployment site for anchoring. Smaller diameter structures may be transported on a small vessel, and larger structures can be towed.

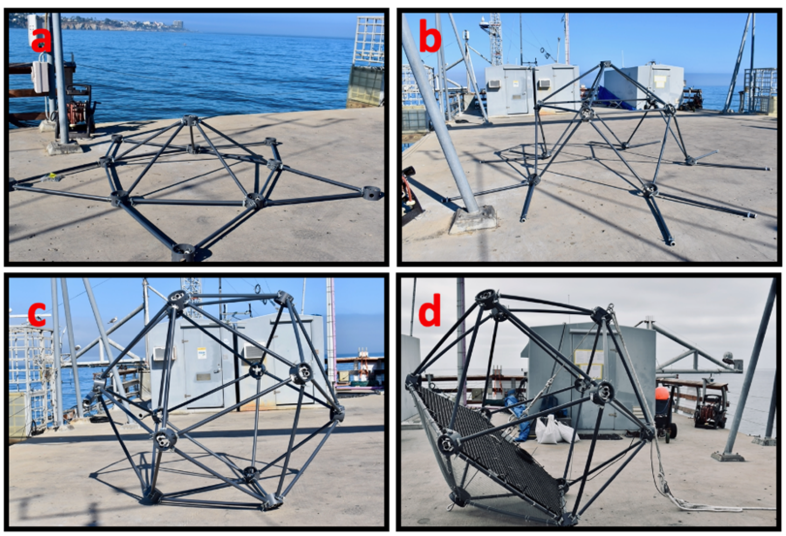

Figure 10. Coral Arks can be assembled in the field from locally-sourced materials.

Coral Arks are being used to house and maintain corals translocated from seafloor munitions in the the ongoing munitions cleanup effort at the Vieques Naval Training Range (VNTR) (part of an Environmental Security Technology Certification Program (ESTCP) within the Department of Defense). Coral Arks offer a new technology for coral mitigation that is expected to result in higher success rates, additional ecosystem benefits, and lower overall costs associated with coral mitigation, compared to traditional approaches.