Coral Restoration Foundation™ boulder coral (Orbicella spp) methodology for in-situ, large-scale restoration.

SEPTEMBER 24, 2021

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CORAL RESTORATION FOUNDATION™

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Suggested citation: Burdeno, D., B. Thomasson, A. Moura and J. Levy (2021). Coral Restoration Foundation™ boulder coral (Orbicella spp) methodology for in situ, large scale restoration. [White paper]. Retrieved [date], from Coral Restoration Foundation™.

Acknowledgements

Boulder coral restoration efforts described within were conducted with in State and Federal waters of the Florida Keys. All activities are permitted by: FKNMS-2011-159-A4, FKNMS-2019-012-A2, FKNMS-2019-183, FWC Special Activities License: SAL-17-1725-SCRP, and ACOE permit # SAJ-2019-04431.

The following individuals were kind enough to provide comments on early drafts of this document, and their suggestions and contributions were invaluable: Kristen Anderson, Alice Grainger, Derek Hagen, Alex Neufeld, and Scott Winters. Additional graphic design work provided by Max Alperstein, Madalen Howard, and Sam Burrell. Additionally, we would like to thank our Restoration Staff and dive teams for their continued support of our restoration efforts and development of novel techniques for species such as boulder corals.

We look forward to continuing to share our experiences and lessons learned with the restoration community. For more information, contact Jessica Levy at 1(305) 453-7030, or via email at Jessica@coralrestoration.org.

Additional resources can be downloaded through the Coral Restoration Foundation website at: www.coralrestoration.org.

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1. Introduction

Coral reefs are keystone ecosystems that are vital to ocean health, providing valuable ecosystem services such as nursery habitat for both recreational and commercially valuable marine species, coastal protection, nutrient recycling, and supporting a robust tourism industry. Over the last three decades, coral reef ecosystems have seen a marked and continued decline in coral coverage (Jackson et al., 2014, De'ath et al., 2012, & Bruno and Selig, 2007). In the Caribbean, the combined effects of local and global threats to the reef have led to the listing of multiple coral species on the International Union for Conservation of Nature (IUCN) Red List, and the United States Endangered Species Act (ESA), necessitating active intervention such as the practice of coral restoration. In Florida and the Caribbean, coral restoration efforts have primarily focused on branching Acroporid species (*Acropora cervicornis* and *Acropora palmata*), with restoration practices seeing great success in both in-situ and ex-situ operations. However, as conditions continue to decline and greater population loss is observed across many different coral species, there is a clear need to expand coral restoration practices to other kinds of stony coral.

One such coral-type prime for investment in deploying restoration techniques is for mounding reef stabilizers such as boulder corals like *Orbicella annularis* and *Orbicella faveolata*. *Orbicella* species are reef stabilizers and have been shown to increase reef fish abundance and diversity on reefs (Newman et al. 2015), highlighting the importance of maintaining species and functional diversity in restoration efforts. To restore the complete ecosystem function of coral reefs, restoration of other species and functional groups must also happen. However, the growth morphologies of these corals pose a challenge for developing propagation and outplanting methods.

As the need to incorporate novel corals into restoration practices increases, techniques for growing and propagating non-branching corals have slowly developed. One technique known as micro-fragmentation has proven to be a successful method for cultivating and asexually propagating boulder corals; it involves the fragmentation of a coral colony into many small (few polyps), multi-centimeter sized pieces to stimulate tissue growth in all directions and produce multiple colonies (Forsman et al., 2015). While micro-fragmentation is a robust strategy for restoration efforts, there can be limitations on the scale at which it can be deployed and its associated costs. To develop large-scale, affordable, solutions for in-situ efforts, Coral Restoration Foundation™ (CRF™) has

worked to develop restoration (propagation and outplanting) techniques that complement the ongoing efforts. These techniques have been developed with the goal of ensuring that restoration occurs at an ecologically relevant scale.

The purpose of this document is to highlight and disseminate the primary methods used by CRF™ to propagate, maintain, and outplant *Orbicella* species in an in-situ setting. The main objectives for developing these techniques are three-fold: 1) incorporate greater number of species and functional diversity within restoration programs, 2) transition proven land-based, ex-situ growth methods to an in-situ nursey setting, and 3) develop low-cost, scalable techniques. The techniques have the potential to be translated and applied to a plethora of coral species with similar morphologies, such as *Pseudodiploria spp.*, *Siderastrea spp.*, and *Montastraea sp.* The methodology for boulder coral propagation and outplanting described in this document is evolving on a day-to-day basis but represents our accomplishments and standardized operations to date. Our hope is for fellow restoration practitioners, from both established and developing restoration programs, to utilize this document as a resource while developing their own propagation and restoration techniques for mounding corals.

2. Methodology

2.1 Broodstock collection and preparation

Wild boulder coral colonies were collected by divers on SCUBA from various reef sites, both in- and offshore, throughout the Florida Keys. Collection activities were conducted under the guidance of the Florida Keys National Marine Sanctuary (FKNMS) and Florida Fish and Wildlife Conservation Commission (FWC) with permit numbers #FKNMS-2011-159-A4 and FWC SAL-18-2077-SCRP. Parent colonies of *O. annularis* and *O. faveolata*, roughly basketball-sized or smaller, were collected as "corals of opportunity" (COO), defined as loose coral structures that have come unattached from the reef substrate and, if left alone, would eventually die. COOs are often created after major storm events or from physical damage to the reef, such as an anchor drag or vessel grounding. This method was chosen to keep from damaging healthy and intact coral colonies on the reef while rescuing or repurposing the loose, vulnerable colonies.

In an effort to ensure high genetic diversity in CRF™'s *Orbicella* restoration program, 36 total individual coral colonies were collected across both species. Each colony was treated as a separate genotype and tagged individually using monofilament and PVC card printed with an ID printer. We utilized a standardized naming convention for new coral collections to help distinguish between clones and putative genotypes. Each collected colony was assigned an ID consisting of the first letter of the genus, the first three letters of the species, and a number following the sequential collection order (ex. Ofav 1 as the first collected *Orbicella faveolata*). Once collected and tagged, COOs were transferred to CRF's™ in-situ nursery off of Tavernier, Florida where they continued to grow on pedestals for at least two years before propagation began. All collection information including colony ID, collection latitude and longitude, and ancillary notes was recorded in a master collections database. Data from this, and all of CRFs™ collections, are now housed in a publicly accessible format known as the Coral Sample Registry published in July 2021 (Moura et al., 2021).

When ready for propagation, colonies were brought to the surface, placed in bins of seawater, and transported to CRF's™ facility on land. A drill press equipped with a 2.5cm (1") diamond coated circular core bit was used to create broodstock core fragments from each parent colony. The drill head is inserted slowly into a colony and removed while saltwater is sprayed across the colony to keep it cool and moist while rinsing away resulting mucus or limestone (Figure 1a). The colony is rotated as subsequent cores are drilled, yielding first-generation broodstock cuttings from the parent colony. Our initial goal was to obtain 24 individual cores per genotype, stemming from CRF™'s tray design as described below. If a colony was unable to produce 24 cores of live tissue, subsequent generations would be used to eventually reach this number. All suitable live tissue from a parent colony was utilized. After all the cores were drilled into a colony, a slotted screwdriver was used to remove each individual one from the parent coral head.

A typical core was taken 3-5cm deep but only contained about 0.5cm depth of living tissue. Drilled cores were trimmed of excess skeleton from the bottom of the core so that the first-generation broodstock fragments were as flat as possible before being mounted onto pre-drilled PVC cards with super glue (Figure 1b). A small band of marine epoxy is formed and carefully placed along the edges of the core and smoothed by hand to form a tight seal against the coral and the card to secure the fragment (Figure 1c). The epoxy helps to: 1) ensure that the coral will skirt tissue around itself and onto the card, 2) prevent biofouling along the exposed skeleton, and 3) add a secondary method of

attachment. Once fully mounted and allowed to set in a bucket of seawater, the cards are ready to be incorporated into nursery infrastructure.

Figure 1a: Parent colony being cored.

Figure 1b: Skeleton of parent core being trimmed (top) and flat final core displayed (bottom).

Figure 1c: Flat boulder coral plugs secured to plastic cards as initial broodstock.

2.2 Incorporating boulder corals into in-situ production

2.2.1 Creating nursery infrastructure

CRF™ was able to leverage its existing nursery infrastructure, requiring minimal modifications and adjustments to support the incorporation of boulder coral species into our nursery framework. One of the primary goals of developing in-situ propagation methods is to provide efficient procedures for growing boulder coral species that can be transferred to other coral restoration organizations. By utilizing affordable and easily accessible materials (i.e., PVC, fiberglass, monofilament, etc.), CRF™ was able to rapidly create, deploy, and scale-up growing and propagation techniques.

CRF™ has gone through several iterations of the original Coral Tree™ design to find the most efficient way of housing boulder coral. The first design, mirroring the original Coral Tree™ (Nedimyer et al. 2011), suspended boulder corals on cards in a similar fashion to how *Acropora* spp. are grown (Figure 2). In time, this design proved to be inefficient due to several detrimental design flaws that posed challenges to coral growth, health, and ease of propagation. For example, the weight and surface area of the cards resulted in the cards swinging into each other, cores fell off their cards and were lost, and the monofilament line occasionally snapped as it wore against the holes of the tree branches. Additionally, we noticed that growth was hindered as the tissue was limited to skirting a vertical wall rather than a horizontal surface as the species typically does. Understanding these difficulties and the need for a more efficient and productive methods, CRF™ worked to develop a new design.

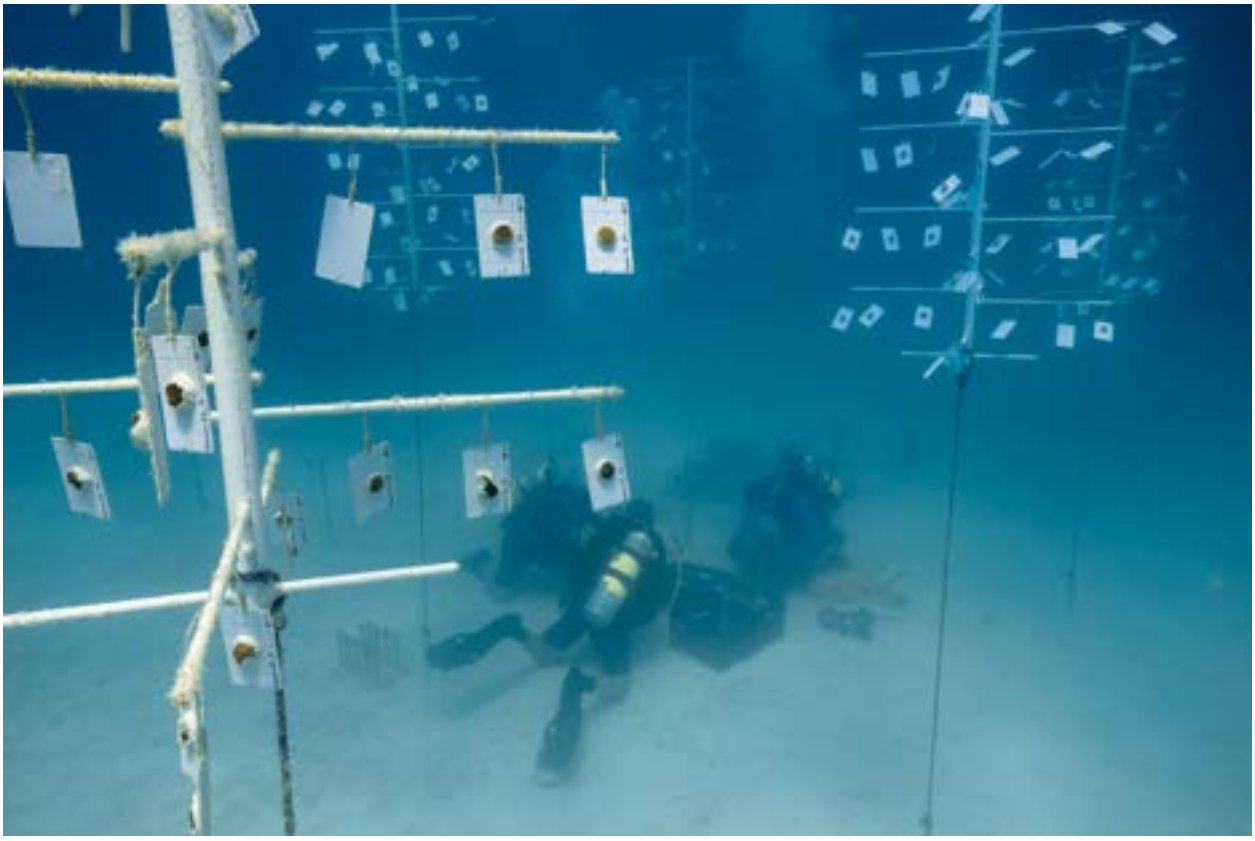

Figure 2: Boulder coral plugs suspended from cards using monofilament, similar to how Acropora corals are traditionally hung in nurseries.

2.2.2 Boulder Coral Tree™ and tray design

Through the process of design and redesign, CRF™ developed and deployed a new Boulder Coral Tree™ to facilitate: 1) easy handling and maintenance of both nursery structures and the corals themselves, 2) quick removal of individual cards or even whole trays from the tree for cleaning, relocation, or fragmentation, 3) the upward facing orientations of the corals to allow them to receive a full day of sunlight and adequate water flow to prevent sedimentation, and 4) a tray structure that can be easily built from readily available material.

The new Boulder Coral Tree™ design (Figure 3) consists of a vertical double "trunk" made of 5-foot 1" PVC in the shape of a narrow rectangle held together with PVC glue and two-part marine epoxy. Three sets of 36" parallel fiberglass rods run through the tree trunk, with 18" of PVC rod emerging on each side of the trunk. Screws are added to the PVC joints and a piece of 1200-pound monofilament is looped around the middle of the trunk to add extra stability and prevent breakage. A tree holds 6 trays total (2 broodstock, 4 outplant plugs), each tray (or set of parallel fiberglass rods) sit with approximately 2' of vertical space from each other. Trays, which are removable, are constructed out of ½" PVC with holes on the sides to slide over each pair of parallel branches on the tree. Mesh covering is secured over the trays that allow corals to be secured on small plugs inserted into the mesh or PVC cards zip-tied to it. Each tree branch has a hole drilled at the end to allow for a thick piece of monofilament to secure the trays onto the branches.

Similar to traditional nursery tree structures, nylon lines are used to secure the bottom of the tree to a duckbill anchor and floats to the top so that the tree is freely suspended in the water column.

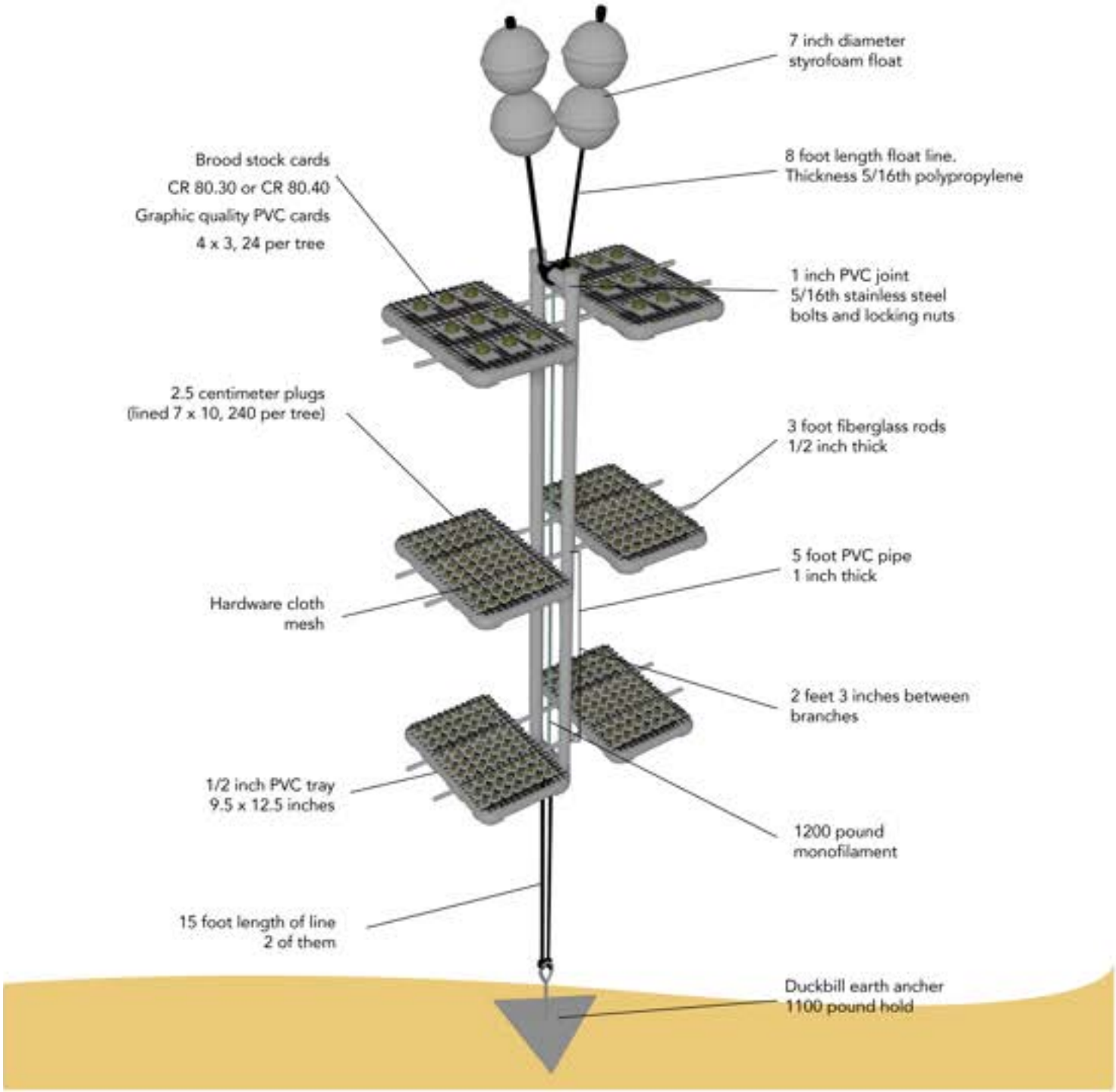

Figure 3: Full Boulder Coral Tree™ schematic with design elements and measurements provided. This design is the product of multiple iterations of in-situ trials in CRF™ nurseries and has proven to be the most efficient version for the curation and propagation of boulder corals for active restoration efforts.

This new Boulder Coral Tree™ design offers a solution to several difficulties encountered with new iterations of trees and in-situ propagation and care of these corals (Table 1).

Table 1: The current Boulder Coral Tree™ design addressed several challenges to in-situ growth/propagation of these corals. Described below is a high-level look at the main challenges, design modifications, and the solutions provided with this new tree design.

Existing challenges	Re-design	Solution seen
Fragments suspended with monofilament	Fragments placed on horizontal trays	• Coral fragments do not swing and hit each other. • Removes loss of corals from monofilament breaking.
Structural integrity	Reinforced PVC joints plus 1200lb mono running between trunks	• More robust tree design, limiting impact of high wave-energy during storm events.
Water movement hindering work efficiency	Removable trays as modular units	• Divers can work on individual trays. • Trays can be removed and worked on at the bottom, limiting challenges of surge and buoyancy.
Harvest inefficiency	Removable trays	• Prior to collection, nuance spaces are more easily removed. • Collection speed increases by being able to simply pull full trays at the time of harvesting.

2.2.3 Populating Boulder Coral Tree™ Structures

Our goal for boulder coral propagation is to be able to maintain a healthy broodstock population while continually producing smaller, subsequent-generation fragments that can be used for active restoration efforts (i.e. outplanting). It takes approximately one year for a broodstock coral to skirt over its original card and produce enough tissue to be viable for second-generation fragmentation (Figure 4).

Figure 4: Broodstock colonies with tissue skirting two over cards prior to fragmentation.

After the initial coring phase, there is no need to remove the corals from the nursery as subsequent fragmentation can be accomplished in-situ. When fragmenting, a broodstock coral card is carefully bent outward until the coral colony works itself free from the card and pops off, leaving a large, flattened coral colony. Diagonal cutters (the same used for *Acropora spp.* work) can then be used to cut (fragment) the resulting colonies into subsequent generations.

To maintain our growth stock, it is crucial that the broodstock cards are replaced first, ensuring that growing tissue for each genotype is present and healthy at all times. The number of broodstock can be adjusted according to production needs, though CRF™ recommends that at least two trays of broodstock cards (24 total cards, 12 cards per tray) are created to build redundancies and prevent total loss in case one tray fails.

New broodstock fragments are produced using the flattest/thinnest pieces of tissue available to promote and accelerate tissue skirting (Figure 5). Thicker fragments of coral, if used for broodstock, can end up producing vertical, bulbous skeletal growth that will hinder future fragmentation. The 24 new broodstock fragments are then attached to new PVC cards using a two-part marine epoxy and zip-tied to two new mesh trays (if the old tray is in suitable condition, it can be reused) (Figure 6). After the initial coring and broodstock placement (on land) we move away from the use of superglue for coral attachment. Epoxy is an equally useful tool for attaching the coral fragment to the card

itself and can be used in water, allowing for all these propagation efforts to be done in-situ. The resulting two broodstock trays are then secured on the top two branch spaces of the Boulder Coral Tree™ for maximum access to sunlight.

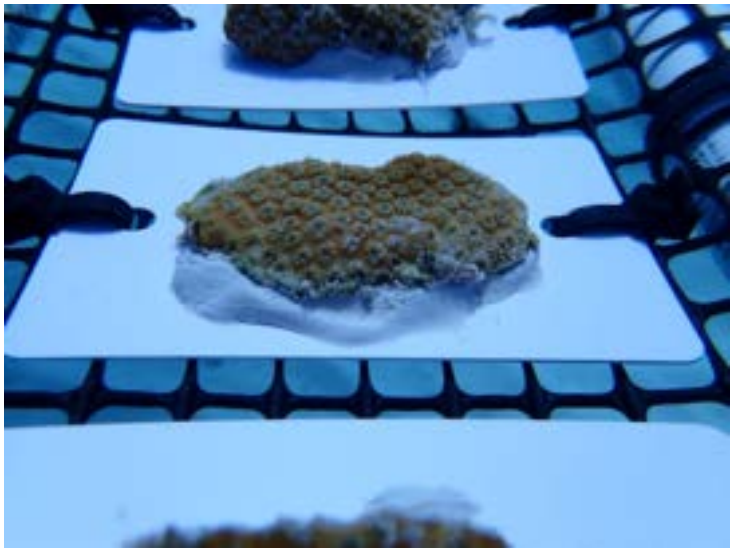

Figure 5: Replacing old broodstock, these newly created (fragmented) broodstock corals have been cut and placed on cards to be as flat as possible.

Figure 6: Completed broodstock tray (12 cards), with flat coral fragments set to re-skirt for subsequent generations and fragmenting.

The excess coral tissue produced from the fragmented broodstock is then used to prepare outplant plugs. We utilize aragonite aquarium plugs with a 2.5cm diameter as substrate for outplant fragments. Single, small (~1-2cm diameter) coral fragments are attached to each plug using a small ball of marine epoxy (fingernail-size). We recommend securing the plugs to the mesh in an array (7 x 10) prior to attaching the coral. Ultimately, 70 plugs with attached coral can be secured onto the mesh on a tray (Figure 7) and attached to the Boulder Coral Tree™. Each Boulder Coral Tree™ can hold six trays.

Figure 7: Completed tray of boulder coral plugs (for eventual outplanting). Plugs are secured to the mesh and coral is attached with a small ball of epoxy.

We recommend installing four trays of 70 plugs and two trays of 12 broodstock, totaling 280 plugs and 24 broodstock of monogenetic coral fragments per tree (Figure 8a). Once all trays are mounted, a genotype marker printed on PVC card is zip-tied to the tree trunk for identification (Figure 8b). This method of using existing broodstock corals to produce smaller fragments on plugs allows for the continual propagation and outplanting of these genotypes without the need to collect further wild colonies.

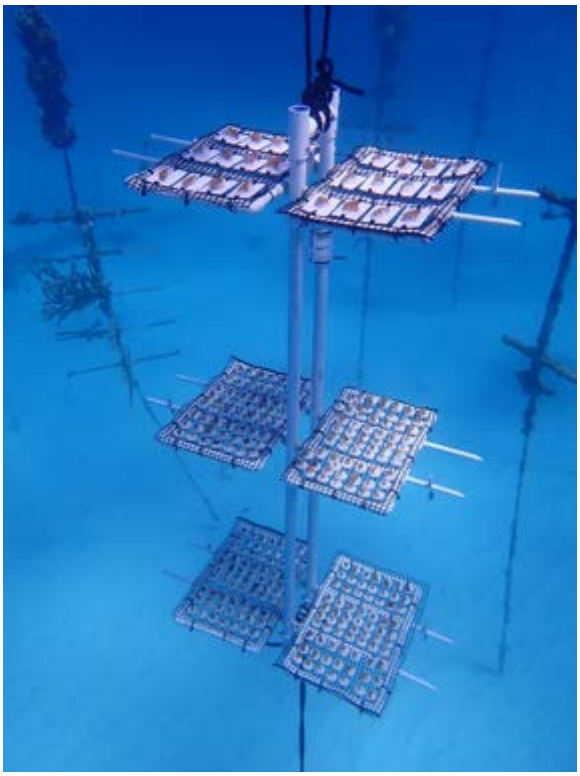

Figure 8a: Completed Boulder Coral Tree™ with broodstock card trays on top two branches and coral plug trays on bottom four branches. Final, full, tree holds 24 broodstock cards, and 280 coral plugs.

Figure 8b: Close-up of genotype identification tag.

2.2.4 Maintenance of Boulder Coral Tree™ and Coral Fragments

Once the coral fragments on plugs are installed on the Boulder Coral Tree™, they are allowed approximately 9-12 months to skirt tissue across the plug and grow to approximately the same size (2.5cm diameter) as the plug before they are "reef ready" for outplanting (Figure 9). During the grow-out phase, routine cleaning is done to ensure

the coral is not overgrown and outcompeted by algae, fire coral, bivalves, or other encrusting biofoul. Cleaning is accomplished using dish and grout brushes, tools already in use for many CRF™ nursery operations; extreme care is taken to not remove any living coral tissue when cleaning, which can be incredibly thin. Larger fouling agents require the use of a small chisel to remove; settled barnacles and fire coral are carefully chiseled off the cards and plugs to allow open and clean substrate for the coral to grow on. The tree structures themselves are also cleaned several times during the grow-out to prevent excessive biofouling.

Figure 9: "Reef ready" plugs suitable for outplanting. Pictured is an old-style tray, but the coral plug sizes and grow out are consistent to what we target with our revised designs described here.

2.3 Outplanting *Orbicella* species

Once nursery fragments cover the surface area of the aragonite plugs (2.5cm in diameter), corals of the same genotype are harvested from the nursery. In most cases, an entire tray is pulled from the tree and carefully cleaned using brushes and chisels. The removable nature of the trays allows for an entire unit of 70 plugs to be harvested at once, making collection, genet tracking, and transport simple and efficient. The trays with plugs are then brought to the surface and placed into bins of seawater to be

transported to a reef site for outplanting; if necessary, the corals can be kept in the seawater bins overnight with aerators for outplanting the following day (Figure 10).

Figure 10: Various configurations of boulder corals colonies on aerators and in seawater to be kept overnight, prior to transporting and outplanting efforts.

Boulder coral plugs are outplanted in monogenetic clusters placed close together onto either existing dead boulder heads on the reef and/or on high relief areas. Suitable coral heads are ones that have no live tissue and are ideally of the same species as the outplants (ideal, not required) (Figure 11). The flat edge of a hammer is used to remove algae from the chosen spot on the reef so that the marine epoxy can properly adhere to the underlying substrate. The stem of each plug is cut off with diagonal cutters so that the plug can lie as flat as possible on the substrate (Figure 12). A small ball of epoxy is then used to adhere the flattened plug to the cleared reef substrate. Plugs are placed close together, approximately 1-2cm apart (Figure 13). This spacing allows for each plug to establish itself on the reef and for the re-skinning of old coral heads after the corals on the plugs grow and fuse together. A cow tag with the genetic information of the cluster is nailed into the substrate nearby for subsequent monitoring.

It is important to note that we began our outplanting techniques similar to other organizations that had successfully used a Nemo hydraulic drill to create holes in the reef substrate for the plugs to fit in to. Initially we incorporated the use of the Nemo drill into our boulder coral outplanting procedures. This method allowed the plugs to be fit into the reef nicely but created a bottleneck, was very time-consuming, and the tool is

expensive. As our process developed, we determined that the additional step of drilling holes is unnecessary as the plug (with the stem removed) can successfully be attached directly to reef substrate with epoxy, thus increasing efficiency and decreasing cost. Additionally, this ensures the reef framework stays intact and limits the potential for further bioerosion to occur through freshly drilled holes. We have seen no negative change in coral fragment attachment or survival between using the drill and attaching plugs to the substrate with marine epoxy.

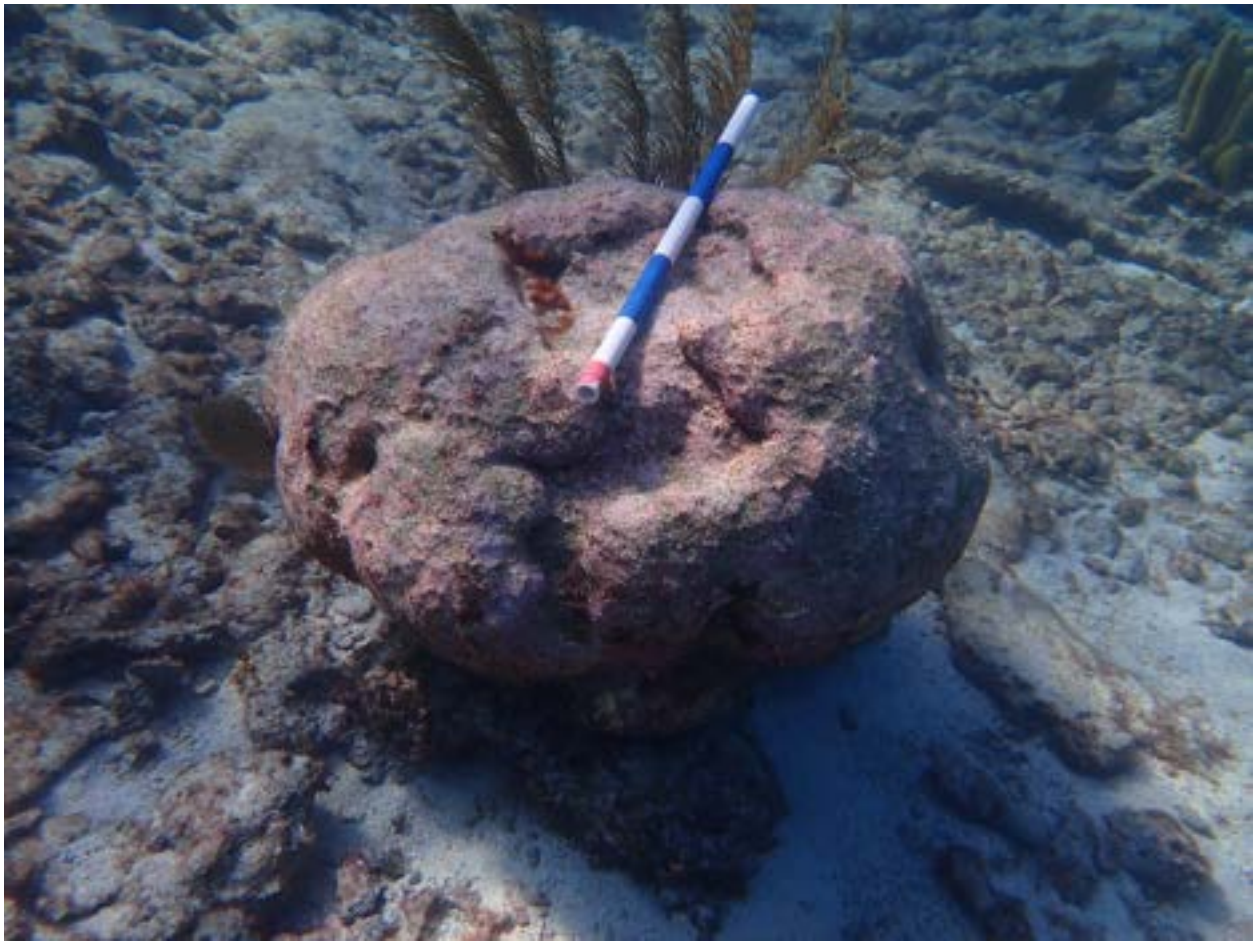

Figure 11: A suitable coral head chosen for boulder coral outplants.

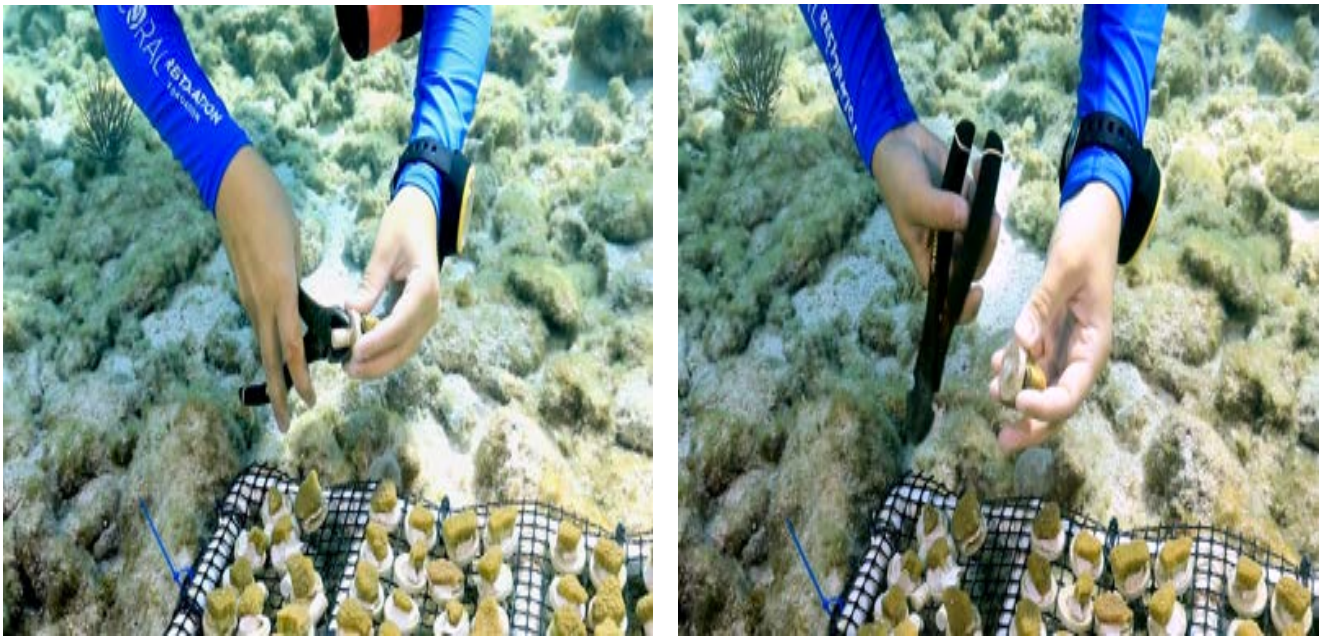

Figure 12: Removal of the coral plug stem to create a flat plug.

Figure 13: Coral plugs placed with epoxy onto the chosen coral head.

2.3.2 Orbicella outplant monitoring

Across all species, CRF™ monitors every coral outplanted. *Orbicella spp.* monitoring captures metrics of attachment success, survivorship, and active stressors affecting live tissue (Figure 14). This monitoring protocol (adapted from Mote Marine Laboratory) has remained largely unchanged since its implementation in late 2018 as the monitoring regime has easily scaled with the changing outplant methodologies.

The data headers can be found in Figure 14. Each are explained briefly here:

- Genotype and Cluster: the combination of these two fields represents the unique identifier of a group of monogenetic corals and is how success is tracked
- Type: as methods of outplanting evolve, corals are being placed both directly onto the substrate and on 3D structures (domes, see below). These differences are tracked here
- # Alive, # Dead (NEW and OLD): the number of corals alive and dead in a cluster. Corals marked as "Dead (NEW)" are those that have recently died (white skeleton exposed) while those marked as "OLD" are those that have died and are already overgrown with algae or other reef organisms
- % Partial Mortality (NEW and OLD): the percentage of colonies that have recent or old mortality. See above for the difference between NEW and OLD mortality
- Disease, Bleaching, and Predation: conditional stressors that are identified and recorded if the remaining live colonies are being impacted by one or more of these stressors
- Fusion: a measure of if corals have begun growing into one another

Coral monitoring is performed twice for every coral outplanted, as is standard with Acroporids. These monitoring events fall between 1-3 months after outplanting and again 9-12 months after outplanting. The initial monitoring, or "Month" monitoring, is used to understand how the stress of outplanting affects colonies while the "Year" monitoring is better suited to help tease apart the varying influences of genotype and reef site on coral survival and growth. The data collection is the same at Month and Year time points. Photographs are also taken of every cluster at monitoring intervals.

BOULDER CORAL MONITORING

Date: Surveyor: Site/Mooring #: Interval: Water Temp:

Overall Tagged Plot						Remaining Live Fragments						
Genotype	Cluster	Type	# Alive	# Dead (NEW)	# Dead (OLD)	% Partial Mort. (NEW)	% Partial Mort. (OLD)	Disease?	Bleaching?	Predation?	Fusion?	Comments

Figure 14: CRF™ boulder coral monitoring data sheet. Each line of data represents a coral cluster.

From this data, CRF™ calculates both partial and total mortality of any given cluster. Combining the # Dead with % Patrial Mortality yields total dead tissue of the corals present in a cluster. Using the outplant metadata, we can also determine how many corals have gone missing since the initial attachment to the reef. Keeping this metric separate from coral mortality is important for understanding the difference between mortality due to poor attachment and mortality due to environmental stressors on the reef. Missing, Dead, and Partial Mortality metrics can all be combined to calculate the total missing/dead coral tissue of a cluster.

Unlike the corals in the nurseries, outplanted colonies often show signs of fish predation at the Month monitoring interval. This is a phenomenon that is also observed by other restoration groups that outplant boulder species. Fortunately, it does not frequently lead to colony mortality because the predation pressure subsides quickly after the first month and the fragments can recover from the initial bites (Figure 15).

Figure 15. Orbicella annularis (Oann1) at three different time points. From left to right: 10.21.18 – 11.27.18 – 01.30.19. The second image, taken during the Month monitoring survey shows recent bite marks. The final image shows tissue recovery and colony fusion after three months on the reef.

CRF™ is aware of and committed to tracking and reducing the stress to outplanted colonies from Stony Coral Tissue Loss Disease (SCTLD). Due to the small size of outplanted colonies, identifying coral diseases accurately can be difficult. Thus, if a white disease lesion is observed, photographs are taken, disease is marked on the data sheet, and, if possible, the affected colony is removed from the reef site. Very few instances of suspected SCTLD-affected outplant colonies have been observed, but CRF™ is constantly monitoring for this and other diseases so that coral survival is maximized.

3.0 Further Development

3.1 Nursery Next Steps and Method Development

Although new collections of COOs are minimal, and only opportunistic (i.e. rescue corals in a grounding), to produce flatter initial broodstock corals from the original COOs, we have found a diamond-coated jeweler's saw can take the place of the drill press and core bit. The jeweler's saw is used to cut small fragments from the large COO. This technique reduces the overall stress that these colonies experience during the drilling and shaving stage while also allowing us to utilize more the of COO tissue area. CRF™ has invested in a jeweler's saw to also increase fragmentation efficiency. If a broodstock coral gets

too large to be cut with diagonal cutters in-situ, it can be transported back to our ex-situ facility and fragmented with the saw.

3.2 Future Outplant Developments

CRF™ has been working closely with the Coral Restoration Consortium (CRC) Engineering and Innovations working group to develop novel techniques and restoration methods for coral restoration practitioners. One of the main focuses has been on the development and fabrication of a 3-D engineered outplant structure that would increase diver efficiency and speed of outplanting for boulder corals that have been micro-fragmented, as well as work to improve long term survivorship (Figure 16). CRF™ in collaboration with the CRC, Secore, Ocean Reef Alliance, and Reef Cells, is testing the first prototype design. The 3-D structures are attached to reef substrate and filled with coral plugs that have been grown in the CRF™ Tavernier nursery for approximately 6 months in hopes that the plugs will grow across the structures and fuse together, thus creating a single unit. In total. this first pilot project involved outplanting of 14 structures (7 small, 7 large) in December 2020. Nine further structures were deployed within the Tavernier Nursery for one year to test growth within a controlled environment prior to being deployed at a reef site. CRF™ hopes that by utilizing structures like these it can increase its operational capacity for boulder coral restoration and outplanting.

Figure 16: Engineered structures with new boulder coral plugs established for in-situ nursery grow-out.

CRF™ will be performing extensive monitoring of these engineered structures to determine the success of the structure itself (attachment, design, etc..) as well as the survivorship and growth of the corals. Soon, CRF™ is also hoping to test a similar design made with different material. We will be evaluating the success of the structure to make any necessary design/technique modifications.

3.3 Future monitoring developments

For Acroporids, CRF™ has completely transitioned to conducting outplant monitoring via photomosaic. This method has greatly reduced the amount of in-water effort required to monitor tens of thousands of outplants without sacrificing data detail (see CRF™ White Paper: Photomosaic Manual). As we adjust our outplanting methodology to a more 3D approach on existing boulder heads, we are also developing ways to modify our monitoring program such that photomosaics can accurately capture key metrics of boulder outplants.

By using 3D mosaics as a monitoring tool, we can do something we have never done before in-water: capture the true area of boulder corals over time. By taking a series of photographs of a single coral cluster, we are able to construct accurate 3D models of boulder outplant plugs and their surroundings (Figure 17). It is from these models that we can derive metrics such as total surface and volumetric area covered. This approach puts our monitoring metrics into context, giving us a better sense of the impact our restoration efforts are having on overall coral coverage. CRF™ has developed a new protocol for conducting boulder coral monitoring via photomosaic which includes the development of new scale bars used by the stitching software to create scale and the re-working of technology already in use to measure the area of a 3D space. The inclusion of this new methodology is helping us better understand the scale and speed at which our efforts are truly restoring previously dead areas of reef.

Figure 17: An example of a 3D image of an outplanted boulder cluster.

4.0 Conclusions

While coral restoration efforts have been ongoing for decades in Florida (and other areas), these original efforts have traditionally focused on the branching, fast-growing Acroporids. As restoration methods evolve and the need to incorporate more species

into restoration activities increases, there is a clear and pressing need to put a priority on developing restoration techniques for non-Acroporid coral species. These techniques need to be low-cost, efficient, and effective in order for a scale-up in restoration efforts to be successful and take on a holistic approach. CRF™ has worked over the years to develop such an approach. Our approach to boulder coral propagation has been developed in such a way that all efforts can take place in-situ, limiting transportation and handling stress of the coral, while being efficient and cost-effective. Our goal in presenting these methods and how they have developed over time for each phase of the restoration process (propagation, outplanting and monitoring) is to aid in the shared practice of restoration and fellow practitioners. We hope that this white paper can act as a guide for others developing their own restoration methods for a variety of coral species.

5.0 Works Cited

Bruno, John, and E. Selig. (2007). Regional Decline of Coral Cover in the Indo-Pacific: Timing, Extent, and Subregional Comparisons. PloS one. 2. e711. 10.1371/journal.pone.0000711.

De'ath, Glenn, K. Fabricius, H. Sweatman, and M. Puotinen. (2012). The 27-year decline of coral cover on the Great Barrier Reef and its causes. Proceedings of the National Academy of Sciences of the United States of America. 109. 10.1073/pnas.1208909109.

Forsman, Zac, C. Page, R. Toonen, and D. Vaughan. (2015). Growing coral larger and faster: Micro-colony-fusion as a strategy for accelerating coral cover. PeerJ. 3. 10.7717/peerj.1313.

Jackson, Jeremy, M. Donovan, K. Cramer, and V. Lam. (2014). Status and Trends of Caribbean Coral Reefs: 1970-2012. 10.13140/2.1.4868.6726.

Moura, Amelia, B. Beck, R. Duffey, L. McEachron, M. Miller, J. Moore, A. Moulding, and R.S. Winters. (2021). Integrating Coral Restoration Data with a Novel Coral Sample Registry. Frontiers in Marine Science. 10.3389/fmars.2021.700172

Nedimyer, Kenneth & Gaines, Kevin & Roach, Stephanie. (2011). Coral tree nursery ©: An innovative approach to growing corals in an ocean-based field nursery. AACL Bioflux. 4. 442-446.

Newman, Steven & Meesters, Erik & Dryden, Charlie & Williams, Stacey & Sanchez, Cristina & Mumby, Peter & Polunin, Nicholas. (2015). Reef flattening effects on total richness and species responses in the Caribbean. The Journal of animal ecology. 84. 10.1111/1365-2656.12429.