Guide to Coral Reef Restoration

Optimizing efficiency and scale for in situ nurseries and outplanting.

The synthesis provided here is a product of the Coral Restoration Consortium's Field-Based Propagation Working Group

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Optimizing efficiency and scale for in situ nurseries and outplanting

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ABOUT THIS DOCUMENT

Founded in 2017, the Coral Restoration Consortium (CRC) brings together a global network of scientists, decision-makers, reef managers, and, crucially, coral restoration practitioners, all united by the mission to restore coral reefs worldwide. The CRC is dedicated to actively listening to the voices of those on the frontlines of reef restoration, ensuring that their insights and experiences shape the field. The CRC continually strives to advance the field by producing high-quality resources, including best practice guidelines, training courses, webinars, interactive maps, and comprehensive databases. The CRC is committed to supporting communities and practitioners in scaling up innovative coral restoration projects, empowering them with the resources needed to ensure coral reef ecosystems thrive for generations to come.

The CRC's Leadership team includes researchers, managers, and practitioners in the field of coral restoration. Core to the function of the CRC is sharing and disseminating knowledge in a way that transcends regional and methodological biases. The CRC has developed working groups to deliver guidance on key topics, including field and land-based restoration efforts, coral larval propagation, restoration genetics, monitoring, and resource management.

In addition, new CRC working groups continue to form to address emerging topics. The core team of the CRC's Field-based Propagation Working Group wrote this report. Members of the Field-based Propagation Working Group and other Working Groups also contributed content. This product synthesizes the best available information at the time of publication, and we recommend that the CRC update this product as new information is available and advances the field.

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Coral Restoration Foundation

Andrew Ross

LIST OF ACRONYMS

BDL	**Buoyant Drop Line**
CCA	**Crustose Coralline Algae**
CNP	**Coral Nurture Program**
CRC	**Coral Restoration Consortium**
CRF	**Coral Restoration Foundation**
DNER	**Department of Natural and Environmental Resources (Puerto Rico State Agency)**
FUCA	**Floating Underwater Coral Apparatus**
FOH	**Fragments of Hope**
GBR	**Great Barrier Reef**
GPS	**Global Positioning System**
HDPE	**High-density polyethylene**
HRM	**Horticultural Ring Mount**
ID	**Identification**
KAUST	**King Abdullah University of Science and Technology**
M/V	**Motor Vessel**
NA	**Not Applicable**
NOAA	**National Oceanic and Atmospheric Administration**
NSU	**Nova Southeastern University**
PAR	**Photosynthetically Active Radiation**
QGIS	**Quantum Geographic Information System**
PET	**Polyethylene terephthalate; as in type of plastic bottle**
PVC	**Polyvinyl chloride**
RPM	**Revolutions per Minute**
RRFB	**Reef Renewal Foundation Bonaire**
SCTLD	**Stony coral tissue loss disease**
TLE	**Total linear extension**
TNC	**The Nature Conservancy**
USVI	**United States Virgin Islands**
WG	**Working Group**

Kaust Coral Restoration Initiative

EXECUTIVE SUMMARY

John Edmondson/Wavelength Reef Cruises

Coral restoration techniques have been developed and implemented at local scales since the late 1960s (Maragos, 1974; Shinn, 1976; Birkeland et al., 1979; Bouchon et al., 1981; Alcala et al., 1982; Auberson, 1982; Harriott and Fisk, 1988). However, accelerating degradation of reef health over the last two decades – in particular through repeat heat stress events – has propelled a global movement to develop viable restoration and rehabilitation practices (Clark and Edwards, 1995; Kaly, 1995; Rinkevich, 1995; Epstein et al., 2003; Young et al., 2012; Boström-Einarsson et al., 2018). Efforts have been motivated by the overwhelming need to act in the face of inaction on global climate change (and pollution control), significantly increasing the geographic, biological, and ecological scale at which restoration has been taking place. The outcome of restoration practices rests on alleviating the sources of stress on reefs; even so, coral restoration has rapidly become a hands-on and proactive means for stakeholders to aid local recovery of coral biomass and/or slow rates of coral loss. Restoration can also help maintain reproductively viable populations of corals with resilient traits that can promote adaptation to the changing climate and buy time to address local stressors. Ecological restoration should be based on a "do no harm" ethos; intervention should consider how the process is providing a net benefit to coral reef conservation. Increasing recognition of coral restoration as a fundamental approach to advance local reef stewardship is captured through the UN Decade on Ecosystem Restoration (2021-2030) and the need to rebuild reef habitats and ecosystems to ensure longer-term environmental and social resilience (Hein et al., 2020).

This Guide was developed to fulfill the priorities of the CRC's Field-based Propagation Working Group. The group itself is a centralized source of broad knowledge in the rapidly expanding field of coral reef restoration. It builds on earlier key resources – notably Edwards (2010), Johnson et al. (2011), Frias-Torres et al. (2018) to capture the growing diversity of innovative methods that are driving restoration operations toward increasingly larger geographic scales. We walk the reader through key factors and methods to consider for in situ field-based coral propagation, as well as lessons learned through case studies. Details for specific approaches are provided as appendices that can be updated as new approaches are developed and tested. We describe in detail the multitude of methods already in place around the world to emphasize that there is no "one-size fits all" approach. The goal is to help current and future practitioners select approaches that suit their goals and environmental-social contexts. We acknowledge that the Guide is not exhaustive, nor is it final. New methods are being developed as we type, and it is our hope that this will serve as a "living document."

Site selection for restoration is arguably the most important element in program success, and is described as a part of Chapter 1 – **Restoration Planning**. Ideally, a restoration site would be selected according to optimal conditions (e.g., depth, substrate type, water quality, species presence – corals, predators, fouling taxa, accessibility, human impacts); however, the actual location may be constrained by logistics or policy. Local knowledge of where coral has or has not historically grown is invaluable as a guide for where restoration may be most successful. Building monitoring (Goergen et al., 2020) into a restoration program early on is critical for determining restoration success and incorporating adaptive management.

In Chapter 2, we explore **nursery setup and design**. In many cases, access to wild-grown material is supplemented by active propagation on nursery structures that can be located under (more) optimal conditions, to generate additional coral material (fragments and whole colonies). Though nurseries often focus on a primary, fast-growing coral, they can — and often should — house multiple different coral species. Environmental conditions at the nursery location play a large role in coral or coral fragment growth and survivorship. Local management, as well as the growth rates and reproductive biology of coral species, governs the efficiency

Santiago Estrada


Coral Restoration Foundation

of the nursery. We provide examples of several types of nurseries that have been tried and tested and found suitable under specific circumstances. These are detailed in coral propagation case studies from the Caribbean, Indo-Pacific, and Great Barrier Reef. While materials available for nursery construction will vary from place to place, we discuss general details of construction to enable practitioners to adapt the designs to local materials. Critical information on **nursery maintenance** – notably controlling factors such as disease, bio-fouling, and physical impacts– is discussed in Chapter 4.

In Chapter 3, we describe how to add **coral stock to the nursery**, using collections from wild populations including "corals of opportunity". While programs often focus on one or two species, it is now clear that species diversity is critical to ensure resilience as reefs are subject to rapidly changing environmental conditions. Species choice may be limited by local restrictions and may be exceptionally complex where species diversity is high, yet capacity for accurate species identification is limited. In all cases, tracking donor colony lines through time is beneficial to track colonies that show advantageous traits, such as high gamete production, fast growth, and disease or bleaching resistance. Collection may be constrained by local logistics or permitting or opportunistic in the case of ship groundings or development projects.

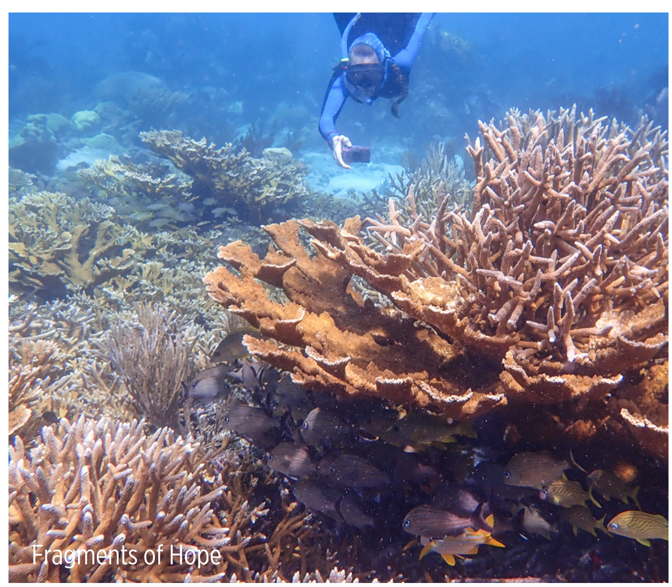
In Chapter 5, we provide a roadmap for nursery **monitoring, ecological surveying, and reporting**. Accurately quantifying what has worked, failed, or changed is a critical step in communicating nursery management success and evaluating whether the program goals for nursery performance are being reached. Importantly, more details on monitoring coral reef restoration sites, such as Universal Metrics and Goal-Based Performance Metrics, are covered in the *Coral reef restoration monitoring guide: Methods to evaluate restoration success from local to ecosystem scales* (Goergen et al., 2020).

Chapter 6 covers **harvesting coral** from nurseries, and transport of material. Holding corals ex situ introduces stress that could impact outcomes of subsequent propagation and outplanting. Until new innovations in transport techniques are developed, this factor is best minimized in practice workflows.

In Chapter 7, we explore **restoration design and techniques**, including where and how to conduct outplanting of propagated coral focusing on various coral attachment methods.

We end the Guide with **scaling up** in Chapter 8 and how to **generate work capacity** in Chapter 9. These chapters outline how optimized activities described in previous chapters can be used to develop bigger and more advanced programs. We also provide guidance on developing funding frameworks and long-term goals. We use case studies from the Caribbean, looking at volunteer and contractor-based operations, as well as the Great Barrier Reef through tourism industry partnerships. We also describe how programs may reach a natural endpoint requiring an **exit strategy**, and when restoration should be discontinued.

This Guide is designed to walk practitioners through the process of developing a restoration program and provide foresight for program success. Each chapter should be treated as an entry point to help you determine whether and how to initiate, maintain, build, or stop program activities relative to the local contexts, goals, and resource availability. This Guide was developed to include only the methods, techniques, and guidance for in situ nursery development and outplanting. We propose that this document could be expanded in future versions to include other restoration techniques, such as land-based nurseries, larval rearing, etc.


Fragments of Hope

OBJECTIVES AND SCOPE OF THIS GUIDE

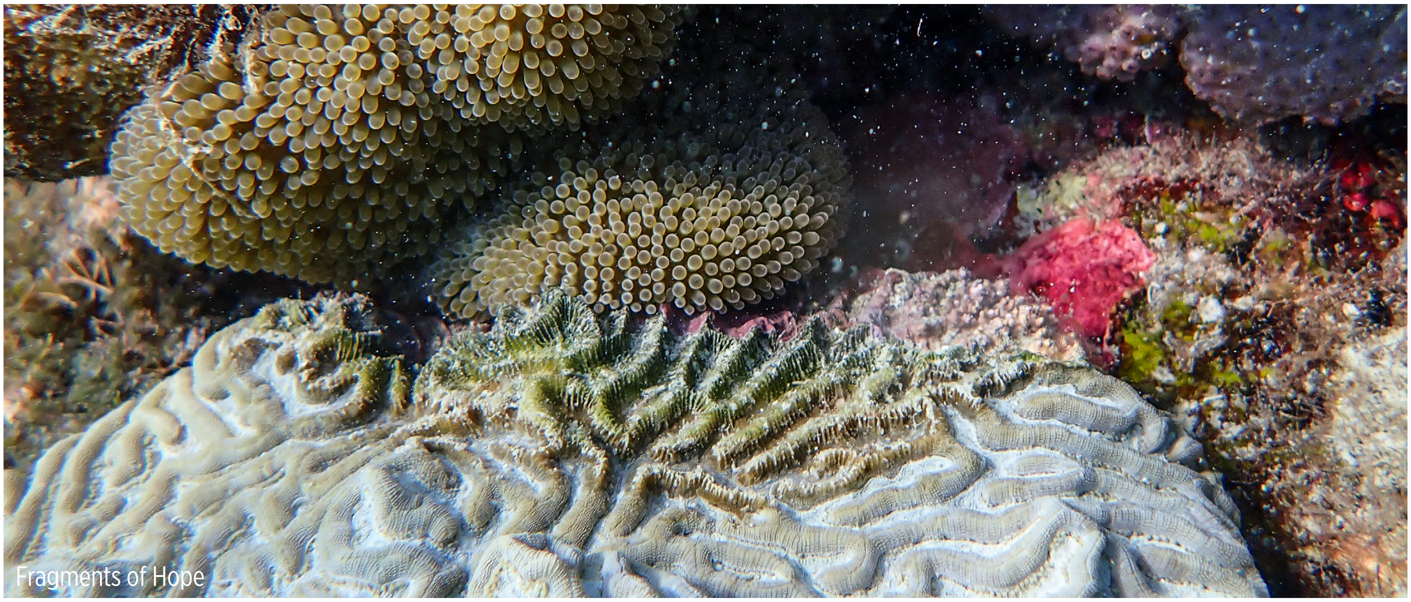
Corales de Paz

Restoration History and Purposes

Restoration, as defined by the Society for Ecological Restoration, has one end goal: return an ecosystem to its historic trajectory (Society for Ecological Restoration International Science & Policy Working Group, 2004). However, there is controversy over the ability for current coral reef ecosystems to reach the historic trajectory due to current conditions (e.g., climate change, loss of habitat, altered ecosystem, sea level rise), so the definition has been altered to include restoring to a stable state with a higher level of ecosystem function and structure.

Coral reef restoration can cover a wide range of activities spanning from the structural "fixing" of a reef after a physical disturbance to the active introduction of a range of desirable reef species, and what qualifies has evolved over the years. Field-based coral nurseries are a central process for many restoration practices and can be used for a variety of different purposes — often fulfilling more than one of these purposes at once — either by design or inadvertently (Rinkevich, 2015a). In addition to being a place where corals are grown and propagated for the purposes of outplanting, nurseries can serve as a place to both study and preserve genetic diversity, helping practitioners and reef managers to identify genotypes that may be adapted to future conditions while also preserving genetic stock that could be lost in the wild. For example, a 2010 cold-water event in Florida caused complete mortality of wild staghorn coral at 43% of the donor colony sites; however, fragments from 73% of those sites were still surviving in field-based nurseries following the event (Schopmeyer et al., 2012). Nurseries may also serve as a repository for rare and threatened species, either through the purposeful introduction of these species into the nursery or by allowing nursery structures to form their own ecosystem through natural recruitment (Frias-Torres and van de Geer, 2015; Taira et al., 2016; Wee et al., 2019). Nurseries can serve as spawning hubs where gametes can be gathered for sexual propagation, or the nurseries can be strategically placed to increase the chances of successful recruitment to down-current reefs (Amar and Rinkevich, 2007; Horoszowski-Fridman and Rinkevich, 2017; Horoszowski-Fridman et al., 2020). Similarly, a set of nurseries could provide connectivity between reefs that have lost that connection due to damage or poor health (Rinkevich, 2015a). Finally, in the case of tourism, coral nurseries can provide a visual draw for showcasing restoration activity (e.g., Howlett et al., 2022).

Capacity to outplant coral — either from nurseries or material sourced directly from wild populations (e.g., corals of opportunity) — is a critical step in ultimately restoring any given site. Historically, limitations to outplanting speed and outplant viability have been a major bottleneck to cost-effectiveness and, in turn, scale of restoration achievable (Bostrom-Einarsson et al., 2020; Suggett and van Oppen, 2022). All outplanting of asexually propagated material as either fragments or whole/partial colonies is achieved through either physical attachment methods — such as nails and cable ties (or plug and screw systems) — or chemical fixatives such as epoxies, glues, and cements. Consequently, recent efforts have particularly focused on developing and implementing novel low-cost variants (e.g., Coralclip ®, Suggett et al., 2019; standardized cement mixes, Unsworth et al., 2020) that can increase the rate of deployment while minimizing early mortality. Both physical and chemical attachment methods have been further adopted as practitioners increasingly implement at-scale deployment of larval settlement devices (e.g., Chamberland et al.; 2017, Randall et al., 2022), seed coral onto substrate enhancement or stabilization structures (e.g., Williams et al., 2018), and implement innovative outplanting methods such as microfragmentation (Rachmilovitz and Rinkevich, 2017; Page et al., 2018; Broquet, 2019). Evolution of the field toward lower cost and simple to deploy approaches has enabled up-scaled capacity through practitioner networks (e.g., Young et al., 2012; Howlett et al., 2022) that retains flexibility in matching the best outplanting approach to any given operational context, reef condition, and/or desired restoration outcome.


Fragments of Hope

Purpose of this Guide

The CRC was established in 2017 to facilitate knowledge transfer between coral restoration practitioners, managers, and scientists. The CRC identified multiple knowledge gaps in many critical aspects of coral restoration, including the need for best management practices on how to develop and maintain a restoration program. Therefore, the CRC established multiple working groups, each with individual priorities to address current gaps. CRC Guides are intended to provide current trialed practices for a range of capacities and to continue to evolve, remain current, and reflect the best available science, tools, and technology.

This Guide was developed using available guides, publications, and expert knowledge from practitioners worldwide. We intended to bring together the information and knowledge from these resources, plus the lessons that have been learned along the way in developing these resources. It was not possible to include or recommend every technique or method used, but we made every attempt possible to include the most relevant and most used practices.

This first version of the Guide includes only the methods, techniques, and guidance for in situ nursery development and outplanting. Future versions could be expanded to include other restoration techniques such as land-based nurseries, larval rearing, scaling up, etc.

Target Audience

This Guide is intended to be a reference for restoration practitioners, resource managers, and scientists. In an effort to accommodate a wide range of experience and resources, many techniques and methods were included. While detailed instructions are included for some methods, it is our hope that practitioners will continue to innovate new techniques and structures that best fit their needs while being guided by what has and has not worked in previous situations.

Using this Guide

Because coral reef restoration is a vibrant and fast-developing field, the contents of this Guide are not all-encompassing, and it should not be used as the only resource for planning for restoration. This Guide provides information on site selection, nursery structures, collections, maintenance, harvesting, monitoring, outplanting techniques, scaling up, and generating capacity. This information is provided as a starting point, and a restoration program should evaluate each section and make the best choices for their respective location, species, objectives, budget, permitting regulations, and capacity. We expect and hope that as practitioners use this Guide and further their restoration practice, lessons learned and new methods will be incorporated into future versions of this document. In tandem with this Guide, we have developed nursery structure one-pagers that provide detailed drawings and instructions for building some of the more common fixed and floating nursery types. These can be downloaded individually from the CRC website.

Definition of Terms

For the purpose of this document, we use the following terms and definitions:

Disease — any harmful deviation from the normal structural or functional state of an organism, generally associated with certain signs and symptoms and differing in nature from physical injury (Britannica). Therefore, a stress response is also a disease.

Donor colony — coral colony that provides material to a nursery.

Ecological restoration — "process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed" (Society for Ecological Restoration International Science & Policy Working Group, 2004).

Fragment/nubbin/micro-fragment — cut or recently cut portion of a larger colony. Micro-fragment and nubbin are generally smaller than 1 and 5 cm, respectively.

Nursery — an area in which corals are being raised on nursery structures.

Nursery colony — a coral that is established and raised within a nursery.

Nursery structure — an artificial structure upon which nursery colonies are grown.

Outplant — the act of attaching nursery colonies or portions of nursery colonies at a restoration site.

Outplant colony — a nursery colony that has been attached at a restoration site.

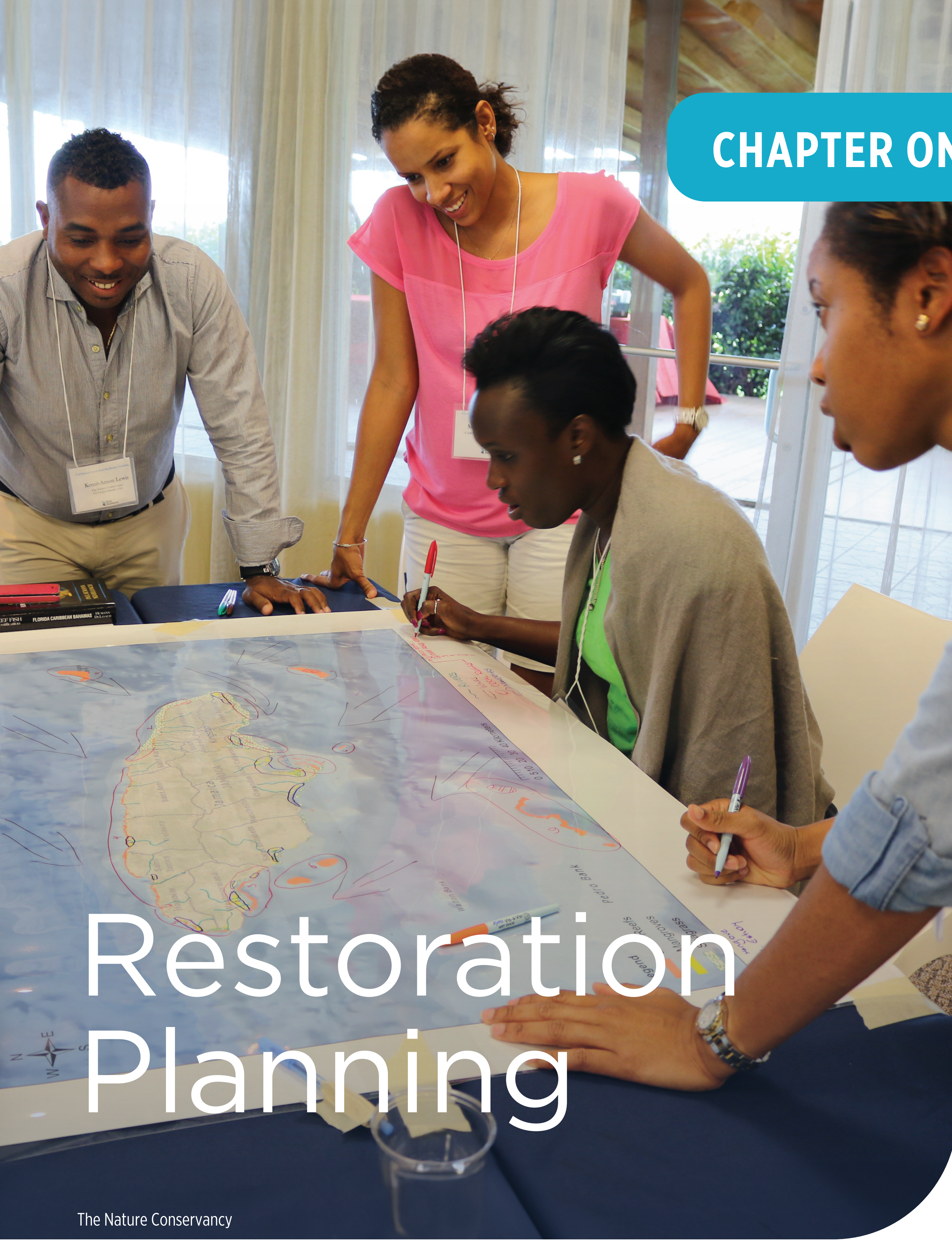
Outplant fragment — a recently cut portion of a larger nursery colony that will be attached at a restoration site.

Propagation — within nursery fragmentation of nursery colonies to produce additional nursery colonies.

Restoration — the act of returning a site, species, or ecosystem to a previous state or new stable state (i.e., healthier, greater abundance, more diverse).

Fragments of Hope

CHAPTER ONE



Restoration Planning

The Nature Conservancy

Establishing a Restoration Program

Prior to establishing a restoration program, practitioners, managers, and researchers must put careful thought into the restoration need, define program goal(s) and objective(s), determine the capacity and resources needed to carry out the proposed work, establish a secure financial backing, obtain necessary permits, become educated on the most up-to-date restoration techniques, and create an exit plan. Guidance on developing a restoration action plan can be found in "A Manager's Guide to Coral Reef Restoration Planning and Design" (Shaver et al., 2020). In addition to the action plan, programs should create a monitoring plan (see Chapter 5: Nursery Monitoring), an operational plan, and a work plan (Figure 1).

The Manager's Guide walks through a stepwise but iterative process to set goals, prioritize restoration sites, identify interventions, and develop an action plan, and then to learn and adapt as the plan is implemented (Figure 2).

By clearly establishing restoration goals, programs will be more likely to succeed and practitioners can strategically and efficiently build their programs to help support those goals. Once carefully planned, a program can begin selecting restoration sites and establishing a nursery. Lirman and Schopmeyer (2016) created a framework that can aid in developing a restoration program (Figure 3). Edwards (2010), Johnson et al. (2011), Rinkevich (2015b), and Bayraktarov et al. (2019) provide additional details on developing a restoration program. It is important to note that adaptive management approaches should be applied throughout the process; making incremental changes throughout program development is more efficient than making large changes after a program is established. This process is meant to be adaptive so that changes can be made in real time as knowledge is gained.


Fragments of Hope

Figure 1. Developing an action plan for restoration as part of a broader strategic plan for restoration. From A Manager's Guide to Coral Reef Restoration Planning and Design (Shaver et al., 2020).

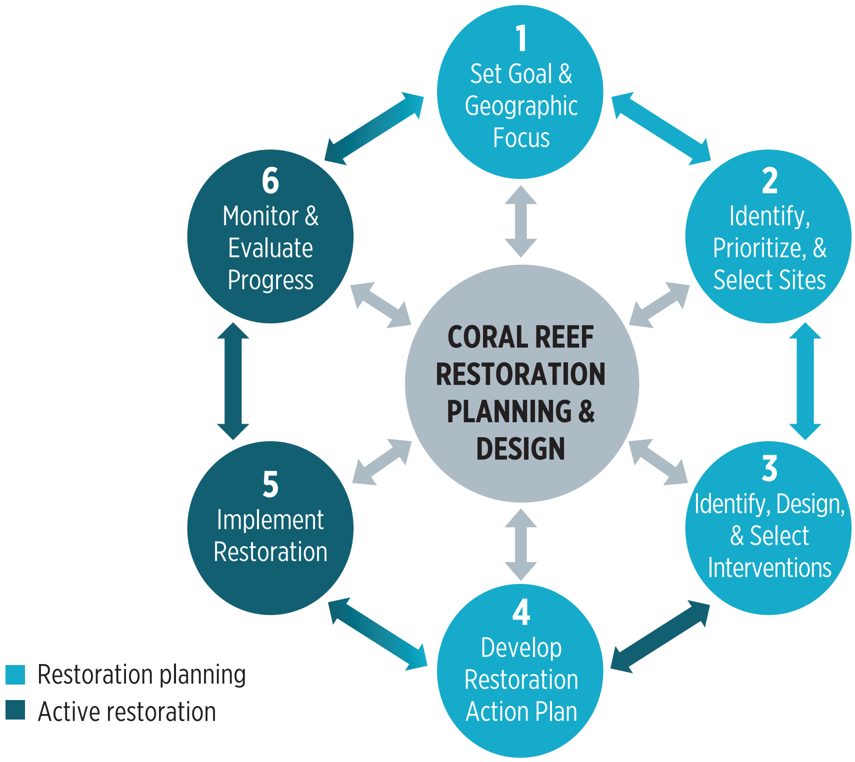


Figure 2. Stepwise approach to restoration planning and design. From A Manager's Guide to Coral Reef Restoration Planning and Design (Shaver et al., 2020).

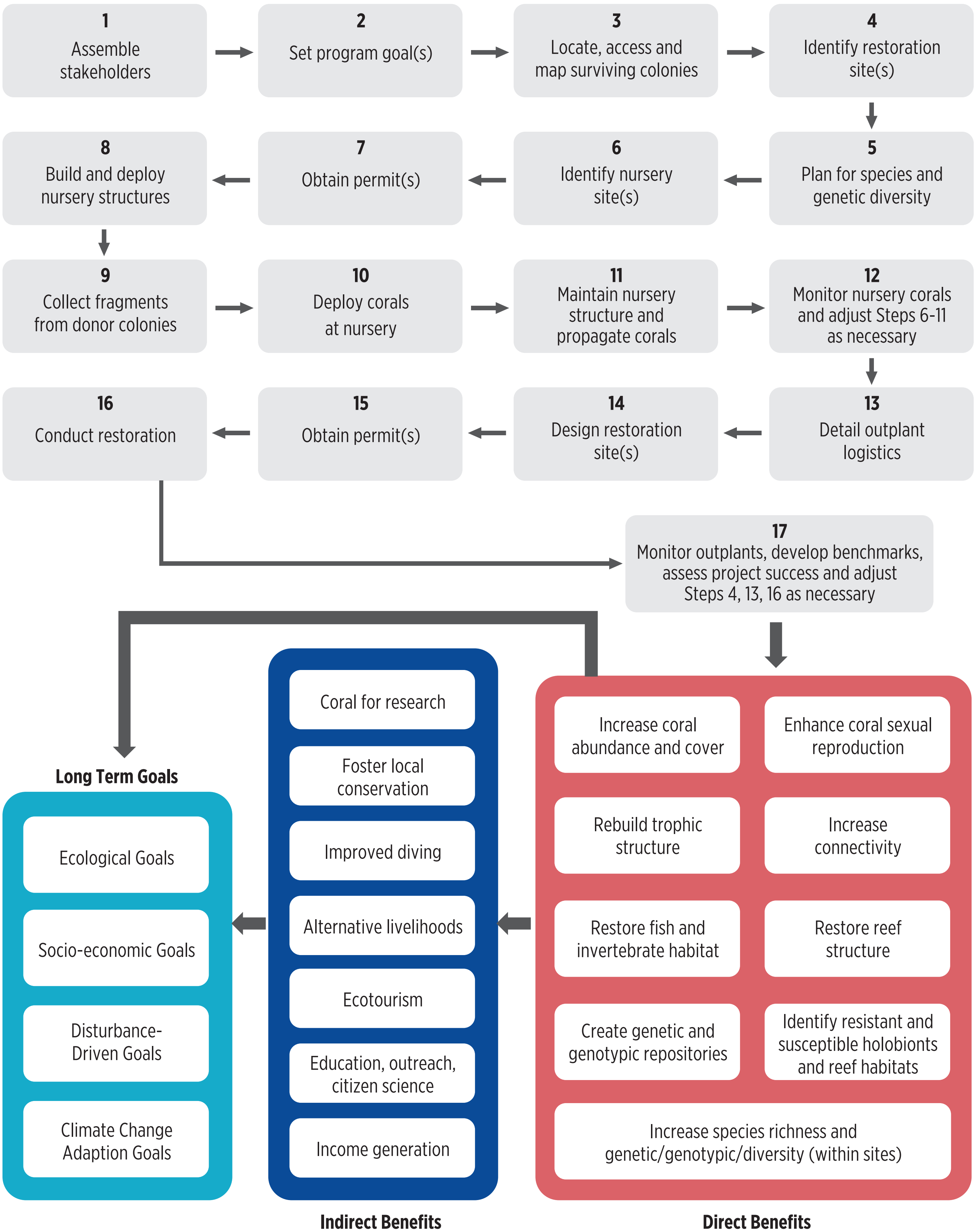


Figure 3. Framework for restoration, adapted from Lirman and Schopmeyer (2016).

This list of general restoration goals is adapted from *Coral Reef Restoration as a Strategy to Improve ecosystem services* (Hein et al. 2020); *Coral Restoration - A Systematic Review of Current Methods, Successes, Failures and Future Directions* (Boström-Einarsson et al. 2020); and *Coral Reef Restoration Monitoring Guide; Methods to Evaluate Success from Local to Ecosystem Scales* (Goergen et al. 2020).

Ecological Goals
- Mitigate coral population declines and preserve biodiversity
- Re-establish reef ecosystem function and structure

Socio-Economic Goals
- Sustain local tourism opportunities
- Promote local coral reef stewardship
- Recover and sustain fisheries production
- Recover and sustain coastal protection

Disturbance-Driven Goals
- Respond to acute disturbance to accelerate reef recovery
- Mitigate anticipated coral loss prior to disturbance

Climate Change Adaptation Goals
- Mitigate impacts and promote reef resilience to climate change

Figure 4. Examples of general restoration goals. From A Manager's Guide to Coral Reef Restoration Planning and Design (Shaver et al., 2020).

Setting Restoration Goals

Prior to developing a restoration program, a clear goal or set of goals should be established. A goal in this context is defined as a formal statement that details the change you want to measure through restoration interventions (CMP, 2020). A list of some of the common general restoration goals is included in Figure 4. When identifying goals, it may be important to include stakeholders who rely on the services that the reef provides in addition to scientists and reef managers, particularly for goals that relate to ecosystem services.

Restoration Site Selection

The selection of sites to be restored is often the most important element in a restoration project or program. Once goals have been identified, sites can be prioritized based on their conditions (likelihood of success) and contribution toward the overall goals. Improper evaluation of a site could lead to failure of a restoration project. We encourage **pilot or trial outplanting** at every site prior to a full-fledged outplanting effort. This process is not fail-safe and will not guarantee success, but it is prudent and provides reassurance in the decision-making process. If possible, pilot or trial outplants should be placed at the proposed site one year prior to proposed outplanting so corals can experience seasonality at the site, which may not be observed during initial site assessments.

During the planning phase, it is important to have a sense of how many outplant sites are appropriate for a program. This will be based on both the goals and capacity of the program (i.e., personnel, funding, corals, distance to travel, etc.). In some cases, a program's efforts will be focused on one site; this may be the case if the goal is to restore a ship grounding site, provide a tourist attraction, or if the program has limited resources. Conversely, a program with a goal of creating breeding populations of a species may want to spread outplants to many sites to increase the chances of successful reproduction to restore population connectivity. Similarly, it is important to consider the anticipated monitoring and maintenance at the sites. For example, a smaller number of sites is more realistic for programs with high monitoring and maintenance requirements. Additional guidance on the process of site selection can be found in A Manager's Guide to Coral Reef Restoration Planning and Design (Shaver et al., 2020).

Factors to consider when choosing a restoration site are broken into two steps and are based on spatial scale. The first step is a broad-scale evaluation of **what habitat should be selected** for restoration and includes identifying sites with appropriate depth, substrate type, water quality, species presence, accessibility, and human impacts. If data are available on factors such as sea-level rise, currents, sea temperature projections, and coastal development plans, these should be used to further help inform site selection (Shaver et al., 2020). This first step of site selection will likely be achieved using benthic habitat maps or local knowledge to select sites that are most suitable for the species being used for restoration. The second site evaluation step should be focused on **where within the sites restoration should be conducted.** This step requires in situ surveys of reef health, predators, space competitors, sediment, and substrate availability — all of which help determine where corals should and should not be planted.

Geographic Area Selection

The first phase of site selection will utilize best available information including benthic characterization maps, historical data, and knowledge of the site, taking into consideration the following key factors:

Presence of species — Choose sites with current or recent past presence of the species to be restored. If there is an obvious and/or persistent cause of coral decline, it should be understood, controlled, or mitigated before outplanting more corals to the habitat or reef site.

Depth — Select sites within the depth range of the species proposed for restoration.

Substrate type — Choose sites with consolidated hard substrate, which will provide a stable surface for attachment. Although there have been some novel approaches used to outplant corals on sandy, algal-covered substrates and coral rubble (e.g., Golomb et al., 2020), such methods should be used only with a full understanding of what has and has not worked in other places.

Water quality — Prioritize sites with good water clarity (low turbidity), flow, and low inputs of land-based runoff. Avoid areas with large temperature fluctuations. Some of these data are obtainable from open data sources.

Connectivity — Consider how the site is connected to others around it, as the goal of restoration is generally to create breeding populations that will populate surrounding reefs. If possible, collaborate with partners to develop regional larval dispersal and/or hydrodynamic models to aid in strategizing site selection based on connectivity.

Human impact — Avoid areas that are likely to be impacted by damaging human activities, such as coastal construction, diving, fishing, trap deployment, and anchoring.

Site Selection

Prior to any restoration project, detailed site surveys should be conducted at the restoration site and the reference site, and any additional site used as a control (see Restoration Site Selection Survey section below). Surveys should concentrate on site health such as: Is disease present? Is there an abundance of coral predators? Does the site support a healthy coral community? If not, why and will those reasons undermine coral restoration or are they something that can be mitigated? Is it far enough away from activities that may cause harm to restoration activities?

Community — A potential outplant site should host a healthy community of corals, fishes, invertebrates, and vertebrates (e.g., coral commensals and herbivores), and crustose coralline algae. There will likely not be an overabundance of any one of these organisms (otherwise, it would likely not be on the list for a potential restoration site), but the organisms present should be healthy.

Predators — Choose sites with low presence of coral predators, such as the bearded fireworm, corallivorous snails, three-spot damselfish, and crown-of-thorns (Miller, 2001; Ferse and Kunzmann, 2009; Omori, 2010; Gomez et al., 2014; Miller et al., 2014a; Cabaitan et al., 2015; Schopmeyer and Lirman, 2015; Goergen and Gilliam, 2018).

- Look for signs of predation on other coral colonies (Figure 5). If there are predators or extensive signs of them (dead tips from fireworms, obvious snail predation trails, and/or many damselfish lawns on nearby colonies), it may be best to try a new site or area.
- Pilot outplanting is a good method to determine predation pressure at a site because fireworms and snails are often hard to find during reef surveys.

Space competitors — Avoid outplanting to areas with excessive macroalgae (van Woesik et al., 2018) or competitive benthic invertebrates such as *Palythoa* (Lustic et al., 2020), encrusting sponges (*Cliona* spp., *Desmapsamma anchoratta, Holopsamma helwigi*), and octocorals (Figure 6). High abundance of Clionid sponges can be an indicator of poor water quality (Chaves-Fonnegra et al., 2007).

- Algae varies by season. Use local knowledge, long-term datasets of the area, or seasonal surveys to measure macroalgae cover and its potential influence (Figure 7).
- High octocoral cover will interfere with outplant design and placement of corals, but in some instances, octocorals may increase site colony retention, especially for species that propagate asexually, like *Acropora* spp.

Figure 5. Examples of coral predation. Snail predation on the left and fireworm predation on the right.

Figure 6. Examples of competitors for space, left and center are the sponge *Holopsamma helwigi*, and right is a zoanthid, *Palythoa caribaeorum*.

Figure 7. Examples of seasonal algae bloom. The same outplant site in August on the left and October on the right after cyanobacteria had settled at the site.

Sediment — Avoid low-lying sites near large sand patches, as sediment can be moved in by storms and smother corals.

Room to Expand — Outplant to locations that allow corals to spread across the site. Evaluate prevailing current direction and outplant up-current with an area directly down-current that is suitable for coral attachment. Try to avoid choosing a site on a reef edge where loose or fragmented colonies will end up off the reef edge in sand or rubble. Loose rubble, including unstable corals/structures may move during storms and dislodge or fragment outplants. In such locations, plant corals higher on a more stable/permanent structure.

Open Space — Choose areas where outplanted corals will not interfere with other living benthic organisms at the site, such as other corals or sponges. Allow appropriate spacing for growth of both organisms without interference. If outplanting on dead coral skeleton, select those that are 100% dead to avoid competition between live tissue of the existing coral and the outplants.

Substrate — Select areas that are conducive to the proposed attachment technique. For example, if using nails, check substrate density by attempting to install nails.

- Newly dead corals and those that appear to be bioeroding may not be good substrates on which to outplant corals because those bioeroding organisms or reason for the recent mortality may affect the outplants.
- Ensure that the substrate is strong enough to support the coral; bioeroding infauna may fill the reef, making it weak and unstable in storms. Nails will also not be secure in such a substrate.
- Rubble can be harmful to outplants if mobilized.

Programmatic goals and incentives — Decide whether to focus on sites that show signs of resilience (i.e., relatively healthy sites) or those that are more degraded but could potentially be made better (i.e., were impacted by an acute event).

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Planting Location

The third step in restoration site selection is the identification of the coral planting location. This step is an in situ step where areas within the site are chosen for planting and can be completed closer to the time when corals will be added to the site. Specific step details are outlined in Chapter 7: Restoration Design and Techniques, but the general ideas are mapping the planting locations and key site characteristics, installing tags, and evaluating space requirements for the planned species, colony spacing, and outplant colony size.

Donor Material Site Selection

During the process of selecting restoration sites, evaluate the same sites or nearby sites as potential donor material sites. When planning for collections, **first get an understanding of what corals are available in the area to determine how many donor colonies and what species should be represented in the nursery**. It is often assumed that each individual donor colony will represent a distinct genotype. However, this is not always the case. If there is a target number of unique genotypes, collections will likely be needed from more donor colonies than the target genotype number. Best practies suggest **that a nursery contain at least 20 to 25 distinct genotypes per species** (Baums et al., 2019).

Type of Collection Sites

Two common methods can be used to stock a nursery: collections from wild healthy colonies and/or collections of corals of opportunity. Wild colonies are those that are naturally found attached to the substrate. Corals of opportunity are defined as broken or detached corals that are unlikely to survive in their current situation. Often, they are found in sand or loose on the reef in a way that prevents reattachment without intervention. They may also be collected following a storm, earthquake, or grounding, prior to coastal construction activities, or by salvaging the remaining living portions of a colony. The identification of corals of opportunity should be clear to project personnel to avoid excessively disturbing branching corals that fragment and reattach readily (e.g., *Acropora* spp.).

Corals of opportunity could be collected for a number of reasons, but the main ones are: 1) to increase genetic diversity in the nursery and 2) to save colonies that may otherwise be lost (see Case Study #3.1). It also may be that local permits only allow for this type of collection, or limit the number of wild donor colony collections, so that collections of corals of opportunity become necessary.


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Yet, corals of opportunity may carry some costs and barriers toward the successful implementation of a restoration activity: 1) dispersed fragments that are partially buried in the sediment may be stressed enough to reveal lower survival rates when farmed in the nursery; 2) the genetic origin is unknown, and many of the fragments could be originating from just a few large genotypes (primarily true for branching species collected from the same location); 3) available corals could be limited in species diversity; and 4) corals may not be in environmental conditions similar to that of the restoration sites and nursery. Spatial dispersal of collection sites can assist with minimizing genetic replication in corals of opportunity.

There are several factors to consider when choosing donor/ collection sites; these apply to both collection types:

Existing wild populations — Knowledge of natural healthy populations of the target species will be critical in guiding collection efforts. The overall size and health of potential donor colonies are important criteria and affect both the health of subsequent fragments and the potential impacts to the donor.

Variability of sites — Collecting from many areas or habitats with different environmental conditions (depth, temperature regime, etc.) may further increase the likelihood of genetic variation as well as the ability of corals to adapt to different habitats and environmental conditions (Baums et al., 2019).

Variability of species — Target collections to cover the variability in a species, such as growth traits, coloration, and size. Evaluate the existence of special genotypes/species of interest and their value to the specific program (e.g., those that are thermally tolerant or resistant to other climate change impacts or disease).

Proximity to the nursery site — Minimizing transport time helps to reduce stress and the likelihood of damage to newly collected fragments. In addition, close proximity to the nursery site may be an important logistical and financial consideration for donor colony monitoring.

Geographic distance — Where possible, donor colony sites should be separated by at least 100 m to increase the likelihood that collections are being made from genetically distinct populations (Baums et al., 2006; Foster et al., 2007; Underwood et al., 2007). Precautions should be taken when collections are proposed from areas outside of the ecoregion or from genetic populations that are not currently represented in the area (resilient/adapted genotypes).

Permitting — Prior to site selection and collections, check with local permitting and marine zoning documentation for guidance and regulations.


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Restoration Site Selection Survey

Conducting a site assessment prior to starting restoration activities is necessary to provide a baseline from which the recovery trajectory can be monitored. Monitoring the recovery trajectory will determine the success or failure of the restoration plan. In addition, these surveys and subsequent monitoring should also be completed at reference and/or control sites (see Goergen et al. (2020) for guidance on selecting restoration sites, references, and controls). There is no one-size-fits-all survey; location (region, habitat type, and historical record) and program goals and objectives will direct what should be included in a reef community structure survey.

Criteria to evaluate for inclusion in a site-level community structure survey may be:

1) State of the fish community (species, abundance, size distribution)
2) State of the herbivore community (fishes, urchins, snails)
3) Abundance or cover of macroalgae
4) Stony coral species survey (e.g., abundance, cover, density, species present, size distribution, health)
5) Evaluation of the health of the species being used for restoration (ratio of loose:attached colonies, signs of predation or disease, etc.)
6) Prevalence of disease on both the species being used for restoration and other benthic organisms
7) Prevalence of predation and presence of predators
8) Sediment accumulation
9) Reef complexity (rugosity or reef height)
10) Water quality (temperature, light, photosynthetically active radiation (PAR), distance from known point source runoff or outfalls, marinas (antifouling and fugitive hydrocarbon), sunscreen, and other chemical sources)
11) Signs of fishing, diving, and tourism pressure (lobster traps, fishing gear, mooring buoys, boat traffic, etc.)

During restoration site evaluation, it is important to collect coordinates (latitude and longitude) at a few key points to aid in relocating the restoration area. These can be obtained with a handheld Global Positioning System (GPS) and snorkeler/diver or by marking the area with a surface buoy tethered securely and safely to the reef and using a boat's GPS by driving close to the buoy.

This list is not exhaustive but is provided to give guidance in developing a community structure survey specific to the program and location (such as the one developed below by TNC for the United States Virgin Islands (USVI) — Case Study #1.1). This survey is meant to help support site selection and can be used as a tool to evaluate restoration success and for defining criteria for an optimal restoration site in each location. For more details on utilizing the Evaluation Tool see Chapter 5: Nursery Monitoring: Evaluation Tool and Appendix 3: Evaluation Tool for Coral Restoration.

Evaluation Tool Criteria Alignment: The completion of pre-outplanting surveys aligns with the evaluation tool criteria: sites are surveyed for reef community structure and species abundance prior to outplanting. Practitioners would receive a score of 1 if the survey was completed prior to outplanting.

Diversity Considerations

Restoration projects should strive to achieve both species and genetic diversity (Shaver and Silliman, 2017) because reefs that maintain a diverse assemblage of both vertebrates and invertebrates generally show the most resilience and persistence (Bellwood and Hughes, 2001; Nyström and Folke, 2001). Species that show resilience, have successful reproductive capabilities, and respond well to stress and fragmentation should be priority species for restoration (Gleason et al., 2001; Baums et al., 2019; Morikawa and Palumbi, 2019); however, other species should not be excluded but may require additional considerations to be included as a primary species for restoration (van Oppen et al., 2017). Restoration designs for multiple species should strive to mimic the restoration reference site (see "Importance of Baseline Data and Reference Sites" in the CRC Coral Reef Restoration Monitoring Guide; Goergen et al., 2020). Historical data (if available) or recent information about similar sites can also be used as guidance for species diversity, abundance, and density. Ideally, the outplant design should mimic or complement the species assemblage that existed in the recent past on that reef.

Species

Unless the goal of the project is to focus specifically on rehabilitation of a single species, **a variety of species should be included in the restoration design**. Baums et al. (2019) recommends that ecosystem-based restoration efforts should focus on coral species that are: 1) foundation reef-builders, 2) experiencing severe declines in cover, and 3) consistently failing to sexually recruit. Programs should consider the coral species of interest early on in planning.

Fragments of Hope

Genetic

Coral colonies of the same species that are distinct genotypes or host different symbiont communities, will perform differentially in response to both known and unknown biotic and environmental factors. It is best practice to outplant a variety of genotypes (and/or phenotypes) to account for site and environmental variation (disease, bleaching, physical impacts and interactions, temperature anomalies, etc.) that may cause differential responses (Tunnicliffe, 1981; Harriott, 1998; Lirman et al., 2014a; Miller et al., 2014b; Drury et al., 2017). It is also important to note that genotypes that perform well in one setting (a nursery, for example) do not always perform well in another (e.g., a restoration site) and can have variable results depending on the year and conditions endured at the restoration site (Goergen and Gilliam, 2018). Therefore, caution should be used when selecting "best performing" nursery genotypes for outplanting as many unknown or competing factors can influence outplanting success.

Furthermore, in order to maintain genetic diversity at a restoration site and to encourage successful sexual reproduction, multiple genotypes should be placed at each site. For example, *A. cervicornis* needs a minimum of five genotypes to reach mean diversity values for an individual reef, although 10 is preferred (replicating the maximum expected genetic variability (Drury et al., 2016). Because this type of genetic analysis is lacking for most coral species, we suggest using this recommendation as a guiding principle until more species-specific research is completed.

CASE STUDY #1.1

Evaluating Site Suitability for Acroporid Corals

Location: USVI

The Nature Conservancy (TNC) created a site evaluation method for surveying and ranking the site using a modified Atlantic and Gulf Rapid Reef Assessment method (Table 1). Outplant sites are then selected based on which score the highest.

At each potential outplant site, the following methodology is used to collect data that can then be translated into a score for each site.

Methodology:

1) Lay out a 10 m transect line.
2) Record the number of three-spot, beaugregory, cocoa, dusky, and yellowtail damselfish and Diadema and all non-Acropora corals within 0.5 m to either side of the transect line.
3) Lay a quadrat along the transect line (at each meter mark) and record % live coral cover, fleshy macroalgae, calcareous algae, uncolonized substrate, and sand.
4) Using the same transect, record all acroporid corals within 5 m on each side of the transect line. Record the species type, size class, % live, % dead, any disease, % bleaching, number of corallivorous snails, number of fireworms, and presence or absence of damselfish predation scars.

Once all of the data have been collected, Table 6 can be used to translate the data into a resilience score for each site. After one year of monitoring outplants at five sites, TNC found that the sites with higher resilience scores also had higher survivorship of outplants, as shown in Figure 8.

There will likely be regional differences in the types of data that should be collected and in how to weigh the importance of certain parameters (i.e., in some regions, predators may have more impact on outplants than competitors while in other regions the opposite may be true), but this concept could easily be adapted to fit the needs of the practitioners.

Case study provided by: Lisa K. Terry, TNC, Caribbean Program, St. Croix, USVI; lisa.terry@tnc.org.

Table1. TNC evaluation criteria for selecting outplanting sites. This table can be modified based on local conditions.

Criteria	Measure	Score		
		3	2	1
Water Quality	Local area knowledge	no issues	moderate issues; typically, after rain events	known issues and point sources of discharge
Flow	Local area knowledge	constant flow	moderate flow	lagoonal; sometimes still
Acroporids	Measured abundance	>50 colonies	25-50 colonies	<25 colonies
Coral Assemblage	Measured % cover and diversity	>20% coverage and >50% coral genera	>20% coverage or >50% coral genera	<20% coverage and <50% coral genera
Diadema	Measured abundance	>50	25-50	<25
Damselfish	Measured % predation mark per colony	<5%	5-15%	>15%
Macroalgae	Measured % coverage	1-5%	6-10%	>10%
Corallivores	Measured abundance	0	1-15	>15
Health	Measured % bleaching and paling	0%	1-20%	>20%

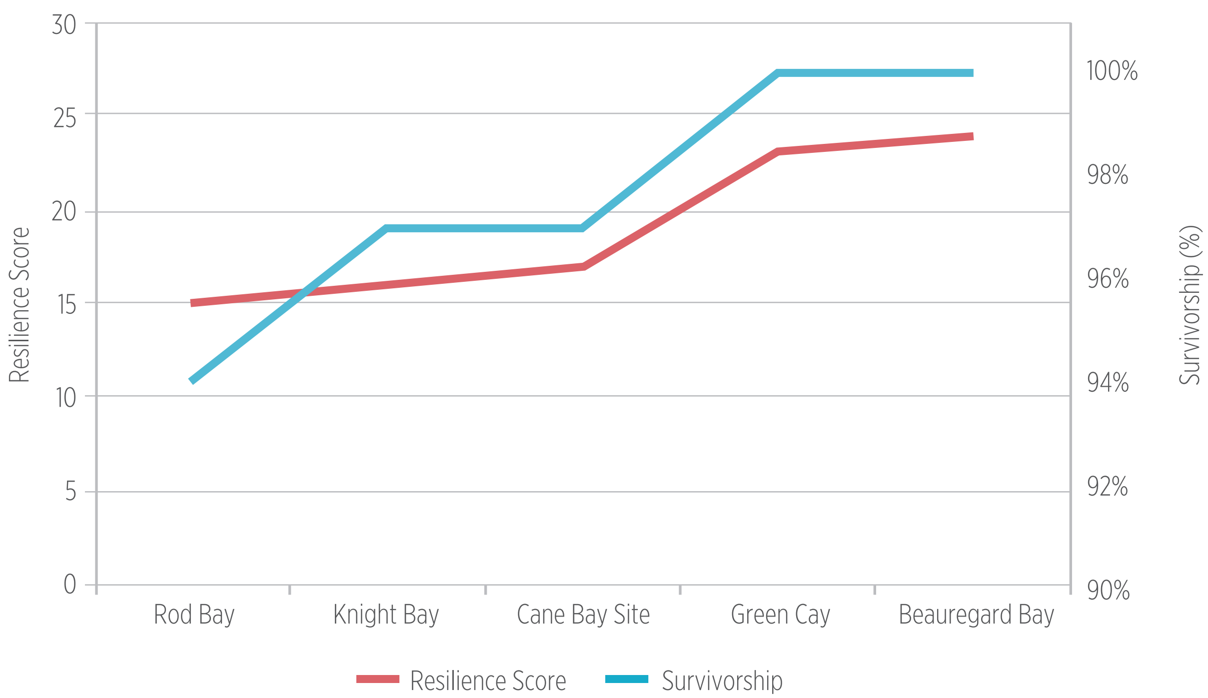
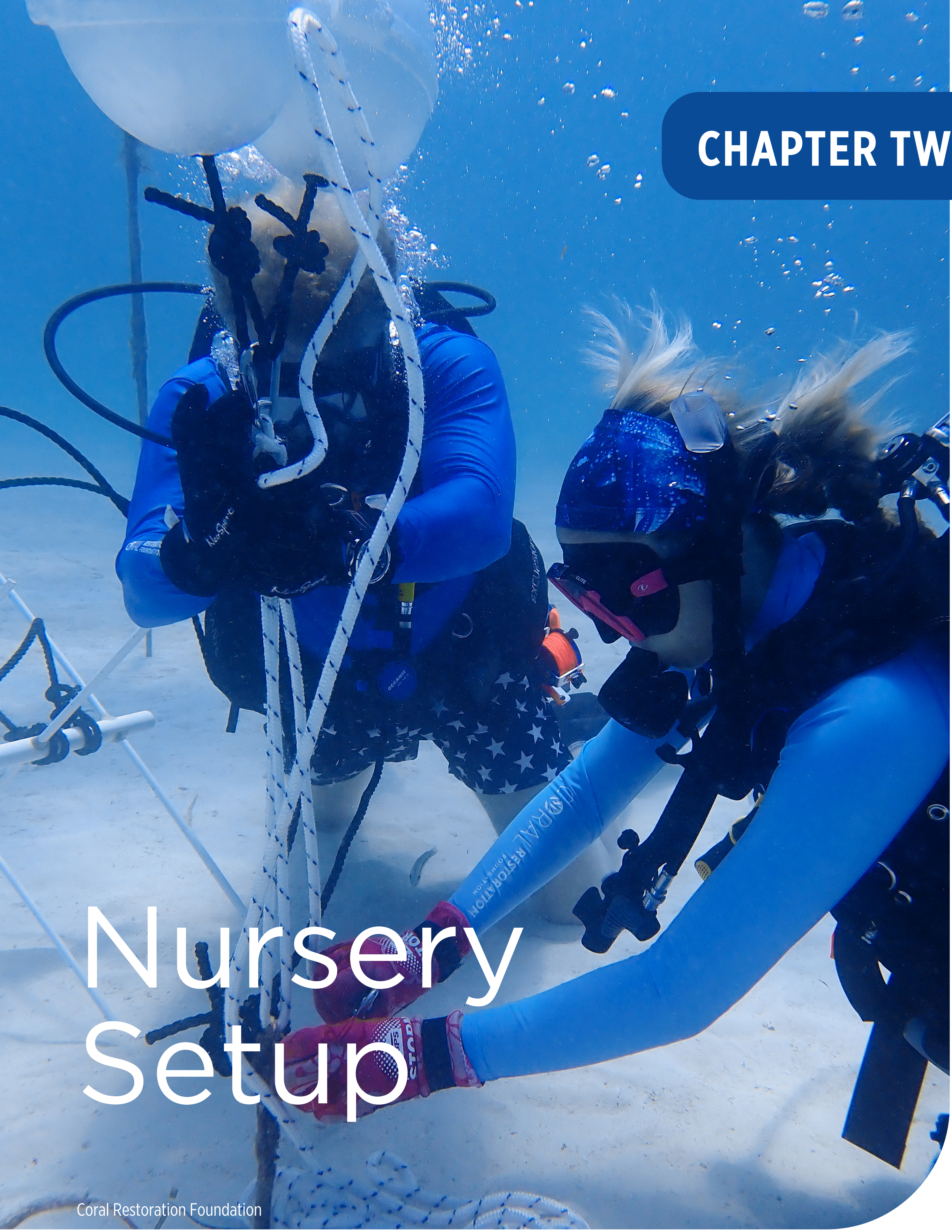


Figure 8. Comparison of resilience score and coral survival at outplant sites in St. Croix. Sites that scored high on the resilience scale also showed higher survivorship of outplants.



CHAPTER TWO

Nursery Setup

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A coral nursery is a location where corals are grown and propagated to sizes suitable for outplanting back into the wild. While the focus of this Guide is building a nursery for propagation for outplanting, it is important to note that nurseries can be used for other purposes, such as a source for gamete collection, an upstream source of larvae production (Amar and Rinkevich, 2007; Horoszowski-Fridman and Rinkevich, 2017), a connection or stepping stone between reef habitats (Frias-Torres and van de Geer, 2015; Frias-Torres et al., 2015), a hotspot for reef organisms (Taira et al., 2016; Wee et al., 2019), or a repository for coral genetics (Schopmeyer et al., 2012), to name a few.

Raising corals in an easily accessible nursery (or a few strategic nurseries) is crucial for creating a cost-effective restoration program. Coral nurseries have successfully been established across the globe and are utilizing various materials, site types, and methods. Within this chapter, we aim to synthesize the established knowledge and practices of these programs in terms of establishing a productive in situ nursery site, as well as selecting and building a structure(s) that is best suited to the needs of your program. Not all techniques could be included in this Guide, and many are well documented elsewhere; in those cases, we provide summaries and citations to other works for reference.

Nursery Site Selection

Selecting an appropriate nursery location will depend both on biological and logistical parameters (Edwards, 2010). This section will help guide practitioners through the different parameters to consider, for any nursery type, program goal, and logistical situation. This section should be used in combination with later sections to help make decisions about what nursery structures will work in different settings.

Even when all of the parameters below have been considered, there may be unexpected factors that make a site undesirable as a nursery location. It is imperative to install small-scale pilot nurseries to help identify and test potential nursery sites. In the best-case scenario, pilot nurseries will experience the full range of seasonal differences at a site, which could reveal different current patterns, fouling rates, and/or water temperature extremes throughout the year. If that is not practical, most potential unknown problems (too much water or sediment movement, excessive algae or predation, etc.) will likely be obvious within a few weeks of deployment. Install nursery structures first, and observe them for a few weeks. Then add a small number of

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genetically diverse corals and monitor closely before expanding to a full-scale nursery. These pilot deployments are extremely useful and provide the necessary information to maximize the likelihood of success.

The following section lists the most important considerations for nursery site selection. Considerations within each category are listed in no particular order, and there are trade-offs among them.

Physical considerations assist in choosing the best habitat or area within a region.

Management considerations present parameters that will be influenced by program-specific needs, goals, capacities, logistics, permitting regulations, and requirements.

Biological considerations guide nursery locations at a finer geographic scale based on biological parameters.

Physical Considerations

Protection from disturbances — Place a nursery in an area protected from or less exposed to a high frequency of high-energy events (increased wave height, surge, and current), coastal construction activities, and high reef-use areas. This strategy will also ease routine nursery structure maintenance. Yet, the environmental conditions should allow enough water movement above the nursery to allow for the clearance of sediment, a supply of plankton, and other conditions that will improve the corals' conditions.

Bottom type — Sand, rubble, and hard substrate areas may all be suitable for rearing corals, but the decision may then depend on the specific nursery structures used. For instance, in sandy environments, floating structures may be a better choice to reduce sedimentation stress on corals. It is preferable that the nursery corals are elevated off the substrate to avoid negative interactions. For whichever bottom type is chosen, nursery structures should be installed to have the least impact on existing benthic communities. Some locations may have specific regulations on what bottom type is acceptable, and the practitioner should seek this information.

Depth — Nurseries should be constructed in depths similar to where the propagated species are typically found and to the site to be restored. Successful nurseries have been established at depths of 2 to 15 m below the surface, with nursery anchoring systems as deep as 30 m (floating nurseries). If temperature stress and storm impacts are of concern, select a site at which structures may be raised and lowered when needed to help buffer impacts. As a rule of thumb, the depths of donor colonies, nurseries, and outplants should be similar.

Environmental Conditions — Important environmental conditions include light availability, albedo, water temperature, water movement, salinity, sedimentation, and turbidity. Each of these factors can affect colony growth, survival, and health to varying degrees (Bongiorni et al., 2003). Be cognizant of changes in seasonal weather patterns that may dramatically affect site conditions at different times of the year. It is generally suggested that nurseries be deployed in conditions where the reared coral species are typically, recently, and/or currently found.

Water Quality — Nurseries should ideally be away from land-based sources of pollution, sewage, freshwater, or sediment discharge. In addition, nursery maintenance choices could also be affected by water quality, especially if poor water conditions cause an increase in algal overgrowth. Water quality effects are complex; therefore, the pilot nursery approach is very helpful here.

Management Considerations

Site Accessibility — This is a key consideration to ensure that nursery personnel can easily get to the site to deliver materials, transport corals to and from nearby reefs, and conduct routine maintenance and monitoring. Site accessibility affects the logistical support needed for the restoration program — a close-to-shore, shallower site may not require a boat or SCUBA diving to maintain. Nurseries should also be sited close to future outplant sites to limit transport stress on corals. Regional nurseries should be sited in central areas for equal distribution of corals.

Size of the Nursery — Available time, budget, and program goals are important for determining the size of a nursery that will be manageable. In addition, plan for nursery expansion so that it will not impact nearby reef habitat (e.g., modular nursery structures).

Human Activities and Impacts — These can be both positive (such as using the nursery for education and citizen science, ease of access by volunteers) and negative (such as avoiding highly trafficked areas, heavily fished areas, common areas to anchor, SCUBA divers) and are important to consider when choosing a nursery location.

Number of Nurseries — A logistical trade-off exists between the number of nursery sites that can be established and the attention and maintenance that can be afforded to each site. Installing and maintaining multiple nurseries will minimize the likelihood that a given disturbance, such as a disease outbreak or storm, will destroy the entire nursery stock.

Permitting — Work in collaboration with local management agencies to obtain permits and select sites that are appropriate for rearing corals that avoid conflicts with other uses and activities.

Programmatic Support/Staff — Experience and diving certifications of those involved in nursery management are important to consider when choosing the depth and location of a nursery. If nurseries will be managed predominantly by snorkelers, shallower and more protected areas are preferred.

Nursery Purpose — Nurseries can be established for the long term (typically in a central or easily accessible location) or as temporary popup nurseries for specific projects, research, or due to logistical constraints. It is important to identify how each nursery will be used prior to selecting the site and techniques used.

Biological Considerations

Existing Wild Populations — Habitats or reef areas that harbor healthy coral populations likely provide adequate environmental conditions for the growth of corals in nearby nurseries. Therefore, establishing nurseries in areas near wild populations is preferred (sandy adjacent areas).

Competitors and Predators — High abundances of competitors and predators, such as predatory snails, worms, starfish, macroalgae, hydroids, sponges, and/or fire coral, that cannot be maintained or managed should be avoided (see Chapter 4: Nursery Maintenance).

Proximity to Reef — Fish have a distance that they will habitually travel away from reef structure to visit and feed from nursery structures. A nursery may be placed close enough to a healthy reef to allow fish to visit the nursery, but far enough away to discourage predator transfer from the reef.

Reef/Site Health — Reef areas with high frequency of coral disease should be avoided.

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Nursery Structures

A common prerequisite for coral propagation and population enhancement is the establishment of coral nurseries that can successfully raise and supply large numbers of corals that can eventually be outplanted at a restoration site, serve as a genetic repository, provide stock material, and/or be a source of larval supply to neighboring coral reef communities or for larval propagation. The chosen design of a nursery structure will depend on the nursery location characteristics, programmatic goals, availability of materials, capacity of the program, coral species to be propagated, proposed number of corals to be raised within the nursery, and permitting regulations. Within this chapter, we provide the information necessary to guide a practitioner to make an informed decision as to what structure design may be best suited for their program. There are a variety of structure designs that have been developed and deployed successfully around the world, so we provide in this Guide the basics of the most commonly used structures. There is no one-size-fits-all design. At the end of this Guide, construction details, material lists, and lessons learned from a variety of structures are provided to act as a basis for the chosen structure (Appendix 1).

Floating versus Fixed Structure

In situ nursery structures can be classified into two types: Floating and Fixed. A floating nursery includes some sort of flotation/buoy to keep the structure raised to the chosen depth in the water column with no rigid support such as legs. If buoyancy were to be lost, the structure would fall to the seafloor. Floating nurseries are not free-floating but are anchored to the seafloor. Floating structures can be anchored in depths much greater than that in which the corals are being raised. Floating nursery structures can be grouped into three basic designs: Coral Tree™, floating table, and floating rope. Fixed structures require no flotation and are anchored directly to the seafloor. Nurseries in which fixed structures are used are generally limited in depth as they should be in depths similar to that of the future restoration (outplanting) site. Fixed nursery structures can be grouped into three basic designs: concrete substrates, tables, and frames/domes. Floating structures, depending on the chosen anchor style, may have a smaller seafloor footprint than most fixed structures. The size of many of the structures described below is customizable to the program's needs.

Table 2. Floating nursery structure benefits and considerations.

Benefits	Considerations
Can exhibit increased coral growth rates, but this depends on nursery location, species, and genotype (Shafir et al., 2006a; Shaish et al., 2008; Ross, 2014; Goergen et al., 2017; Kuffner et al., 2017; O'Donnell et al., 2017).	Raising coral on floating structures may have an effect on the skeletal density and calcification rates. While corals grown on trees showed significantly faster linear extension, corals grown on blocks showed significantly greater skeletal density. The calcification rate was not significantly different between the two methods (Kuffner et al., 2017).
Movement of floating nurseries enhances supply of oxygen and plankton that positively affect coral growth and survivorship (Bongiorni et al., 2003; Shafir and Rinkevich, 2010; Shafir et al., 2010).	Floating structures require continued maintenance and observations to minimize fouling, sinking, and structure loss; design systems, program, time, and budgets accordingly. Yet, some floating nurseries are easily supported with reduced maintenance (Levy et al., 2010; Frias-Torres et al., 2018).
Reduced predation from corallivores (Bowden-Kerby, 2014; Ross, 2014).	The height that a structure sits above the substrate will depend on the conditions at the site. They require adequate distance from reef structure that they will not contact said reef even in the largest storms, even when one or more anchors or buoy fails.
Reduced sedimentation impacts (Rinkevich, 2014).	In high current areas, practitioners may want the structures to sit higher so they are less likely to interact with the substrate.
Smaller structural footprint (small anchor point), so more corals can fit in any given space.	Floating nurseries require mid-water space and may not be appropriate in shallow locations, including those with high tidal changes.
Depth adjustable for rearing corals at restoration site conditions or to reduce storm and temperature stress (Shafir and Rinkevich, 2008; Nedimyer et al., 2011; Rinkevich, 2019b).	

Table 3. Fixed nursery structure benefits and considerations.

Benefits	Considerations
Fewer fail points. Can be left unmaintained for longer periods without the worry of the structure failing or sinking. Reduced vertical height, which allows for use in shallow water habitats. Not restricted by weight, thus may be of heavier, more durable materials and may carry heavier, larger corals. Increased ability to withstand higher wave energy. Fixed structures may be the best choice for shallow water nursery environments and/or areas where floating structures could be a navigational hazard. Corals are typically grown on a mounting substrate that can be outplanted directly.	Fixed structures need to be secured to the bottom, most often using rebar stakes, but could include weights, guy-lines, Duckbill or helix anchors, and heavy-duty cable ties. In places with high wave energy, multiple anchor points for each structure may be necessary. Anchoring stability should be tested over a pilot period before expansion. Fragment orientation of branching corals on pucks (horizontal vs. vertical) can affect coral growth, survival, and branching, and should be evaluated during the pilot program (Larson, 2010). Fixed structures may have a larger surface area which needs to be maintained so as to not interact with the coral.

Corals can be reared either fixed to or suspended from either structure type, and the method used depends on which design is chosen (see below for more details). How the corals will be raised may influence which nursery structure is chosen; for example, nursery colonies being directly outplanted may benefit from being raised on a substrate that can be outplanted such as a plug, rope, or disk (Edwards, 2010). There are many benefits and considerations to both types of nursery structures. Table 2 and Table 3 outline many of the key points of each structure type.


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Floating Structures

Floating structures require flotation to keep them from falling to the seafloor. These structures are grouped into three design types: Coral Tree™, floating table, and floating rope. Here, we group them based on their basic design structure. Floating tables have a horizontal (parallel to the substrate) surface on which corals are placed or attached. Floating ropes may be horizontal or vertical in the water column and consist mainly of ropes or lines on which corals are hung or attached. Most of these structures can be modified to the size that suits a program's needs.

Coral Tree

Among floating structures, the Coral Tree™ nursery (Figure 9) has become widely adopted as the preferred nursery method in the Caribbean where conditions are suitable. The Coral Tree™, first pioneered by the Coral Restoration Foundation (Nedimyer et al., 2011), is simple, low-cost, easily built and installed, and has the capacity to grow large numbers of corals within a single structure. The Coral Tree™ provides a rigid framework that allows coral to develop in the water column. Corals are attached to "tree branches" and are either hung from holes in each branch or installed on pucks secured directly to branches or on trays secured to the branches. The standard design of a tree nursery (Figure 9) can hold 60 to 120 corals and allows for 360° of water circulation and movement of the tree.

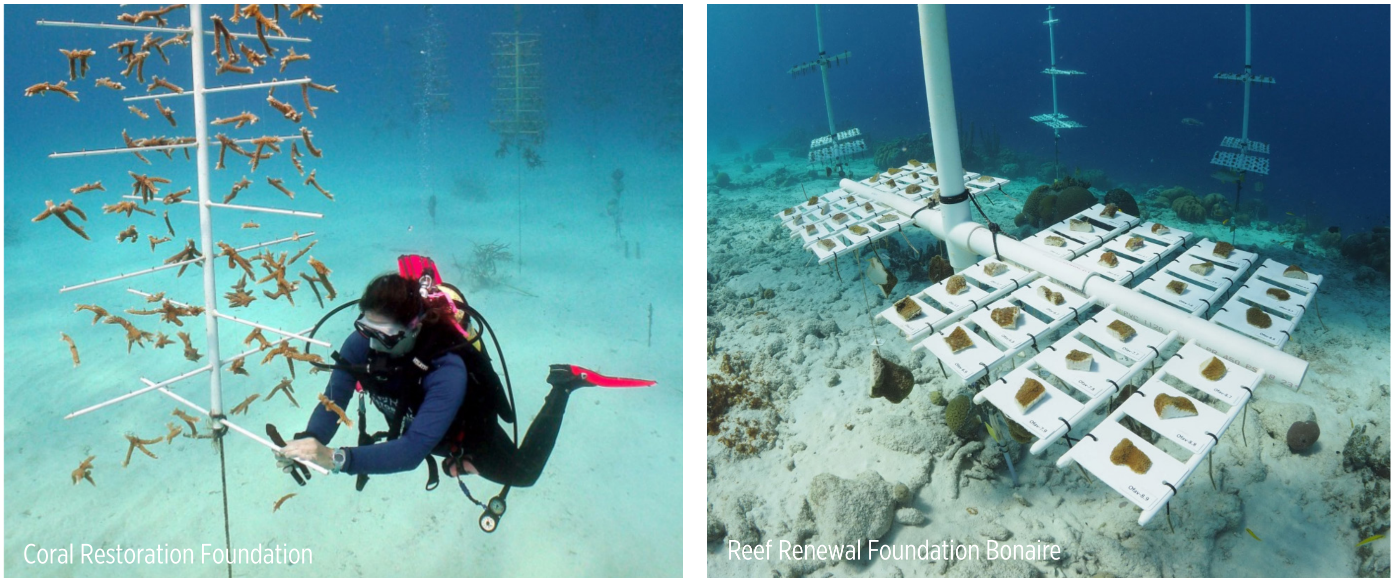


Figure 9. Examples of Coral Tree™ nursery structures.

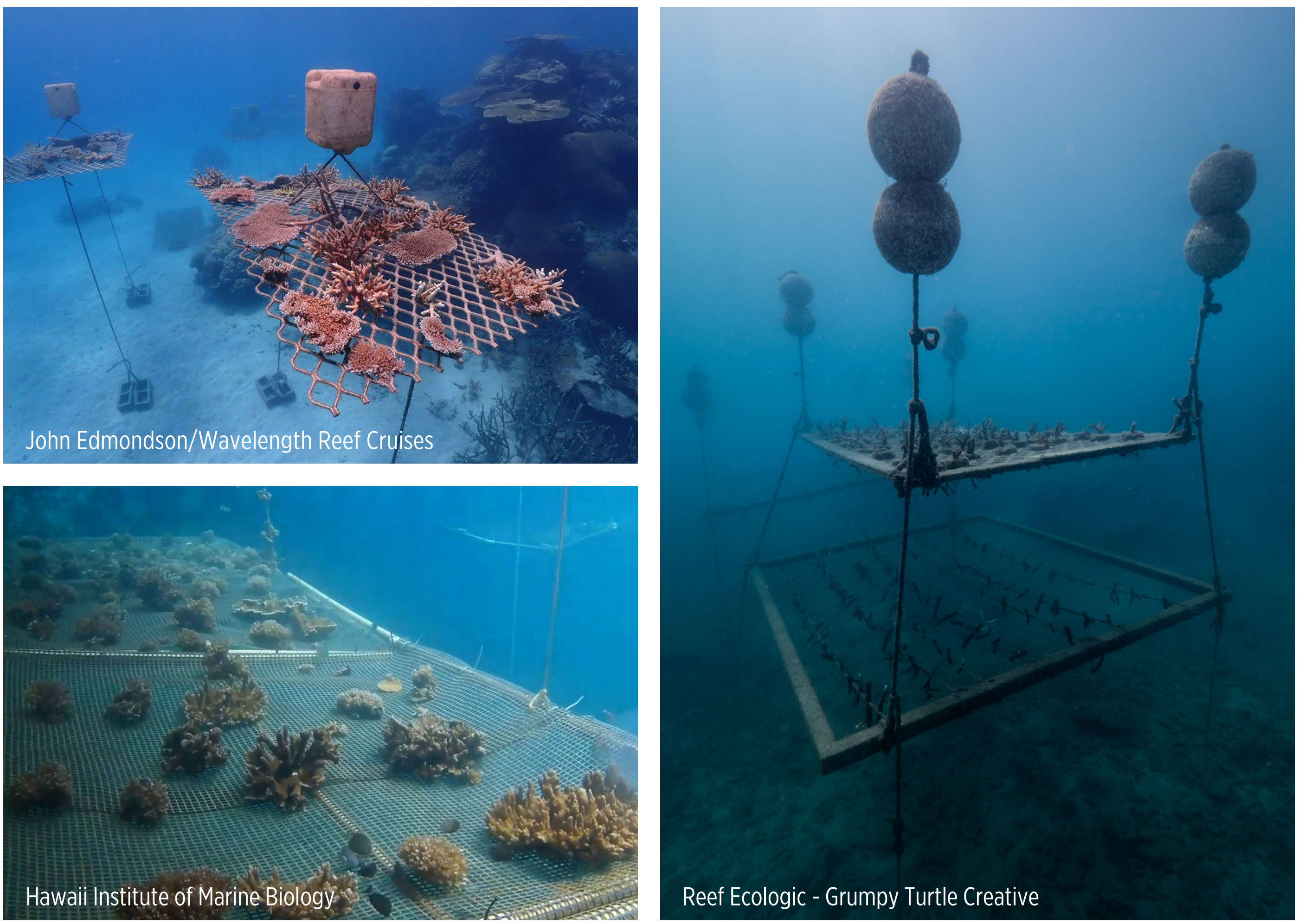


Figure 10. Examples of Floating Table nursery structures.

Figure 11. Examples of Floating Rope nursery structures.

For detailed examples, see Appendix 1.

Some examples of coral trees from literature include: Johnson et al. (2011); Nedimyer et al. (2011); Young et al. (2012); Lohr et al. (2015); Sen and Yousif (2016); Drury et al. (2017); Kuffner et al. (2017); Lohr and Patterson (2017); O'Donnell et al. (2017); Boström-Einarsson et al. (2018); Galárraga Galarza (2018); Hernández-Delgado et al. (2018); O'Donnell et al. (2018); Knoester et al. (2019); VanWynen (2020).

Floating Table

Floating tables are structures that have a horizontal (parallel to the substrate) surface on which corals are placed or attached (Figure 10). These structures have a rigid component or frame creating the "table"; typically made of polyvinyl chloride (PVC) or aluminum pipe. This rigid structure may be covered in a mesh on which corals or trays of corals are attached, or to reduce cleaning time, the corals or coral trays are attached directly to the frame. The size of the table is fully customizable to a program's needs. The larger the table, the more difficult it will be to monitor, clean, and maintain the corals in the center. Some programs have therefore chosen to open up the center of the table so divers can be on all sides (Shafir and Rinkevich, 2008). Buoyancy for tables can be added above or below, but for larger structures, flotation is often from above. The number of anchors required, and the strength of those anchors will increase with the size of the table.

This design is also known as: Open water floating nursery, lagoonal floating nursery, net nursery, bed nursery, or mid-water floating nursery. For detailed examples, see Appendix 1.

Some examples of floating tables from literature include: Shafir et al. (2006b); Shafir et al. (2006a); Putchim et al. (2008); Shafir and Rinkevich (2008); Shaish et al. (2008); Shafir et al. (2009); Edwards (2010); Mbije et al. (2010); Shafir and Rinkevich (2010); Frias-Torres et al. (2018); Hernández-Delgado et al. (2018); Nithyanandan et al. (2018); Suggett et al. (2018); Rinkevich (2019b); Golomb et al. (2020); Howlett et al. (2021).

Floating Rope

Floating ropes may be horizontal or vertical in the water column and consist mainly of rope or lines on which corals are hung or attached. These designs do not always include a rigid structure or frame. All of these designs use rope, line, or monofilament to create the structure upon which corals are mounted. The structure can be horizontal in the water column stretching ropes between horizontal floating pipes (Figure 11), or the structure can be vertical in the water column stretching lines between vertical guy-lines, pipes, or frames — see below for considerations when using the vertical arrangement. Rope nurseries are easy to assemble, are low-cost, and can be made to the size necessary for each program's needs. However, when building large rope nurseries, consider the possible risk of wildlife entanglement and modify/build each structure to address these concerns, especially for vertical structures. Long vertical line components can be sheathed in PVC pipe; this maintains flexibility and function but adds rigidity to reduce wildlife entanglement risk.

This design is also known as: FUCA (floating underwater coral apparatus), mid-water rope nursery, line nursery, [floating] rope [nursery], buoyant drop line nursery, mid-water horizontal line nursery, or ladder. For detailed examples, see Appendix 1.

Some examples of floating rope nurseries from literature include: Edwards (2010); Levy et al. (2010); Johnson et al. (2011); Griffin et al. (2012); Ross (2012); Young et al. (2012); Ostroff (2013); Lirman et al. (2014a); Lohr et al. (2015); Ross (2016); Goergen et al. (2017); Pratt (2017); Schopmeyer et al. (2017); Frias-Torres et al. (2018); Hernández-Delgado et al. (2018); Calle-Triviño et al. (2020).

There can be drawbacks to rope/line nurseries, and some programs and regions have moved away from using them because of the following reasons:

Entanglement Risk — Line nurseries can introduce a risk of entanglement for marine megafauna such as sea turtles. If ensnared, a flexible nursery system may entangle and drown the animal without breaking. The risk is heightened once line nurseries start to bow or sag (Figure 12), because there is nothing that prevents an animal from wrapping themselves in the line as they try to free themselves. Structures with more rigidity, or those that are horizontal in design (rope nursery) eliminate that problem by keeping lines taut even as the corals grow and become heavier.

Bowing and Sagging — These systems are not recommended for larger or heavier corals as the weight of the corals and overgrowth draw the support lines inward and cause sag in the horizontal lines. This brings the corals closer together, increasing contact stress, and the corals may eventually reach the substrate causing abrasion, breakage, smothering, predation, and disease. This may be mitigated by adding more or larger support buoys, or by the FUCA adaptation (Griffin et al., 2012).

Storm Self-Entanglement — Although line nurseries have proved reasonably durable during storms, they are susceptible to wrapping and entanglement of the corals. This may be mitigated by making sure the drop-line length does not exceed two-thirds of the length between drop lines; i.e., 15 cm spacing between corals should not employ a drop line of more than 10 cm.

Fixed Structures

Fixed nursery structures are characterized by the use of a rigid structure attached to the seafloor to grow and propagate corals. Fixed structures require no buoyancy and have been built using a variety of designs and materials. The most common materials include concrete, PVC, and rebar to form the main structural component. These structures are grouped into three designs: concrete structure, table, and frame/dome.

Figure 12. Example of a sagging line nursery. While line nurseries were once used extensively in Florida, most practitioners have now moved toward coral trees to eliminate the risk of entanglement caused by sagging lines.

Concrete Structure

These structures involve securing corals to cinder blocks, concrete blocks, or concrete slabs anchored or resting on the seafloor (Figure 13). These structures were some of the first coral nursery platforms used in Florida and the Greater Caribbean and are still valuable nursery platforms for many practitioners. Block nurseries are modular to an extent, but will become cumbersome due to weight if they get too large. The tops of blocks can accumulate sediment, so many practitioners create a mounting substrate (i.e., pucks, disks, pedestals) for the nursery corals, which serve to both raise the coral off of the block and, with an appropriate label, uniquely identify each nursery coral. Many artificial reefs are made out of concrete, and if the shape (flat platform for raising and monitoring corals) and location are appropriate, they could be repurposed as a nursery structure. Note that the buoyant weight of a concrete block is 40% less than its weight on land, so this should be considered when deciding how many blocks are needed or whether a secondary anchoring system is required.

This design is also known as: cinder blocks, concrete blocks, modules, block nursery, or concrete tiles. For detailed examples, see Appendix 1.

Some examples of concrete structure nurseries from literature include: Epstein et al. (2001); Monty et al. (2006); Quinn and Kojis (2006); Yeemin et al. (2006); Herlan and Lirman (2008); Larson (2010); Johnson et al. (2011); Schopmeyer et al. (2012); Lirman et al. (2014a); Johnson (2015); O'Neil (2015); Goergen et al. (2017); Kuffner et al. (2017); O'Donnell et al. (2017); Schopmeyer et al. (2017).

Figure 13. Examples of Concrete Structure nursery structures.

Figure 14. Examples of Table nursery structures.

Table

Tables can come in many different shapes and sizes, and the most appropriate design depends on the environment in which they will be used and the availability of materials. Tables can be used in various locations, substrate types, and energy environments. The basic layout of this type of structure is the creation of a rigid structure or frame that is either attached directly to the substrate or elevated using legs (Figure 14). Corals can be attached directly to the frame using disks/tiles/pucks or suspended with rope, line, or monofilament. Within Appendix 1, there are a number of different styles described to provide practitioners with starting points and tools to make decisions on which structure would be best suited for their program.

This design is also known as: frames, benthic, coral tables, crates, fixed nursery, fixed rope, horizontal line nursery, table units, coral farming table, modular tray nursery, racks, or rope table. For detailed examples, see Appendix 1.

Some examples of table nurseries from literature include: Epstein et al. (2001); Soong and Chen (2003); Quinn and Kojis (2006); Shaish et al. (2008); Edwards (2010); Bongiorni et al. (2011); Johnson et al. (2011); Bowden-Kerby (2014); Hernández-Delgado et al. (2014); dela Cruz et al. (2015); Nava-Martínez et al. (2015); Carne (2016); Carne et al. (2016); Omori et al. (2016); Afiq-Rosli et al. (2017); Todinanahary et al. (2017); Toh et al. (2017); Hernández-Delgado et al. (2018); Nithyanandan et al. (2018); Broquet (2019); Ishida-Castañeda et al. (2019); Konh and Parry (2019); Calle-Triviño et al. (2020).

Figure 15. Examples of Frame and Dome nursery structures.

Frame and Dome

Frame and dome structures are made of metal rods or heavy-duty wire mesh in various shapes and sizes (Bowden-Kerby, 2014; Williams et al., 2018). Frames and domes differ from tables in that they do not generally have a flat-top surface to attach corals but are angled platforms such as an A-frame shape (Figure 15). They are typically deployed in sand or rubble areas and have been used to raise *Acropora* spp. While the materials, shape, and size of these structures can vary, the basic design consists of a rigid or semi-rigid mounding or branched structure that keeps fragments away from the substrate. Frames and domes are less modular than other structures and are more commonly built in smaller sizes. These structures have also been used as a substrate for outplanting (see Attachment Techniques in Chapter 7: Restoration Design and Techniques).

This design is also known as: A-frame, spiders, stars, rebar frame, welded frame, dome, metal frame, or wire mesh A-frame.

For detailed examples see Appendix 1. Some examples of frame/dome nurseries from literature include: Bowden-Kerby (2001); Quinn and Kojis (2006); Johnson et al. (2011); Young et al. (2012); Bowden-Kerby (2014); Hernández-Delgado et al. (2014); Lirman et al. (2014a); Carne (2016); Carne et al. (2016); Hernández-Delgado et al. (2018); Williams et al. (2018); Calle-Triviño et al. (2020).

Fragment Bases

Nursery fragments need to be securely fastened to the nursery structure to provide them the stability to grow and to be tracked by the practitioner. Just like the nursery structures themselves, nursery colonies can either be fixed to a structure or suspended

Table 4. Benefits and drawbacks to attaching a fragment to a structural base.

Benefits	Challenges
The cut edge of the fragment can be sealed to prevent competitors from interacting with the unhealed tissue.	The coral grows only in one direction, away from the base.
The base can be used as an outplanting substrate, a practice commonly used with micro-fragmented nursery colonies.	Bases add weight to the structure, which must be considered for floating structures.
The base can have a unique colony identification color or inscribed number good for research and fate tracking.	Bases add material to clean.
Bases can be attached to trays making installation in the nursery more efficient as only the tray needs to be attached and not every nursery fragment.	Bases could serve as a failure point, (i.e., the attachment of the base to the structure may fail), which may result in the loss of a colony.
Bases can be removed and replaced without compromising the structure.	Bases with stems (e.g., plug) could be more difficult to outplant and may require more adhesive to attach.
A base moves the colony away from the structure, which may reduce competition or predation.	
May reduce handling of tissue as coral is moved from one location to another.	

in the water column from the structure. For either the fixed or suspended method of attaching fragments, a base may be used. The base is attached to or hung from the nursery structure, either before or after the coral is attached (Table 4).

A base can be thought of as a temporary component of the nursery structure, as it can be removed without compromising the nursery structure. Some bases have unique identifiers written on them to aid in keeping track of colonies, and they can also be outplanted with the colony or reused if a colony is removed or dies. Some nursery structures or designs will not require the use of a base, and fragments can be attached directly to the structure. There are a number of different forms of bases, all of which can be adapted to fit almost any need. Some of the more commonly used bases are described here:

Reef Renewal Foundation Bonaire

Disks/Cookies/Pucks/Tiles — generally made of concrete, aragonite, or ceramic (Figure 16). These can be made at varying sizes and thicknesses, depending on the intended use, or store-bought (e.g., bathroom tiles or frag disks). Most often, colonies are fixed to the base, then installed on nursery structures such as blocks, floating platforms, or tables. Small disks/tiles are often used as larval settlement substrates. Following larval settlement, small holes can be drilled in the substrate; then they can be fixed or suspended on nursery structures (e.g., Figure 16-D). Bases can also be attached to trays prior to attachment to nursery structures, such that trays can be pre-assembled and quickly attached to nursery structures. Additional materials, such as monofilament, cable ties, or wire, can be embedded into these bases during production for attachment to the nursery structure.

Plugs — a base that has a stalk and/or can be "plugged" into mesh, trays, coupling, or something similar. They are made of various materials, but aragonite, concrete, and plastic may be the most common materials. Plugs can be store-bought, such as frag plugs, PVC connectors, or wall anchors (Figure 17), or can be handmade of concrete with an embedded stalk such as a plastic bolt (Figure 17). Plugs can be used on any floating or fixed structures.

Cards — plastic cards typically the size of a credit card can be used as a base (Figure 18). This is a lightweight option for suspending corals or attaching to trays. Cards can also be custom labeled to include information like practitioner logo, genotype identification (ID), etc.

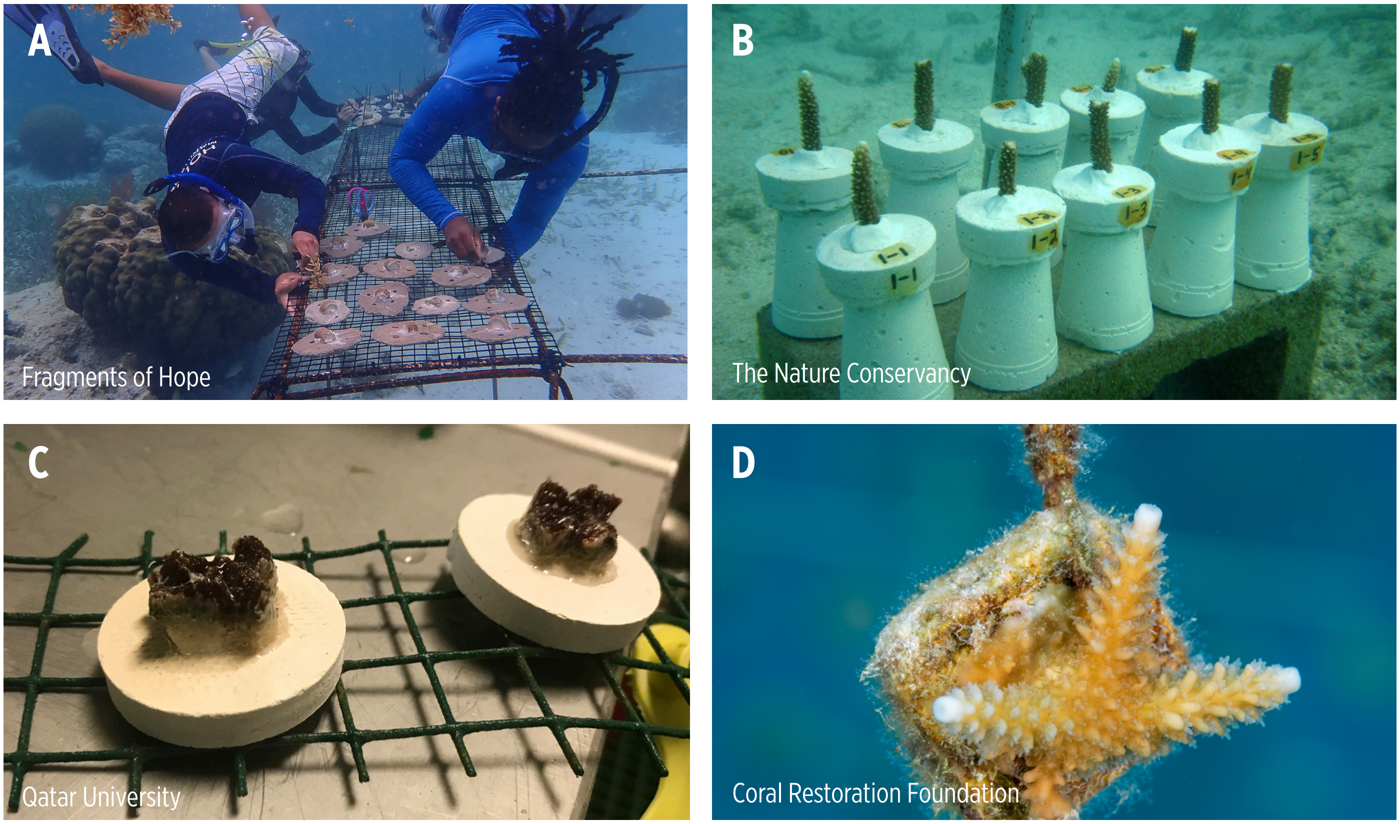


Figure 16. Examples of cookies (A), pucks (B), disks (C), and tiles (D).

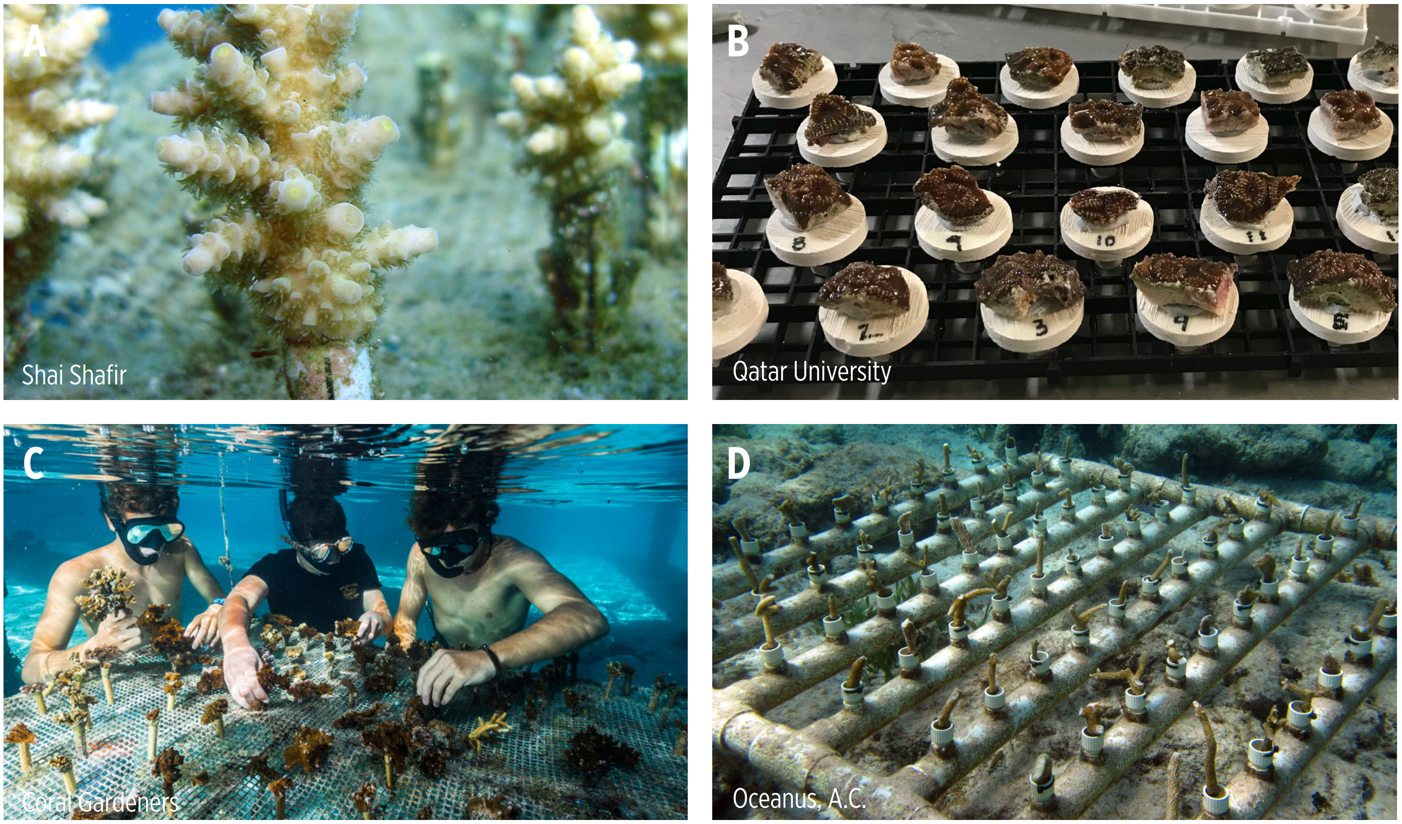


Figure 17. Examples of plugs used as bases for nursery colonies. A plastic wall anchor (A), aragonite frag plugs (B), concrete plugs (C) and PVC connector (D).

Figure 18. Example of plastic cards used as bases for nursery colonies.

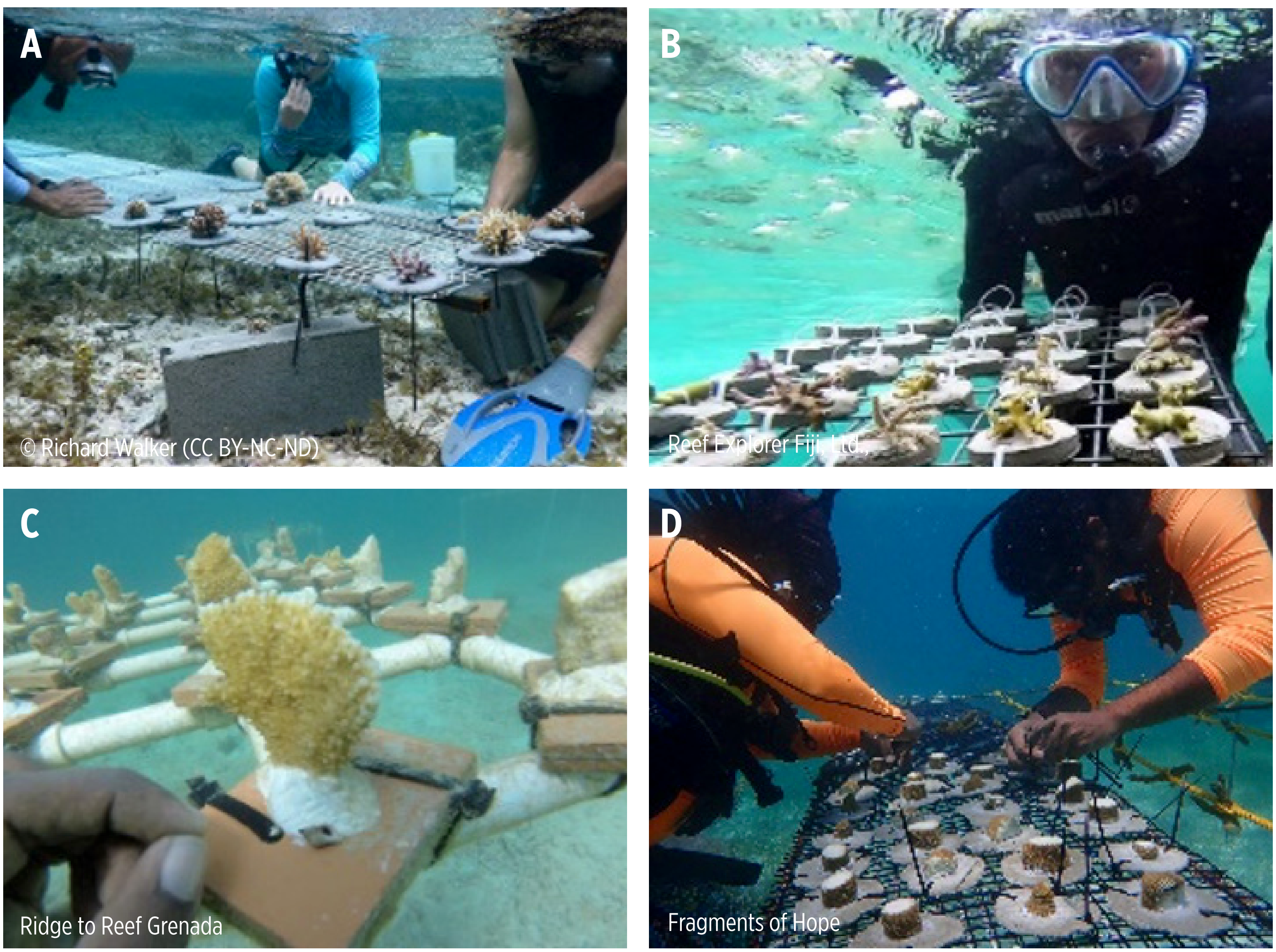


Figure 19. Examples of attaching cookies (A & D), pucks (B), tiles (C) directly to a nursery structure.

Securing Bases to Structures

Nearly every base type can be used on every nursery structure. Below we provide guidance on methods for attaching each base type to various structures.

Disks/Cookies/Pucks/Tiles can be used on both fixed and floating structures and either secured directly to the structure or suspended. Removable trays can be used to accommodate many of these bases and can help increase efficiency because they are easily removed and attached as needed.

Methods:

1) Attaching a base directly to a structure or tray — epoxy, cement, cable tie, wire, or monofilament (Figure 19)
2) Attaching trays to structures — cable tie, wire, or monofilament (Figure 20)
3) Suspended from structures — wire or monofilament (Figure 21)

Considerations:

- When suspending bases, avoid abrasion on the wire and monofilament by securing the monofilament or wire tightly to the base.
- On floating structures, the added weight of the bases will affect the buoyancy of the structure, so be prepared to add extra flotation.
- When using cement or epoxy to attach bases, strong water movement may dislodge the base prior to the curing of the adhesive. This may become worse if the fragment attached to the base causes drag or is top-heavy. Therefore, in some instances, bases should be attached to the nursery structure prior to attachment of corals to ensure secure attachment of the base.


Andrew Taylor/Reef Explorer Fiji.


Blue Corner Conservation.

Figure 20. Examples of attaching disks/cookies/pucks/tiles on trays to a nursery structure.

Reef Renewal Foundation Bonaire

Figure 21. Example of suspending disks/cookies/pucks/tiles on nursery structures.

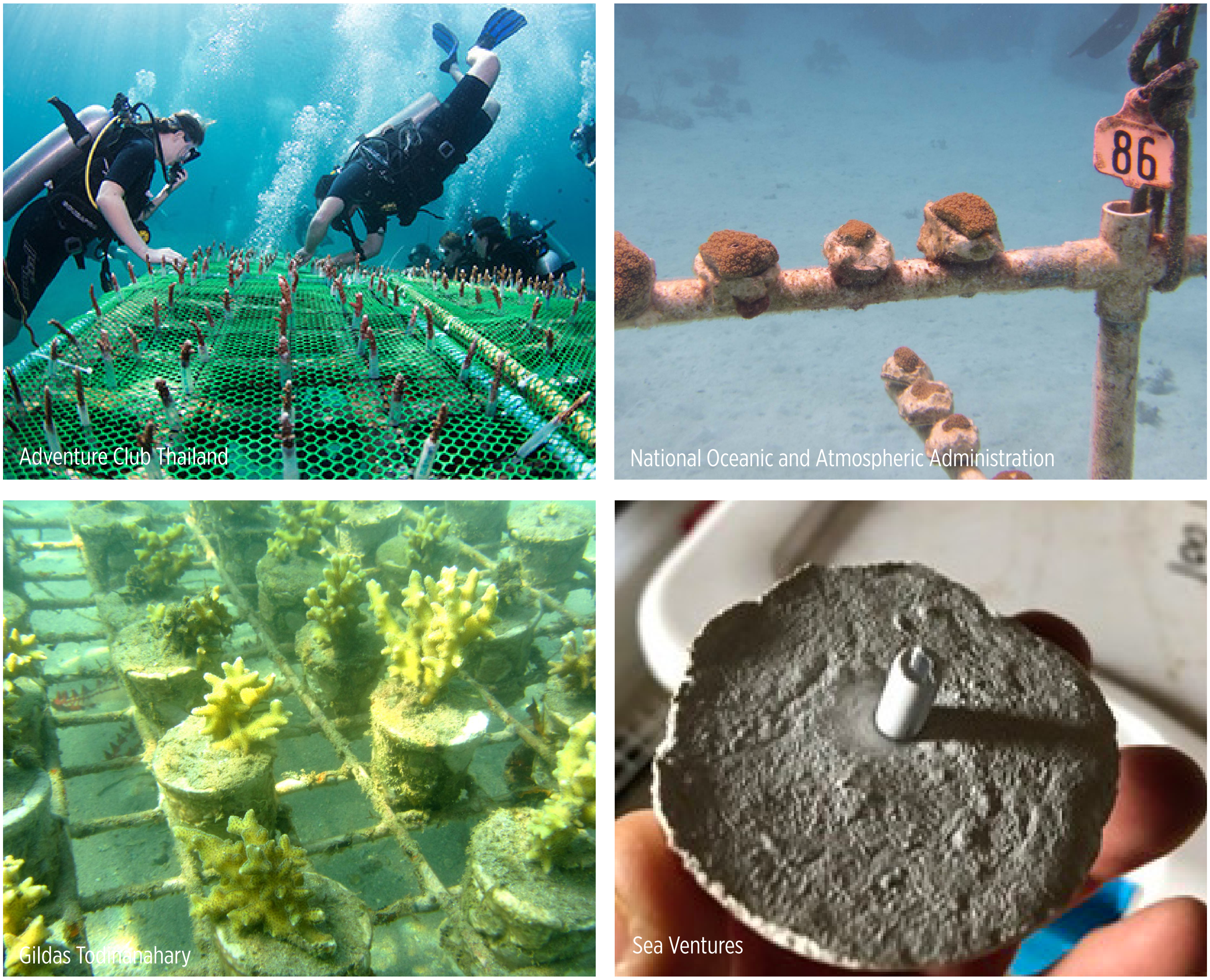


Figure 22. Examples of attaching plugs directly to a nursery structure.

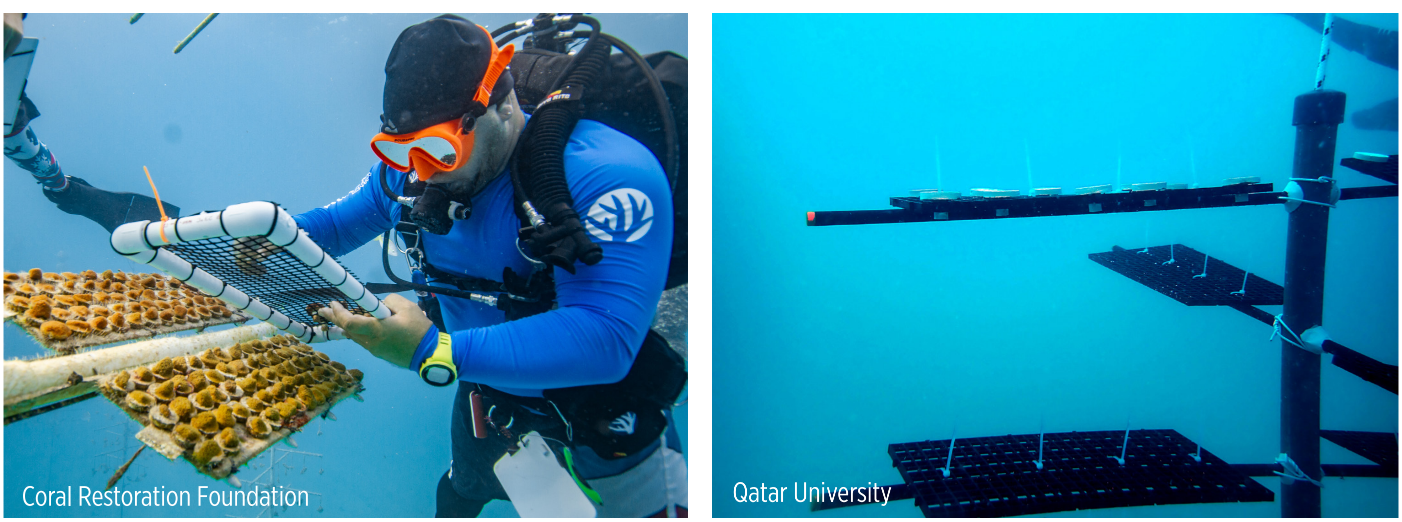


Figure 23. Examples of attaching trays to a nursery structure.

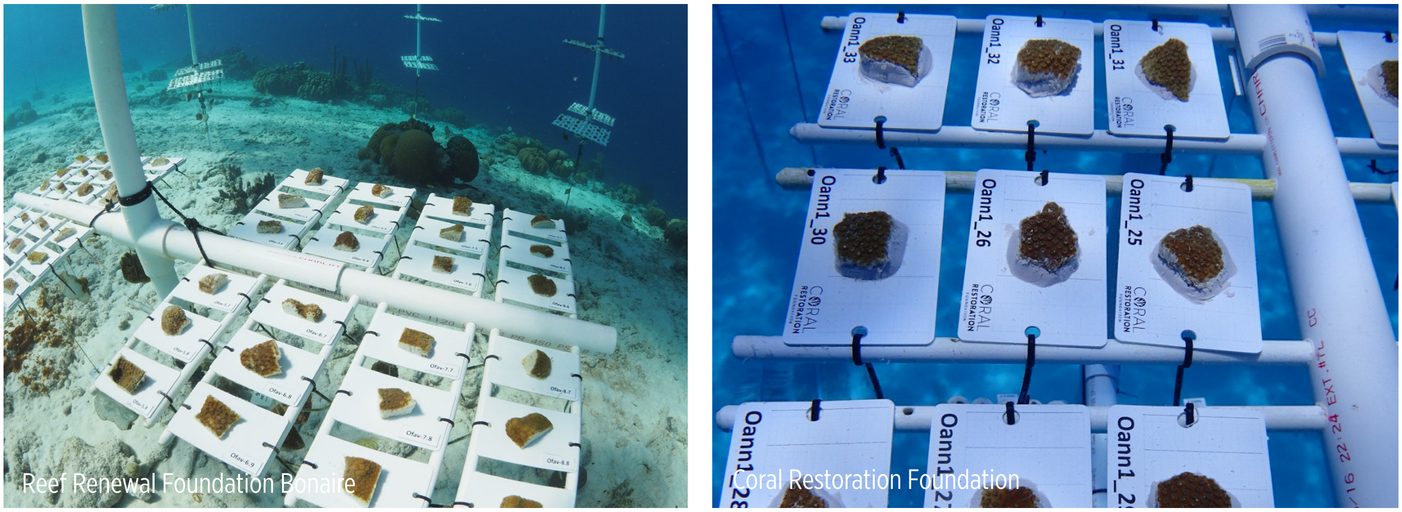


Figure 24. Examples of attaching cards directly to a structure — cable tie, wire, or monofilament.

Figure 25. Example of attaching trays with cards to a nursery structure.

Plugs are directly attached to a nursery structure by "plugging" them into size-appropriate materials. These can be used on both fixed and floating structures and with or without trays (Figures 22 and 23).

Methods:

1) Attaching plugs directly to a structure — mesh/grid, hole, or connector that closely matches the diameter of the plug stalk (Figure 22)

2) Attaching trays to structures — cable tie, wire, or monofilament (Figure 23)

Considerations:

- On floating structures, the added weight of the bases will affect the buoyancy of the structure, so be prepared to add extra flotation.

Cards can be attached directly to the structure or attached to a tray and then attached to the structure. It is not recommended that cards be hung or suspended from structures. These can be used on both fixed and floating structures.

Methods:

1) Attaching cards directly to a structure — cable tie, wire, or monofilament (Figure 24)

2) Attaching trays to structures — cable tie, wire, or monofilament (Figure 25)

Considerations:

- Card thickness — thicker card(s) have a longer nursery duration but are less flexible. Thinner cards are recommended if you plan to use the cards to grow tissue and then further fragment that tissue onto outplant plugs.
- Smooth card texture allows for coral tissue to skirt easily and for ease of cleaning. Textured cards tend to increase overgrowth, making cleaning difficult.
- Avoid using laminate; it flakes off easily over time.
- Corals can be attached to the card using epoxy, cable ties, or superglue.

Monofilament and wire — corals are first attached to a wire or monofilament line and then suspended from a structure. Wire can be attached to a structure by wrapping it around a portion of the structure a number of times. If the structure is soft (i.e., a rope), squishing the wrapped wire onto the rope will help keep it in place. Monofilament can be attached to a structure using a clinch knot, sleeve crimps, or swivels. Pre-drilled holes in the structure (e.g., holes in a tree branch), through which both of these materials can be inserted, aid in maintaining desired colony spacing. Similarly, knots along a rope, or crimps along a line can also hold corals in the desired locations. Any excess monofilament or wire should be cut as close to the attachment point as possible to avoid added surface area for algae and other competitors to colonize.

Methods:

1) Crimps and Crimper (Figure 26)

2). Wrapping/knots (Figure 27)

Considerations:

- When using wire, see suggestions in the direct tie-down section in Chapter 7: Restoration Design and Techniques.
- For heavier, larger corals that will remain in the nursery for long periods of time, such as brood stock, a thicker monofilament is recommended (e.g., >100 lb test for *A. palmata*).
- Ensure proper spacing between corals, to prevent affecting neighboring corals, by using predrilled holes, knots, or crimps along the structure.

Rope — Ropes filled with corals (or filled after installation on the structure) can be attached to both floating or fixed structures relatively quickly by using either cable ties or wrapping the rope around the structure at set distances. Alternatively, ropes can also serve as the nursery structure by anchoring one end to the bottom and floating the other end with a buoy.

Methods:

1) Attach rope to structure — cable ties, wire, or rope (Figure 28)

Considerations:

- Space ropes appropriately to avoid tangling with neighboring ropes and corals.
- Install ropes with enough tension to avoid line sagging; ropes may need to be tightened as corals grow.
- Ropes may break down over time; check the integrity frequently to avoid nursery failure (See Case Study #8.1).
- Ropes can be removed, with corals attached, from the nursery for outplanting.

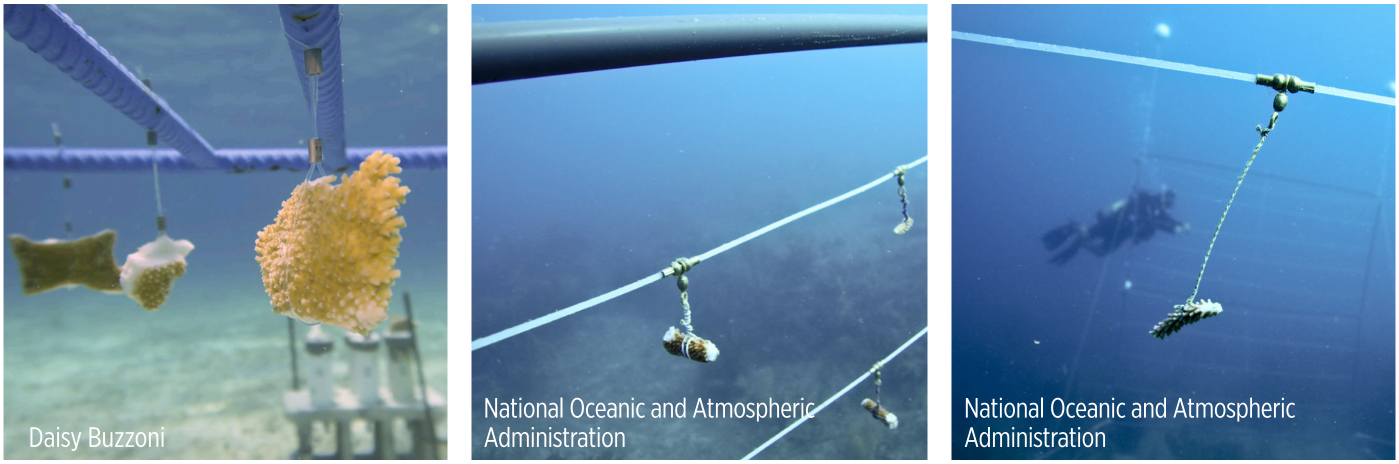


Figure 26. Examples of attaching monofilament to a nursery structure using crimps.

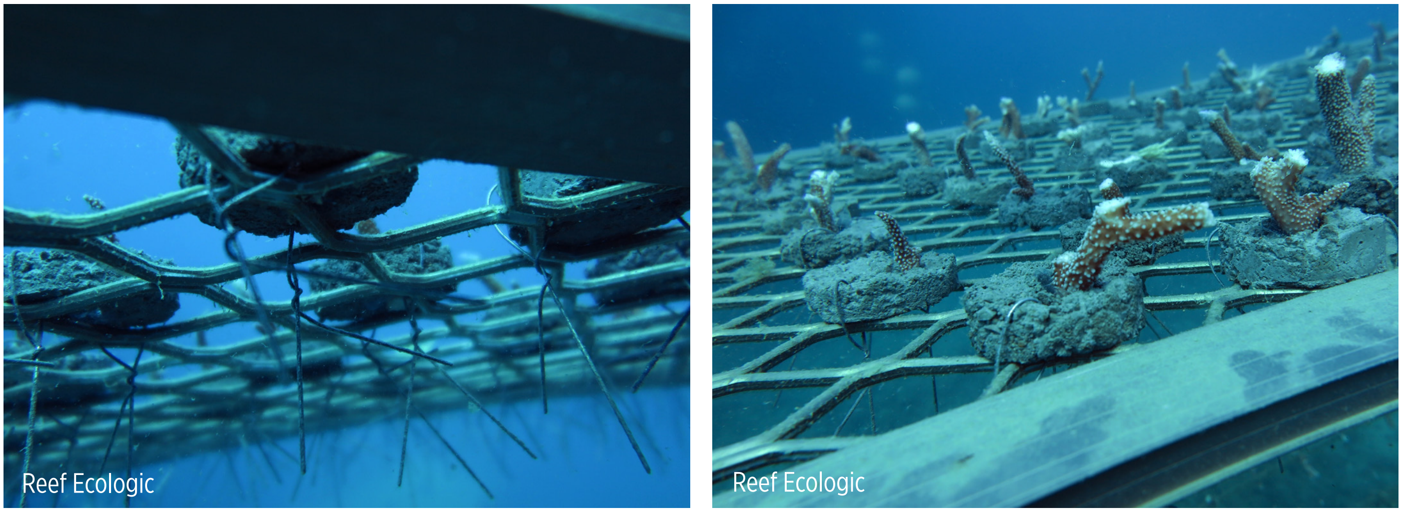


Figure 27. Examples of attaching monofilament and wire to a nursery structure using knots or wrapping.

Figure 28. Examples of attaching ropes to structures.

Fragments can be attached to the chosen base using a variety of materials, and methods should be selected based on the availability of materials, program logistics, budget, and coral morphology. See Chapter 3: Nursery Stocking, for methods and materials for attaching corals to their bases or structures.

Anchor Types

There are many different types of materials that can be used as anchors for securing nursery structures on various types of sediment. Table 5 provides information on how to make a decision about what type of anchor(s) may be best. The main concernwhen choosing an anchor is ensuring that the structure will stay in its location (both side to side and up and down) with large waves, swells, or strong currents. Depending on the size of the structure, this may require multiple anchors. A secondary/safety anchor is recommended for longer-term installations. See Appendix 1 for information on the number of anchors needed per structure.

A concrete block is the least costly, most available, and most flexible anchoring option for midwater nursery systems. However, blocks may shift during storms, causing line abrasion or system entanglement, and should not be relied upon long-term unless thoroughly tested. A more durable anchor device or a secondary anchor device is needed if concrete blocks will be used.

Anchor Line Types

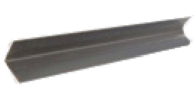
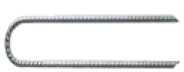
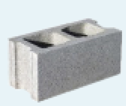
Line, rope, wire, cable, monofilament, and cable ties can all be used to attach the anchor to the nursery structure. The required strength of this attachment material will depend on the nursery structure, size, and weight and on oceanographic conditions at the nursery location. Anchor line diameter and strength will need to be increased when working with larger nursery structures such as tables, nets, and rope nurseries. Frias-Torres et al. (2018) and Edwards (2010) suggest using coiled or woven lines between 8 to 25 mm in diameter for anchoring rope and table nurseries that are upward of 30 m in length. In locations known to have a lot of current or strong water movement (waves and flow), materials that can easily snap or abrade are not the best options.

Monofilament of 1,000 to 1,200 lb test is recommended over steel cables to attach to the anchor because the crimps last longer on monofilament line and have a tendency to corrode steel cables within five years. Generally, be aware of bi-metallic connections that may enhance corrosion.

Double braided polyester rope or woven high-density polyethylene (HDPE) chord including Spectra^{TM}/Dyneema^{TM} are other options for an anchoring line, especially with a Helix screw anchor; ropes may be expected to last approximately three to five years. Shedding of microplastics may be notable at 12 months in some materials and sunnier locations.

Coral Restoration Foundation

Table 5. Anchor options for nursery structures.

Anchor Type	Structure Type	Substrate Type	Length/ weight	Width	Cost	Anchoring line materials (floating)	Securing materials (fixed)	Lifespan of line materials	Fail Points
Duckbill 	Coral Tree Smaller Floating Tables & Ropes Fixed Tables Fixed Frames	Sand	13 cm (5 in) + anchor line	2.5 cm (1 in)	$5	Steel Cable* 1,000-1,200 lb test Monofilament	Steel Cable Polyester Rope Industrial Cable Tie	5 years	Cable/Monofilament breaks; Dislodgement during storms
Helix 	Coral Tree Smaller Floating Tables & Ropes Fixed Tables Fixed Frames	Sand, Sand/ Rubble	51- 76 cm (20-30 in)	10 cm (4 in)	$8	Double-braided Polyester Rope 1,000-1,200 lb test Monofilament	Steel Cable Polyester Rope Industrial Cable Tie	3-5 years 5-10 years (anchor)	Cable/Monofilament breaks; Corrosion of top loop
Penatrator Screw 	Coral Tree Smaller Floating Tables & Ropes Fixed Tables Fixed Frames	Rubble	66 cm (26 in)	2.5 cm (1 in)	$24	Steel Cable* 1,000-1,200 lb test Monofilament	Steel Cable Polyester Rope Industrial Cable Tie	Cable/Mono: 5 years Screw: 10+ years	Cable/Monofilament breaks
Angle Bar/pipe 	Floating Tables Floating Ropes Fixed Tables	Sand	2 m (72 in)	5-6 cm (2 in)	$24	Woven or coiled rope (8-25 mm)	NA	8+ years	Rope wears or breaks
Rebar 	Fixed Tables Fixed Frames Cement Strucutres	Sand	1-1.5 m (36-48 in)	½ in	$2	NA	Polyester Rope Industrial Cable Tie	1 year (cable tie) 10+ yrs (rebar)	Cable tie
Rebar Staples 	Fixed Tables Fixed Frames Cement Strucutres	Sand, Sand/ Rubble	20 in (total length before bending 48 in)	6 in (#3 or 4)	$1	NA	NA	10+ years	Some Corrosion, some species of coral won't grow over rebar
Cement/Cement block 	All*	Sand, Sand/ Rubble, Hard bottom (cement as an adhe- sive)	25-100 kg	various	$2 block	Woven or coiled rope (8-25 mm)	Polyester Rope Industrial Cable Tie	10+ years	As an adhesive it may fail if not applied correctly; cable tie

*See Line Types for more information

Figure 29. Methods to prevent rope chafing: vinyl tubing, thimbles, or garden hose.

If ropes are used to secure floating structures, there are several knot options. In general, if the knot needs to be undone in the future, a bowline is recommended, particularly when paired with an abrasion sleeve to protect the loop (Figure 29). If the knot does not need to be undone, a modified clinch knot can be used; two to three wraps of the securing eye will minimize points of wear while drawing the knot tight enough that wear is occurring in the knot and not against the structure (Frias-Torres et al., 2018). A clinch knot will not generally require an abrasion sleeve. See the knot-tying section in Frias-Torres et al. (2018) for additional suggestions and knot-tying techniques.

Anti-chafing gear, shackles, or tubing should be used on the monofilament, cable, or rope at the sand/water interface and anywhere that the monofilament, cable, or rope interacts with another material to prevent chafing (Figure 29). Preventing chafe in this manner and inspecting periodically is extremely important to avoid structure loss.

Redundant Anchor

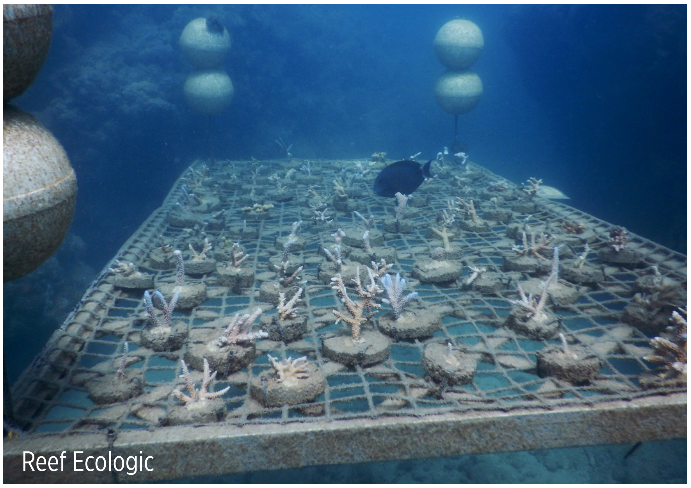
A redundant anchor or attachment point is a good idea for floating structures as a fail-safe in case the primary anchor fails. There are a few methods for achieving this (Figure 30), as described below:

- One anchor with two attachment points: In this scenario, if a crimp or knot fails on one of the attachment lines, the second could hold the floating structure in place.
- Two anchors with slack on one line: Two anchors, either of the same type or two different types, can be used to secure the structure. By keeping slack in one line, the practitioner can select a primary anchor and a redundant anchor.
- Two anchors with equal tension on both lines.

In the first two cases, the redundant line should not be much longer than the “primary” line so that if the primary line fails, the upward momentum on the redundant line is kept to a minimum, reducing the chances of it snapping from the force. Also, if the secondary line is too long, it can become tangled in the first line and cause fraying. If necessary, the longer line can be secured to itself with a small cable tie that would break if there were tension on the line.

Alternatively, two anchors with two equal-length lines can be installed. This helps to eliminate the problem of the lines fraying from interacting with each other and theoretically splits the upward force between the two anchors. The distance between the two anchors will depend on the anchors used, as some anchor designs will make them less effective if the upward force is pulling at an angle.

Figure 30. Examples of redundant anchor attachment methods; the first shows two anchors with slack in one line, and the second shows two anchors with equal length lines.



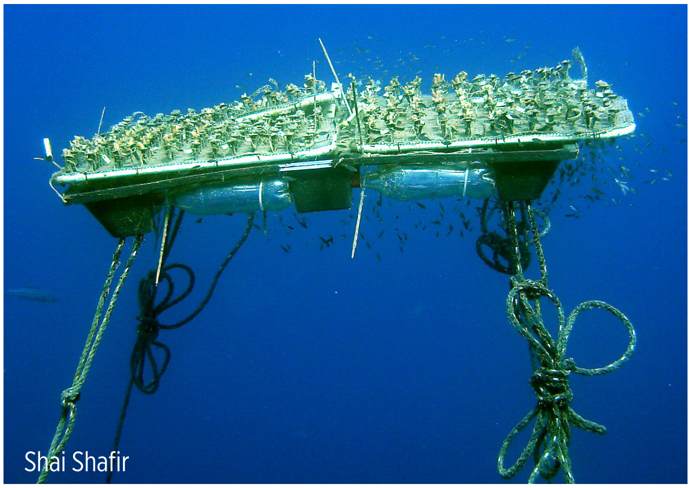


Figure 31. Examples of buoy locations on nursery structures.

Floats/Buoys

Anything that floats can be used for buoyancy for a nursery structure. Flotation can be added above or below nursery structures, and where they are placed will depend on structure design and availability of materials (Figure 31). The amount of flotation needed can be determined from an estimation of the combined weight of the nursery structure and corals; guidance on the number of buoys needed for large nursery structures can be found in Edwards (2010) and Frias-Torres et al. (2018). The buoyancy of the structure should be enough to keep the anchor lines taut; after buoy installation, push the nursery structure down, and it should bounce back to its position fairly quickly. Buoys may need to be added or augmented as corals grow and the structures become overgrown. To avoid hazards to navigation, we advise that buoys are at least 2 to 3 m below the surface.

Lobster trap buoys [17.8 cm (7 in) round Styrofoam buoys] are commonly used because they are inexpensive. Hard-pressed bullet floats and plastic buoys may last longer and provide more lift but are more expensive. Plastic bottles may work well (Figure 32) as they are inexpensive, readily available, reuse plastic garbage, and may be inflated underwater, but they should be monitored as fish (especially Triggerfish) may bite and puncture the bottles. White HDPE such as bleach bottles may degrade with UV (sunshine), whereas clear PET/PEET bottles are more durable. Glass bottles have also worked for some, although they can be relatively cumbersome.

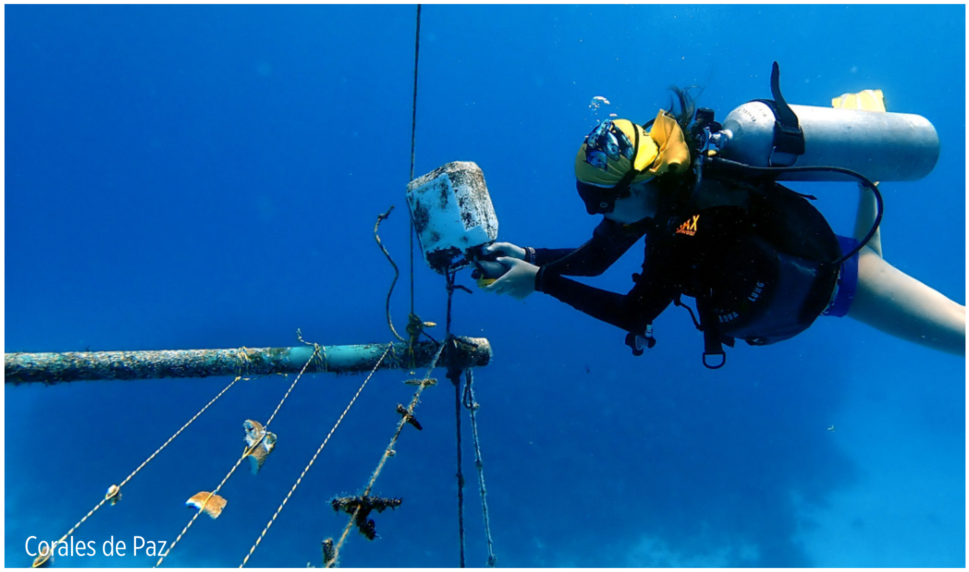


Figure 32. Example of plastic bottles or jerrycans for buoy. Flotation made of plastic may be used, but should be checked frequently, as any leak is a comprehensive failure.

Buoys can be attached to floating structures in several ways; here are a few suggestions:

- A line is run straight from the anchor to the buoys with the floating structure suspended on it (i.e. through a PVC spine on a tree). The benefit of this technique is if the line is broken, the structure will often remain, and only the buoy and line will be lost.
- On a tree, the buoy lines can be wrapped around a fiberglass branch, and on floating tables, the line can be wrapped through or around the frame. The possible downside is that if the anchor line breaks, the entire structure could be lost. Similarly, if the portion of the structure holding the line breaks, the entire structure can be lost, or buoyancy is lost.
- The buoy line can be attached to the structure with a secondary line using a shackle for easy exchange or addition of buoys.

Installation

When installing floating structures, the order in which pieces are installed is important for both efficiency and safety.

STEP 1: Installation of anchors depends on the type of anchors used.

Duckbill Anchors — Using a hammer or post-driver, install the anchor 1.5 m (4 to 5 ft) down using a pointed rebar stake that fits inside the duckbill and can easily be removed. Pound the duckbill to a depth where the monofilament loop is just above the sand once installed. Remove the rebar and pull up on the monofilament loop to turn the anchor, securing it. Duckbill anchors are difficult to remove once installed; it requires digging the anchor out.

Helix Anchor — Helix anchors can be installed using a metal rod through the eye at the top for leverage. The anchor should be installed until the eye is at the sand/rubble line. Helix anchors can be removed using the same method as installation.

Penetrator Screw — Using a 1.5 kg (3 to 4 lbs) mini sledgehammer, pound the screw into the rubble. Penetrator screw anchors can be removed with a wrench.

Angle Bar — Using angle bars (iron L-bars cut to ~2 m length) anchored at 45º may provide a quick and easy permanent anchor. Angle bars can be installed by pounding them into the substrate or using a water pump with four to six bars pressure (Edwards 2010).

Rebar — Rebar stakes and staples can be used in a variety of ways. In soft substrates they can easily be pounded in using a sledgehammer; in hard substrates, cutting the end of the stake at an angle (creating a sharp point like a nail) will make installation easier. Alternatively, pilot holes could be drilled and partially filled with cement or epoxy prior to pounding in the stake.

Concrete/Concrete Block – May provide a quick, easy and adjustable setup, but timely augmentation with a more permanent anchor is highly recommended. If using concrete blocks as an anchor, carefully lower them into the designated place to avoid swimming or moving blocks long distance. Staple, rope, or eye-bolt can be set into wet concrete for anchor line attachment. Note that the buoyant weight of a concrete block is 40% less than its weight on land, so this should be considered when deciding how many blocks are needed or whether a secondary anchoring system is required.

Before installing the anchors, lay them out to make sure there is sufficient space between the structures to prevent them from bumping into each other and to allow divers to easily move between them for cleaning, monitoring, and restocking. For larger structures, anchor spacing is important to keep the lines taut and square to each other to prevent unwanted sagging and torque.

Step 2: Attach the structure to the anchors.

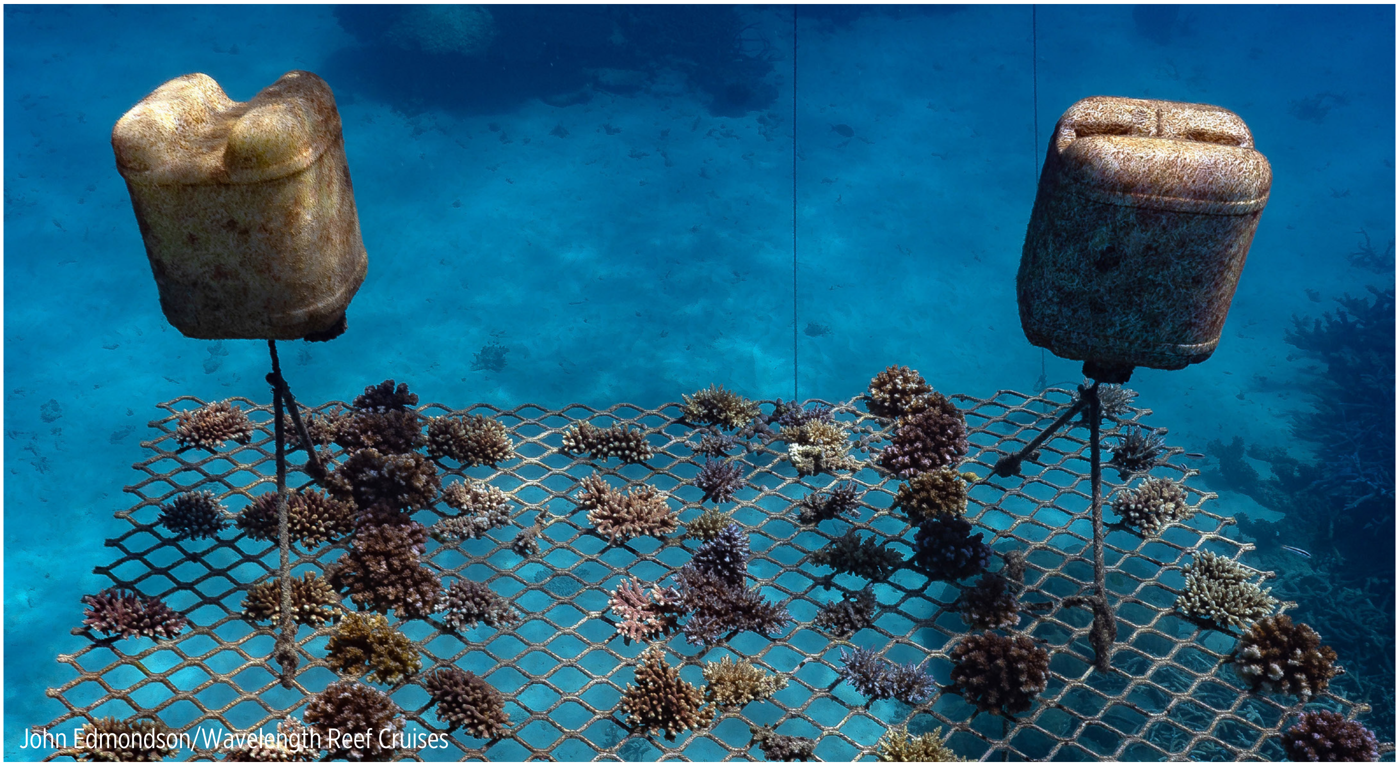
Step 3: If a floating structure, attach buoys and float the structure.

Buoys can be difficult to handle underwater; for safety, have a detailed plan in place and adequate counterweight so buoys do not rocket to the surface or cause injury to divers. Never attach buoys to a diver. A rope can be attached to the buoy and run through the anchor or the nursery structure to create a pulley system, bringing the buoy to the bottom or depth necessary. Jerrycans or other similar containers can be filled underwater using a spare SCUBA cylinder.

> It is important to always be very aware of your surroundings when installing and changing buoys on floating structures. When the structure is first floated, it will have a significant amount of buoyancy, so be certain that nothing attached to any diver is caught on the structure. Make a plan with fellow divers about installation to ensure the safety of everyone. Let go of a rogue buoy or structure if it threatens to pull a diver to the surface.

Step 4: Attach coral on the newly installed structure.

In some cases, it is more efficient to attach corals before floating a structure. If this is the case, make sure corals are situated so they are not tangled in any of the lines when the structure is floated.


John Edmondson/Wavelength Reef Cruises

CASE STUDY #2.1

Growing *Dendrogyra cylindrus* on trees

Location: Puerto Rico and St. Thomas, United States Virgin Islands (USVI)

By adding tiles to the tops of the branches on the trees, it is possible to propagate *Dendrogyra cylindrus* (Pillar coral) in nurseries (Figure 33). Fragments are brought back to a nursery and cut into 3 to 5 cm pieces. Corals can be cut on the vessel using a coral band saw with a diamond blade or cut underwater using either a lopper and/or a hammer and chisel. Cutting corals with a band saw gives the cleanest cut but is not always logistically possible. A hammer and chisel is the last choice for cutting because it is an imprecise method and damages a lot of tissue. Pieces are mounted with epoxy onto PVC tiles (5 cm x 5 cm) that are bolted to holes in the tree branches. After a year or so, once the coral tissue has grown down to the tile, *D. cylindrus* colonies are ready for outplanting.

Important Considerations

- Outplant corals before the tissue grows over the edges of the tile and starts fusing with the tree branch. This will minimize damage to corals during the outplanting phase.
- To outplant, corals can either be removed from the tiles or outplanted with the tiles as a base.
- Ceramic tiles can be used as well, but it can be difficult to drill holes in the tiles.
- Epoxy or cement can be used to attach the corals to the reef, although cement is cheaper and stronger than epoxy.

Case study and images provided by: Sean Griffin, NOAA Restoration Center, Aguadilla, PR; reeftechinternational@gmail.com

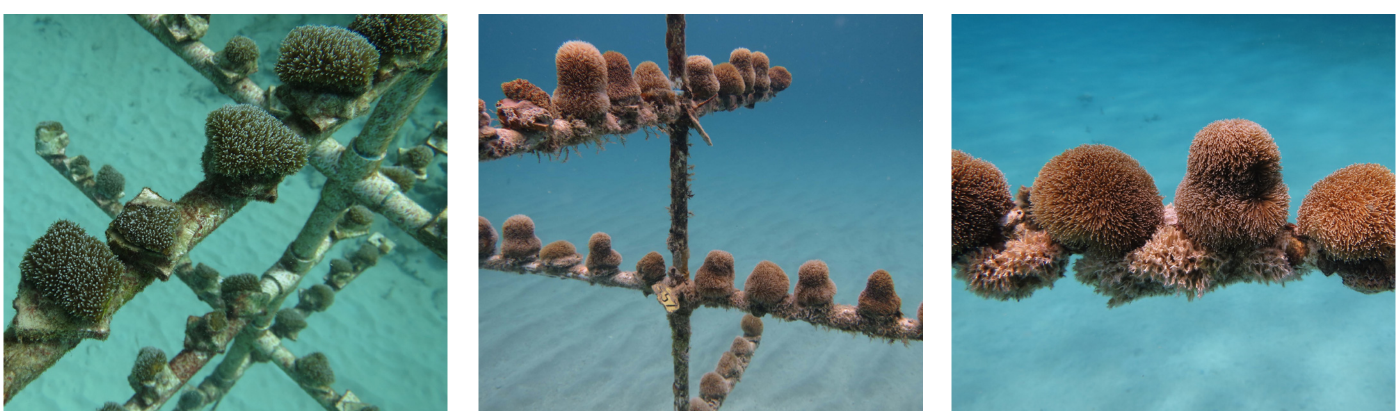


Figure 33. Modified tree design.

CASE STUDY #2.2

Growing *Meandrina meandrites* on floating structures

Location: Puerto Rico

Over the last few years, *M. meandrites* has been successfully grown by hanging them from Floating Underwater Coral Apparatus (FUCA)s and trees using thermostat cables and monofilament that is at least 100 lb test (Figure 34). Survival rates for this species are low when grown on tiles. Growth rates ranged from 1.2-2.0 cm/yr. Based on these results, *M. meandrites* production has been increased in two of the nurseries in Puerto Rico which currently house 100 fragments. Corals will likely have to be cut in half to outplant them and will be reattached using cement or epoxy.

Important Consideration

- *M. meandrites* has a very brittle skeleton, which can be challenging when fragmenting. If possible, it is better to use a coral band saw or underwater grinder to cut fragments.

Case study and images provided by: Sean Griffin, NOAA Restoration Center, Aguadilla, PR; reeftechinternational@gmail.com

The Nature Conservancy

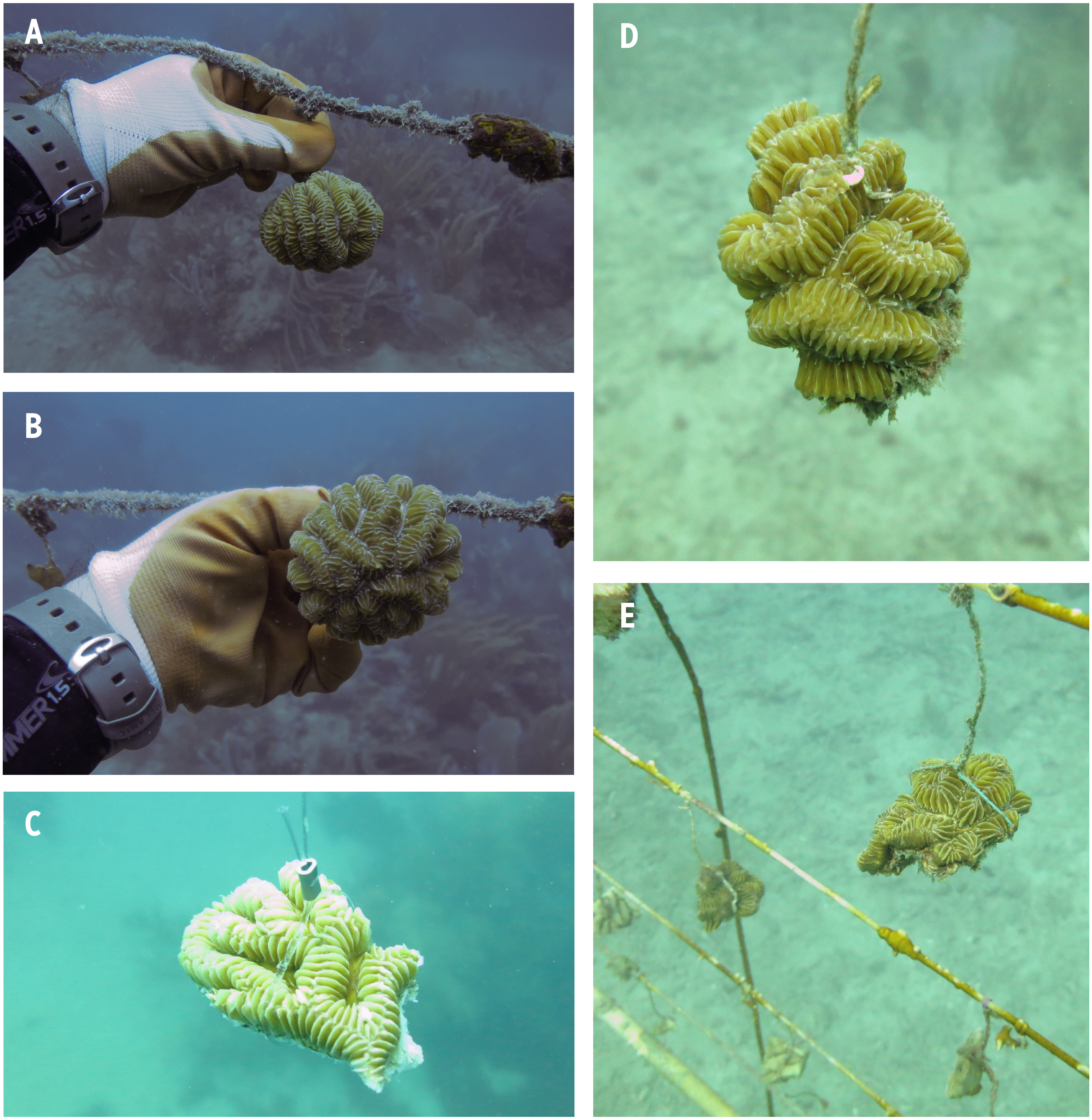


Figure 34. *Meandrina meandrites* hanging from a line nursery with thermostat cable (A and B), a Tree^{TM} with monofilament line (C and D), and a FUCA with thermostat cable (E).

CASE STUDY #2.3

Growing *Orbicella annularis* and *O. faveolata* on trees

Location: Key Largo, Florida

Coral Restoration Foundation (CRF) has developed a modified version of their Coral Tree^{TM} that allows for the mass production of *Orbicella annularis* and *O. faveolata*. Previously CRF had been hanging massive species from ID card stock using monofilament. These corals were cored, and then the cores were attached to the cards using epoxy or superglue. The cards were then suspended from a standard Coral Tree^{TM} using monofilament. CRF encountered numerous problems with this method, including lack of space, detachment of corals, detachment of monofilament (due to the movement of the card), and inadequate light levels. Given the slower growth rates and different morphology of massive species compared to branching species, CRF developed a modified structure to allow for upward facing corals, minimize/eliminate movement of individual cards, maximize nursery space, and of course minimize loss.

CRF's modified tree is made from the same material as the standard tree and consists of a PVC trunk segmented with 4-way crosses. Slotted into the 4-way crosses are horizontal, upward facing panels on which the corals are placed. A single tree can hold four to eight panels, and they are held in place with cable ties or more recently, stainless steel bolts. The panels are made from a small PVC section, cross-sectioned by fiberglass rods within the same plane, creating a "tray-like" structure. Coral cards can either be attached directly to the panel, or a mesh netting (gutter guard) can be placed on top, creating an attachment surface for plugs or cards. This design can be potentially used for any massive coral or brain coral species.

CRF has been growing *O. annularis* and *O. faveolata* on two different substrates, ID card stock (broodstock) and ceramic plugs (outplant). This two-fold method allows CRF to distinguish between production corals and outplantable corals, ensuring the continued propagation of every genotype (Figure 35). Corals are allowed to skirt over the ID card before they are detached and fragmented in situ. New fragments are attached to outplant plugs using epoxy or superglue and allowed to grow until fully covering the plugs. This whole process can be achieved in situ at the nursery site, eliminating any transport shock/stress. These plugs can then be outplanted directly to the substrate or by using a NEMO^{TM} underwater drill and epoxy (Figure 36).

Important Considerations

- Avoid the direct cleaning of cards and plugs as new coral tissue can be easily damaged or dislodged; however, the nursery structures should be routinely cleaned.
- Trees are kept monogenetic, and each panel is tagged with the appropriate genotype in order to maintain diversity and separation.
- Outplant plugs should not be left too long in the nursery; the coral will overgrow the plug and even fuse to adjacent ones, causing damage when removed for outplanting.
- Plugs should be outplanted in monogenetic units, close together to promote post-outplant fusion.

Case study and images provided by: Daniel Burdeno, CRF, Key Largo, FL, USA; Contact: Sam@coralrestoration.org

Figure 35. CRF modified coral tree to accommodate massive species. ID card "broodstock" (left) and "outplant" plugs (right) on trays, with mesh gutter guard to house plugs.

Figure 36. CRF massive coral outplant process. Left to right: NEMO drill use, epoxying plugs into drilled holes, finished "cluster" of 10 plugs. Stems of plugs can also be removed the plugs can then be outplanted without the use of a drill.

CASE STUDY #2.4

Propagating multiple coral species on floating nursery platforms

Location: Multiple sites, Great Barrier Reef, Australia

In order to propagate multiple coral species spanning numerous coral morphologies, the Coral Nurture Program introduced platform-based floating structures (Figure 37; Suggett et al., 2018). Initial propagation efforts using these systems involved conditioning the aluminum platforms in situ for a period of about two weeks prior to attaching coral fragments. Corals can be attached using cable ties or simply wedged into the holes in the aluminum frame. All platforms are labeled by row and column such that each fragment has a unique identification number (location) for fate tracking.

Since their first introduction, the Coral Nurture Program has deployed more than 50 frames across several sites of different environmental conditions at tourism reef sites across the northern Great Barrier Reef (GBR), but predominantly at Opal Reef (Suggett et al., 2018; Howlett et al., 2021). More than 4,000 fragments have been added, covering multiple coral taxa but focusing on the acroporid species that were hit hard during the 2016/2017 mass bleaching event. Growth rates are highly variable across sites, seasons, and taxa, but they can reach greater than 10 cm per month (*Acropora hyacinthus*). For subsequent harvesting, either whole fragments (colonies) are removed or small cuttings are made to retain parent colonies. In all cases, harvesting is done in situ by clipping corals from the frames (and into wire mesh baskets, sometimes held under the frames for smaller fragments) for direct outplanting to neighboring reefs. Small shades were manufactured and placed over the platforms, in addition to slightly lowering the depth of the platforms, where possible, during the 2020 bleaching event on the Great Barrier Reef.

Important Considerations

- Nursery frames are best placed at a distance from the reef that enables large grazing fish to clean frames while minimizing small corallivores from venturing to the frames.

- Frames have sufficient “give” (restriction to drag), even in high-flow channels; understanding the extent of variance in both flow and tidal height at any one site may be important for initially optimizing the extent of buoyancy.

- Colonies should be pruned/removed regularly to avoid colony fusion or overgrowth.

Case study and images provided by: John Edmondson, Wavelength Reef Cruises and Coral Nurture Program; info@coralnurtureprogram.org; and David Suggett, University of Technology Sydney; david.suggett@kaust.edu.sa

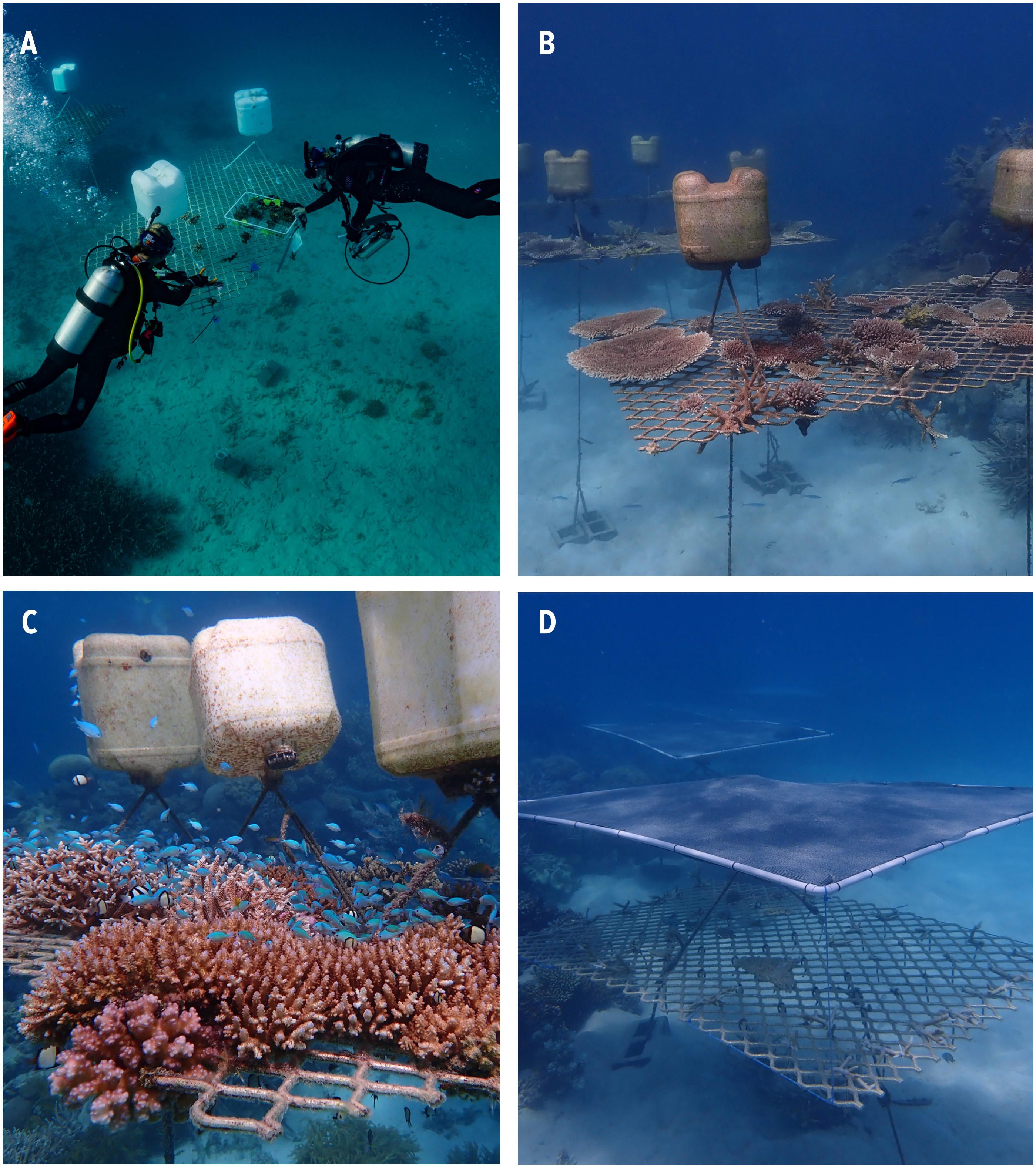


Figure 37. Application of the floating coral propagation nursery platforms, Opal Reef Great Barrier Reef. A shows stocking of nursery platform. B and C show progression of coral growth on platforms. D is shade deployed over the platforms during the 2020 GBR heat wave.

CASE STUDY #2.5

Growing fast-growing branching corals in midwater floating rope nurseries

Location: Colombia, Maldives, and Seychelles

Over the last five years, mid-water rope nurseries, following methodology modified from Levy et al. (2010), have been used for large-scale coral reef restoration in Seychelles, Maldives, and Colombia. Ropes loaded with farmed *Acropora* spp and *Pocillopora* spp. Corals obtained through asexual propagation are floated 4 to 8 m below the sea surface to form a rope nursery (Figure 38). The entire structure is moored to angle bars hammered into the sandy seabed. A 3 x 20 m rope nursery can hold approximately 2,500 corals (Colombia) while a 6 x 20 m nursery can hold up to 5,000 corals (Seychelles). The maintenance and cleaning of biofouling organisms at each midwater rope nursery are site-specific, but in the Seychelles 22.7 ± 9.78 (mean ± SD, n = 9) diver hours (range 12 to 36 diver hours) per month, repeated every two to four months, were required (Frias-Torres and Van der Geer, 2015). Corals take up to 12 months to grow from 5 to 15 cm in diameter, when they are ready for outplanting.

Important Considerations

- This is a low-cost durable nursery type that allows large-scale cultivation of fast-growing branching corals.
- Proper nursery site selection and maintenance are key to ensure high survival rates.

Case study and images provided by: Phanor H Montoya-Maya, Corales de Paz, Colombia. phanor@coralrestoration.org

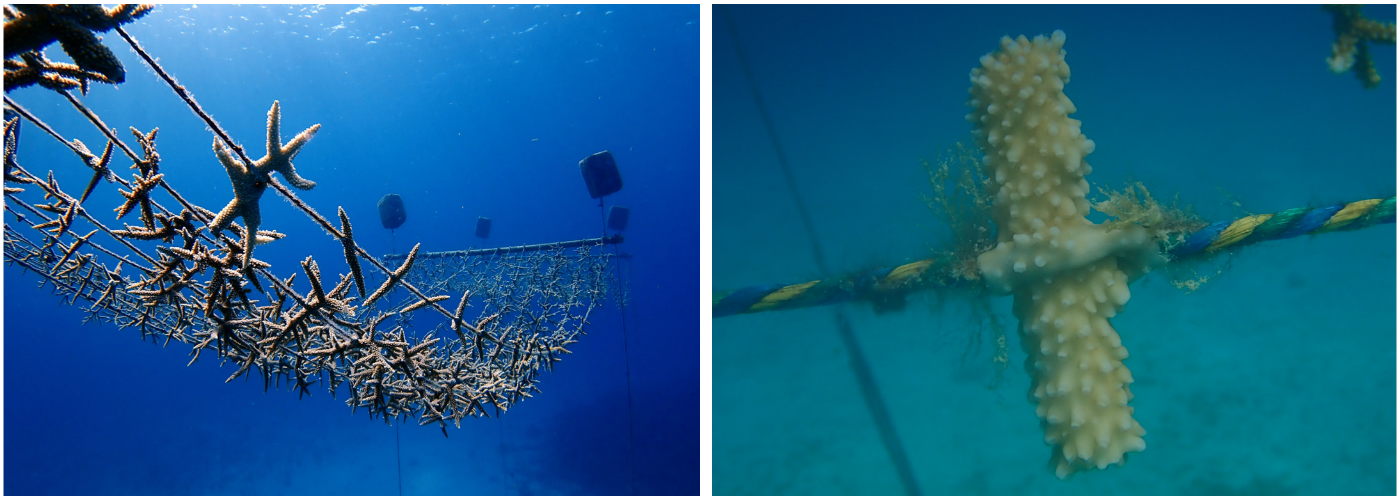
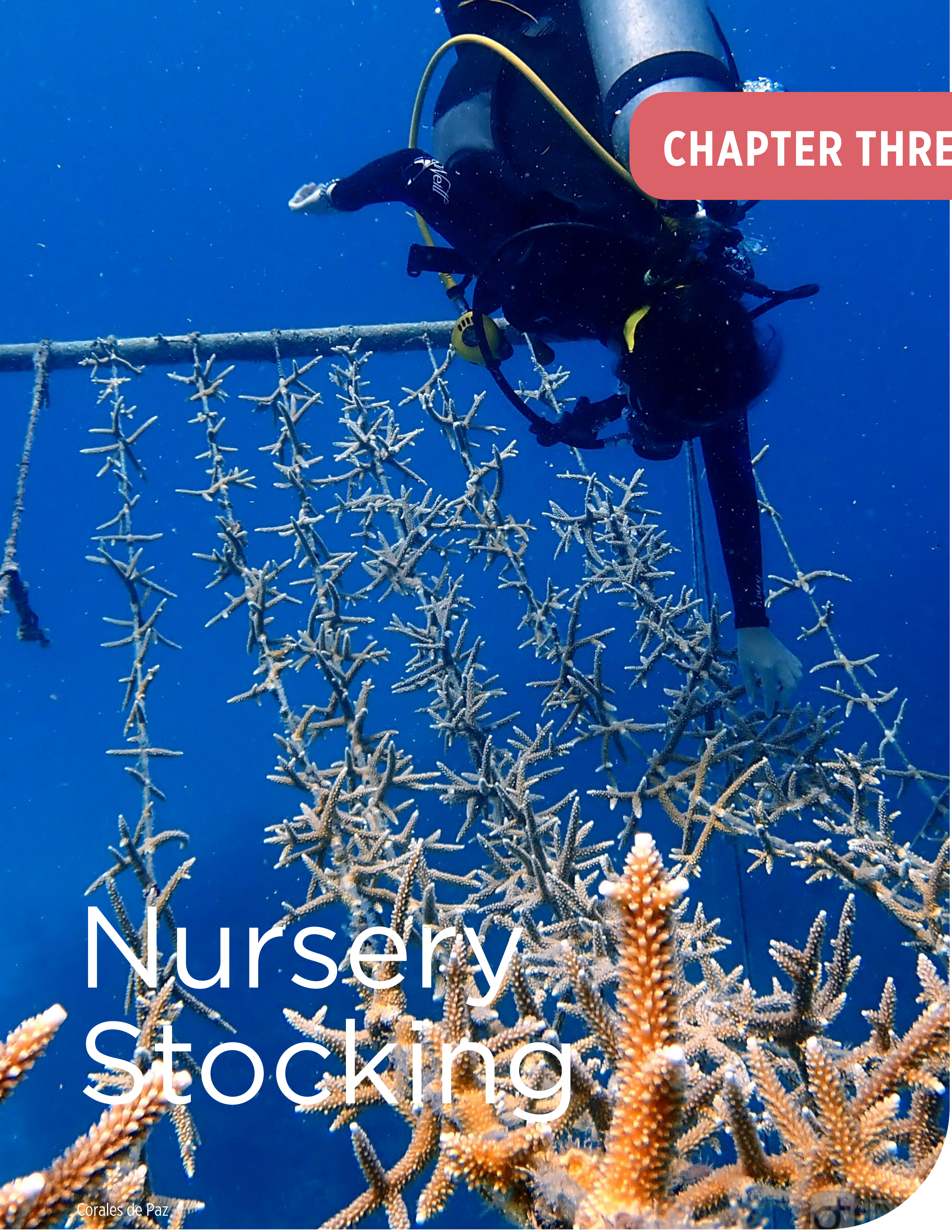


Figure 38. *Acropora cervicornis* fragments overgrowing ropes.

CHAPTER THREE



Nursery Stocking

Corales de Paz

Once a suitable site for the coral nursery has been selected and structures have been deployed, corals will need to be collected to serve as nursery stock. There are two key tenets of coral restoration: 1) do not cause irreversible harm to parent/donor/wild populations, and 2) maximize coral productivity. To meet these principles, certain practices should be followed when collecting coral fragments for future nursery propagation. Over-pruning of donor colonies, >10% of the colony for some species, can be detrimental to donor colony survival and reduce reproductive activity (Epstein et al., 2001), whereas pruning vigor was observed in other species when up to 95% of the colony was removed (Lirman et al., 2014b; Lohr et al., 2015). This chapter will provide research-based recommendations for donor colony collections and adding coral stock to nursery structures — both from established wild colonies and corals of opportunity.

Collection Protocols

For wild colonies where only a portion is being collected, that colony should be large enough that the collection of fragments removes less than 10% of the colony (Epstein et al., 2001; Schopmeyer et al., 2017). Prior to collecting, colonies should be assessed for the presence of recent mortality, discoloration, and/or abundance of predation wounds. A colony may exhibit some of these signs, but still have healthy tissue and should be more thoroughly assessed to determine if observed conditions will affect collected fragments. Discoloration and signs of recent disease are more concerning than evidence of predation on one section of a colony. Collections should be made from three to six genets (colonies) per reef, selecting colonies that show some differences in morphology and/or size (Baums et al., 2019). Fragments should also be collected from a range of depths that are appropriate for that species. Collections from donor colonies should be completed during periods of lowered environmental stressors (e.g., unusual or predictable weather and climate) and avoid periods directly prior to or following predicted spawning times. The CRC's Larval Propagation Working Group, along with other experts in the field, have completed an extensive literature review, and compiled spawning observation data to generate yearly spawning predictions. These predictions plus additional resources can be found on the Larval Propagation Working Group's webpage (https://www.crc.world/).

Colonies selected as corals of opportunity should be carefully assessed for dead tissue, lesions, and/or discoloration. Dead portions on the colony should be removed at the collection site, which reduces the weight for transport and the possible transfer of harmful diseased tissue. When collecting corals of opportunity,


Coral Restoration Foundation

be cautious that whatever killed the rest of the colony is not still impacting the remaining tissue. For example, if the colony shows signs of recent disease, it is best practice to monitor the remaining tissue for some time prior to collection to make sure it is not infected and asymptomatic. At the very least, conduct a thorough visual health assessment prior to introducing fragments from previously diseased colonies into the nursery. When collecting corals of opportunity, be cognizant of the impacts being made to the collection site, such as how many colonies should be removed from the site versus stabilized in place to assist in site recovery (Edwards and Clark, 1999). Additionally, for branching species, keep each coral of opportunity separate during transport so that if breakage occurs, it is clear which fragments came from which colony (for presumed genetic tracking). Similarly, if the coral will be fragmented for transport, keep all fragments from the original coral together and separated (or marked) from other corals.

Ultimately, the number of genotypes will depend on the goal of the project, but the following should be considered:

- The nursery corals will continue to grow over time; remember to leave space (or have a plan for adding nursery structures when needed) for propagation (creation of ramets) of each genotype.
- In places with severely limited genetic diversity, a nursery may hold representatives of every genotype to safeguard against complete loss (genetic bank).
- In smaller nurseries, the number of replicates per genotype may be limited by the practical consideration of space.
- Particularly with nurseries or projects developed to answer specific questions, the number of genotypes necessary may be dictated by the study design rather than a goal of increasing diversity on the reef.

Clipping/Cutting

Small branch clippings from branching species of wild donor colonies can be collected using a variety of cutting tools, including bone cutters, wire cutters, gardening shears, needle-nose pliers, chisels and hammers, etc. For branching species with thicker branches, ratcheting pruning shears, loppers, and PVC cutters have also been proven effective. Taking care to cut the coral cleanly and evenly ensures optimal survival of the fragments, as well as rapid healing and recovery of the donor colony.

For massive corals, removal from the substrate can be done using a hammer and chisel. These colonies can then be fragmented into smaller nursery colonies using a hammer and chisel, tile saw, angle grinder, or coral bandsaw (Page et al., 2018; Broquet, 2019). The cleaner the cut to the coral, the more rapidly the cut edge will heal, and smoother cuts are easier to adhere to the coral base. Detailed protocols for creating coral nubbins (a few polyps in size) can be found in Shafir et al. (2006c). If planning to take the remaining live tissue from an existing massive coral, a hammer and chisel, coring drill, or angle grinder can be used.

The initial size of nursery colonies can affect the overall nursery performance, including colony growth, survival, productivity, branching, and time to outplanting. Soong and Chen (2003) found that 4 cm fragments of *Acropora* may be an ideal size for coral production as the branching frequency was no less than larger fragments. Creating a nursery using small colonies may increase the overall nursery output, but it will also delay the time at which colonies are ready for outplanting (Shafir et al., 2006a).

Transport

Many methods have been tested and used for transporting coral fragments, and the selection of one particular method will depend on the equipment available and distance to the nursery (Delbeek, 2008). The following should be considered:

- Transport colonies in seawater when possible.
- Take precautions to keep track of which fragments are from which donor colony, such as wrapping in bubble wrap, using tags, or using separate containers per genotype.
- Transport colonies as quickly as possible in a shaded and cool environment. Use wet towels to shade corals, ice packs taped to the container lid to keep ambient temperature down, and/or perform water changes frequently.
- Larger massive corals, perhaps being transported to the nursery for use in micro-fragmenting, can be transported using bubble wrap between colonies within a cooler or large container to minimize abrasion and damage from each other.
- If long distance transport is necessary, additional concerns must be considered such as the use of bubblers and chillers (see Chapter 6: Harvesting and Transporting Corals).

Donor Colony (Genotype) Tracking

To allow for donor (and possibly genetic) tracking, each fragment (or group of fragments from the same donor colony) should be given a unique identifier. This will allow for accurate tracking during subsequent creation of next-generation fragments in the nursery, as well as during outplanting efforts, to ensure genetic diversity at a restoration site. If the donor colony is being monitored over time, this may also give insight into the health and survivorship of the nursery colonies.

Genetic and Genotypic Diversity

Genetic diversity can be defined on several levels in organisms that have sexual and asexual reproductive modes such as corals and plants. Genetic diversity (or gene diversity) refers to the amount of variation on the level of individual genes in a population. Genetic diversity may be expressed as heterozygosity or allelic richness. Traditionally, molecular markers (such as microsatellite loci) target non-coding regions of the genome to measure genetic diversity. The data then reflect demographic processes not subject to selection, thereby satisfying assumptions of standard population genetic models that yield measures of the scale of dispersal (Baums et al., 2019).

Genotypic diversity is a measurement of the number of unique genotypes (genets) per species that are used for restoration. Genotypic diversity refers to the number of genets in a population as defined via multilocus genotyping. Genets are the result of sexual reproduction. Each genet may consist of many ramets - colonies that were the result of asexual processes such as fragmentation. It is important for a nursery program to host as many genotypes as the program and nursery capacity allows. Having a high genotypic diversity in the nursery will allow for mixed genotypic diversity when outplanting, consequently increasing the potential for future genetic diversity through sexual reproduction. Further, genetic diversity is an important driver of long-term facilitation of species recovery and conservation (Baums, 2008; Drury et al., 2016).

Genet in this Guide is broadly defined as the collection of ramets that represent a unique coral genotype. It is recognized that not all restoration programs have the resources to collect and have samples processed for genetic analysis. Therefore, geographic distance can also be used to designate putative genets (lineages, donor colonies, etc.). Based on literature, we suggest a conservative distance between donor colonies to be at least 100 m to increase the likelihood of unique genets (Baums et al., 2006; Foster et al., 2007; Underwood et al., 2007).

Coral Chimera — is a colony that simultaneously consists of cells originating from two or more conspecific genets, essentially exhibiting a natural tissue transplantation phenomenon, that is usually developed in corals only within a short window in ontogeny (Frank et al., 1997). Coral chimerism is considered as an evolutionary rescue tool for accelerating adaptive responses to global climate change impacts and has been suggested as an integral part of the ecological engineering toolbox being developed for active reef restoration (Rinkevich, 2019a; Shefy et al., 2020; Huffmyer et al., 2021). It should be noted that when fragmenting coral chimeras, different fragments may exhibit uneven genetic backgrounds (Maier et al., 2011), or completely different genetic background, as was recently documented in chimeric algae (Varela-Álvarez et al., 2021).

See Coral Reef Restoration Monitoring Guide (Goergen et al., 2020) for methods to determine distinct genotypes.

Donor Colony Monitoring

Some basic information should be collected for every donor colony. Additional monitoring can benefit your overall restoration program. For example, in Lirman et al (2010) monitoring revealed that certain donor colonies typically heal within a month (Lirman et al., 2010; Figure 39). By tracking donor colonies, you may find certain colonies that are bleaching resistant, and those could be targeted for nursery growth and outplanting. Basic donor colony monitoring includes: GPS coordinates, colony size and condition, and photos of the donor colony at the time of collection. Donor colonies can also be marked with a tag to track health and wound healing over time (See Frias-Torres et al., 2018 for examples). With branching coral, accurate tracking can become more difficult over time as the colony is likely to fragment naturally, making it harder to know from which branches the fragments were taken.

Figure 39. Healing *Acropora palmata* and *A. cervicornis* donor colonies less than one month after fragments were removed.

Installing Nursery Fragments

Chapter 2 provides guidance on the more common types of bases to which corals can be secured. As discussed, not all corals need to be attached to a base, and whether a coral is attached to a base or not does not necessarily dictate the type of nursery structure to which it can be attached.

Fragments can be attached to a chosen base using a variety of materials, and the combination should be selected based on the availability of materials, program logistics, budget, and coral morphology. Below are some of the more common methods and materials for installing fragments in the nursery.

Cyanoacrylate adhesive (examples: Super Glue, Loctite, Gorilla Glue) — These adhesives must be applied while corals are out of the water and when there is ample space to glue and attend to corals being mounted (Figure 40). Only a small amount of glue is needed to attach the fragment to a base; however, the base and the fragment must be flush (coral cut straight, not jagged) together for secure bonding. These glues generally cure quickly but do not provide stability to the coral until cured; therefore top-heavy corals, such as branching corals may need to be held/supported until completely cured. This is a good option when the corals are already on the boat for transportation or fragmentation but not ideal when corals are already in the nursery and not on the surface.

Epoxy (commonly used brands: All-Fix, Magic Sculpt, Apoxie) — Typically these are two-part, marine epoxies that are made to be mixed and used in saltwater. We recommend using a small amount of epoxy and pressing it into the base unit first, then gently pressing the coral into the epoxy and smoothing the edges of the epoxy (Figure 41). Epoxy takes time to set. However, unlike cyanoacrylate adhesives, epoxies provide support to the fragment before fully cured, but surge waves, or movement around the fragments can cause dislodgement.


Kemit-Amon Lewis

Figure 41. Examples of attaching fragments using epoxy.

Concrete — a mix of Portland cement, sand, water, and additives can be used to attach fragments to a base (Figure 42). Compared to cyanoacrylate and epoxy adhesives, cement takes a long time to set. Therefore, this material may not be efficient in cases where fast curing is needed, such as if the base is to be hung soon, during surge or rough seas, or when a fragment needs initial stability to keep it upright. However, cement is a widely available and relatively inexpensive material.


Fragments of Hope

Figure 40. Examples of attaching fragments using cyanoacrylate adhesive.


Andrew Taylor/Blue Corner Conservation

Figure 42. Examples of attaching fragments using cement.

Cable ties and wire — Cable ties can be used to secure a fragment to a base by wrapping them around the coral and base as one unit, or they can be built into the base (Figure 43). Cable ties are cinched tightly around the fragment, ensuring that the fragment will not move around under the cable tie (tight enough to hear a slight crunch). Thinner cable ties reduce the amount of tissue smothered, and for some species will fit between the calyces. Cut off any remaining portion of the cable tie to reduce settlement of algae and other competitors. Wire (single-stranded, plastic-coated steel or galvanized) can be wrapped tightly around coral and twisted back on the other end, like a twist-tie.

Monofilament — Monofilament (approximately 30 lb test) passed through small holes in the bases can be used to secure a fragment to the base. Sleeve crimps can tightly secure the fragment to the base.

Alternatively, a baseless structure can be attached to the coral, such as monofilament or rope. Both options require minimal materials and are generally low-cost. These can also be attached to the coral prior to installation on the nursery structure or after the base is attached to the nursery structure.

Monofilament and wire — These are common materials used to suspend fragments from nursery structures. A piece of monofilament is wrapped around the fragment and held tight to the fragment with a single- or double-barrel crimp sleeve (Figure 44). The other end of the strand is left long to attach to the nursery structure. For heavier, larger corals that will remain in the nursery for long periods of time, such as brood stock, a thicker monofilament is recommended (e.g., 100 lb test for *A. palmata*). Similarly, wire can be twisted tightly around the fragment (see Chapter 7: Restoration Design and Techniques Direct Tie-down for wire considerations). These attachment types are commonly used for branching corals but have been used for massive corals as well (see Case Study #2.2).

Rope — Rope is used for coral attachment when the twist of a tri-twist rope is temporarily untwisted, and a coral is placed between the lines and re-twisted (Figure 45). This base can also be outplanted with the corals. See Case Study #8.1 for rope type considerations and outplanting methods.

Some nursery structures are designed to have fragments attached directly to the structure, rather than suspended (Figure 46). If

Figure 43. Example of using cable ties/ wire to attach a fragment to a base.

Figure 44. Examples of attaching fragments using monofilament/wire.

Figure 45. Examples of attaching fragments using ropes.

Figure 46. Examples of attaching nursery colonies directly to nursery structures.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choosing this method, be aware that it is not easy to remove a coral from the structure without damaging the coral. In some instances, the entire frame is moved to an area in need of restoration, rather than moving individual corals off the frame. (See Chapter 7: Restoration Design and Techniques).

Consider the following when determining whether a fragment is attached to the base first or the base is first attached to the nursery structure. Ultimately, decisions should prioritize the safety of the staff and the health of the corals.

Nursery depth — Dive time may be limited because of the depth of the nursery; in these cases, tasks such as mounting corals on bases could be completed on land or boat to reduce the number of tasks while diving.

Materials — Some materials must be used ex situ, such as cyanoacrylate adhesive. Other materials, such as longer-setting adhesives like cement, may be more efficient to use on the boat so that newly mounted fragments can be frequently maintained.

Staff experience — Staff that have a variety of experience, including those that do not dive, may choose to complete some tasks on land or boat to utilize all levels of experience.

Program capacity — Similar to experience, total number of available workers will determine how tasks can be completed.

Sea state conditions — Surface conditions can vary from bottom/nursery conditions and will affect the tasks that can be subsequently completed and the materials that may be able to be used. Adhesives require calmer conditions, whereas tying and cinching of corals using monofilament, cable ties, and wire can be completed in less stable states.

Location of donor material — If donor material is distant from the nursery location, corals may need to be housed during transport. Securing fragments to a base as soon as possible will reduce stress on the fragments; however, this may require additional space and logistical constraints and must be evaluated.

Nursery structure — Depending on the structure chosen, the base may be incorporated into the structure and likely deployed with the structure.

Preference — Trial and error on what option works best for your program.

Spacing of Nursery Fragments

Nursery fragments should be spaced enough to allow for adequate growth and to avoid negative interactions with adjacent colonies and nursery structures (Shafir and Rinkevich, 2008; Lohr et al., 2015). Ideally, corals should be spaced to allow for at least one year of growth because corals will either be ready for outplanting or in-nursery pruning (to produce additional nursery colonies). Some genotypes and coral species have competitive interactions; therefore, additional spacing should be taken into consideration. In addition, if colonies are too close, cleaning and maintenance may be less efficient (Shafir et al., 2006a) and increase the likelihood that corals may fuse together. Fusing isn't always a negative, but it should be included in the planning.

CASE STUDY #3.1

Collecting *Acropora palmata* corals of opportunity after a hurricane and a vessel grounding

Location: Puerto Rico

Storms and groundings can create thousands of at-risk fragments that are loose, broken, and will likely die if not stabilized (Figure 47). These corals can be:

- Reattached in situ on the same reef to restore some of the damage that occurred there.
- Transplanted to other reefs to assist recovery of coral populations in other areas.
- Brought into a nursery for propagation.

Figure 47. Hurricane Matthew damage to Gilligan's Reef in Guanica, Puerto Rico, in 2016.

For example, swells from Hurricane Matthew in 2016 severely impacted *A. palmata* thickets on Gilligan's Reef in Guanica on the south side of Puerto Rico (Figure 48). Approximately 30 acres of reef had significant damage to *A. palmata* colonies, and there were more than 10,000 at-risk, loose fragments. While many colonies were impacted, there were still a lot of healthy colonies at Gilligan's, so it was decided to transplant as many at-risk colonies as possible to other sites that no longer had healthy populations and bring some of the corals into nurseries. During this work, approximately 8,500 fragments were transplanted from Gilligan's Reef to 10 different sites and three nurseries.

Another example is the 2017 grounding of the M/V Noemi del Mar on the north side of Palomino Island off the east coast of Puerto Rico. The grounding resulted in extensive damage to *A. palmata* (Figure 49). Based on experience working in this area, responders knew that reattaching corals would be difficult since the north side of Palomino Island is heavily exposed to waves. Similar to the Hurricane Matthew incident, there were a lot of at-risk fragments, but there were still plenty of healthy un-impacted *A. palmata* at the site. Based on these factors, Puerto Rico's Department of Natural and Environmental Resources (DNER) and NOAA decided to transplant at-risk, loose fragments to other sites and leave behind any of the stable fragments that were likely to survive. By the end of this work, more than 2,000 fragments of *A. palmata* were rescued. Fragments were transplanted to six different sites and brought into three nurseries (Figure 50).

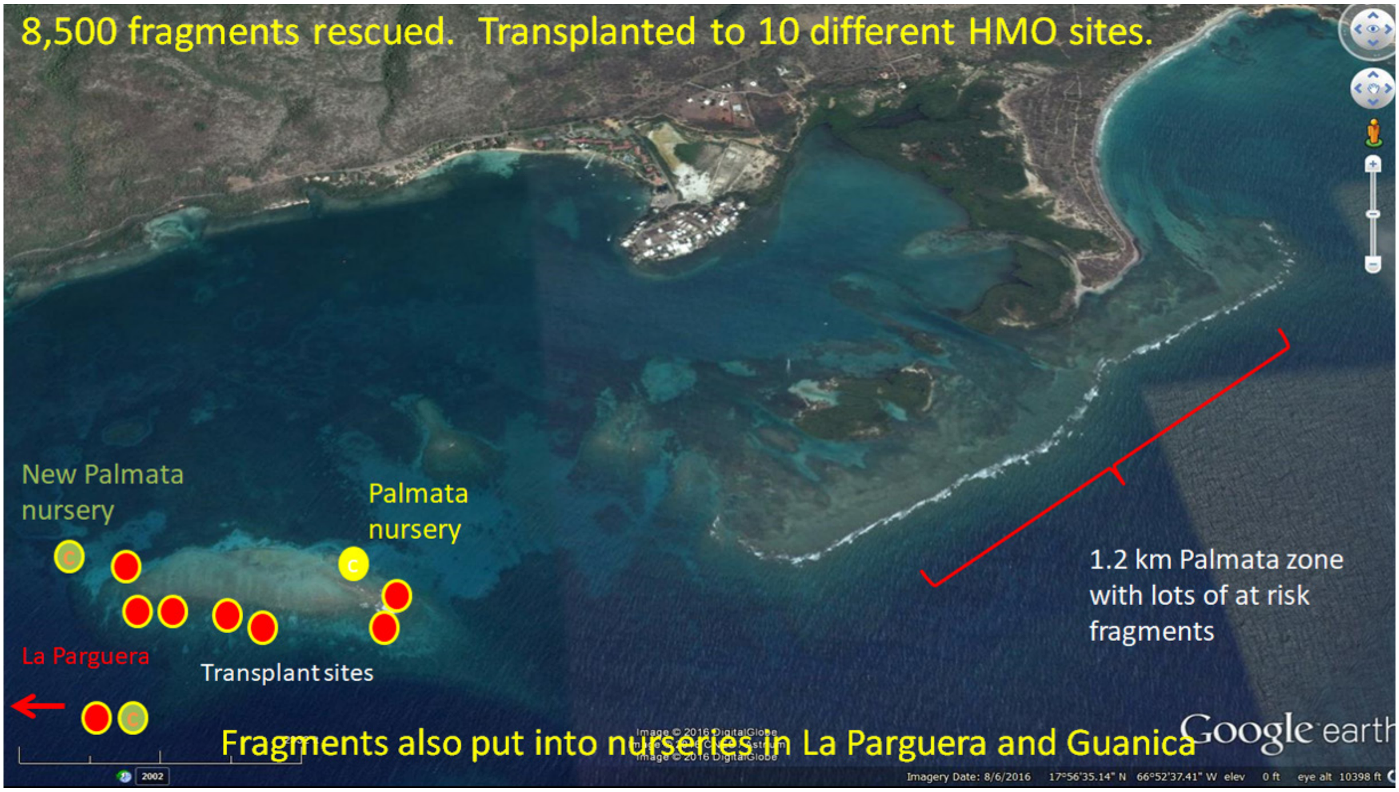

Figure 48. Map showing Gilligan's Reef, on the right, where there is 1.2 km of reef with a robust population of *A. palmata*, and Cayo Coral on the left, which had very little *A. palmata*. Red circles represent transplant sites, and yellow circles represent where corals were brought into nursery.

Figure 49. Images of physical impacts to *Acropora palmata*. Photo on left of un-impacted *A. palmata* thickets at the M/V Noemi grounding site. Photo on right of *A. palmata* impacted by M/V Noemi grounding.

Important Considerations:

- The sooner the response after an incident, the better. More fragments will be available for transplantation, and they will be in better condition.
- How long fragments are available after an incident is dependent on individual site conditions: depth, exposure, and time between the next storm or swell. At some sites, fragments may only be available for weeks while others may still have viable fragments after a couple of years.
- Caching fragments in a protected area on the reef will keep them alive longer.
- Some sites may be difficult to access because of shallow depths and wave exposure.

Case study and images provided by: Sean Griffin, NOAA Restoration Center, Aguadilla, PR; reeftechinternational@gmail.com

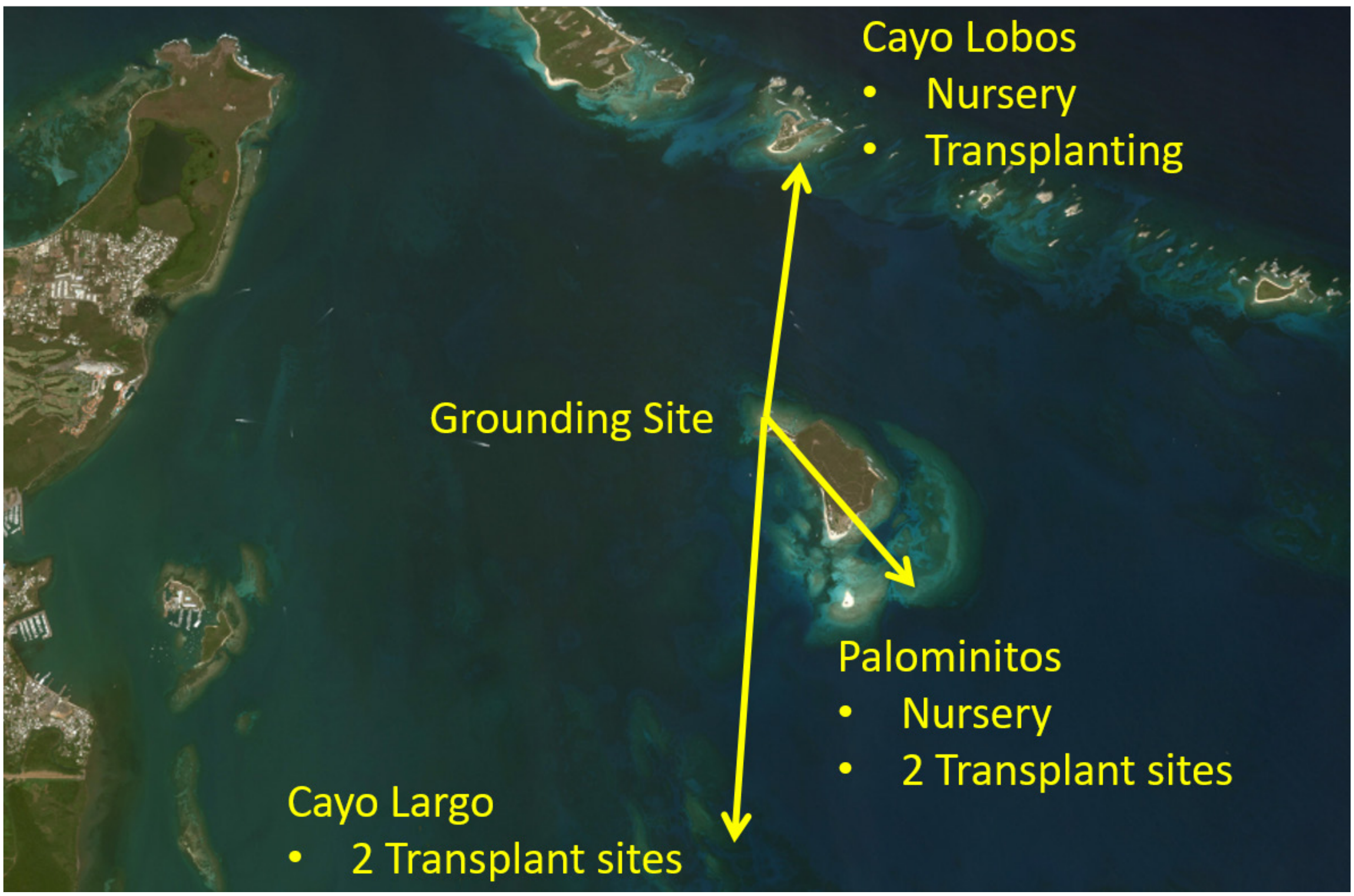

Figure 50. Map depicting where coral fragments were relocated following the M/V Noemi grounding on Palomino Island.

CHAPTER FOUR

Nursery Maintenance

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Maintaining the corals housed within a nursery as well as the nursery structures is a critical aspect of restoration programs. Poor nursery maintenance and management can lead to two challenges: a decline in overall coral condition, and a breakdown in the integrity of the structures. Nursery corals require maintenance such as pruning, disease mitigation, and predator removal.

Biofouling in nurseries can be a cause of reduced productivity through stress caused by direct contact, abrasion, chemical interaction, stinging, and shading. These can impact survivorship, growth rates, and even coral growth morphologies. The more common biofouling organisms include:

- Barnacles
- Bivalves
- Bryozoans
- Cyanobacteria
- Fire coral
- Hydroids
- Macroalgae
- Sponges
- Tunicates
- Viatrix anemones

Other organisms such as tubeworms, crustose coralline algae, and other hard and soft corals can impact the health of nursery corals. Additionally, these biofouling organisms also add weight to nursery structures and impact their functionality and longevity.

Maintenance in the nursery is important for many reasons. Coral competitors such as algae and encrusting sponges can overgrow nursery colonies, smothering them and/or making them more susceptible to disease (Nugues et al., 2004; Smith et al., 2006). Coral predators can also spread disease and create lesions on the nursery corals that affect their overall health (Sussman et al., 2003; Williams and Miller, 2005; Miller et al., 2014a; Bright et al., 2015). Many of the things that can impact coral health in the nursery setting can be mitigated if caught within a reasonable timeframe.

Frequency

Routine nursery maintenance is time-consuming but a very necessary part of coral restoration. Nursery maintenance and observation are critical during the first month following the initial introduction of colonies to reduce structure failure and colony loss. Depending on the size of the nursery, type of nursery structures, seasonal algal blooms, and location-specific overgrowth, maintenance trips to the nursery should be scheduled accordingly, and this portion of the work should be factored into budgeting, staffing, and time commitment from the beginning of a project. First-year nursery operators should plan to visit their nursery weekly during the first month post-installation, then monthly for the first year to determine seasonal changes at the nursery site. Following the first year, practitioners should be able to determine the frequency appropriate to their location. However, the more time and resources spent cleaning the nursery, the less is spent on planting and maintaining corals. Cleaning should be built into a program and is a simple activity that could be completed by volunteers. Below we recommend some practices that will help to reduce the amount of time spent cleaning the nursery. Some more details on cleaning protocols and procedures can be found in Shafir et al. (2006a); Shafir and Rinkevich (2008); Edwards (2010); Frias-Torres et al. (2018).

Coral Disease, Predation, Competition and Bleaching

The condition of a coral is affected by environmental conditions, disease, physical impacts, and/or predation by motile organisms. Therefore, by obtaining data on the occurrence of negative interaction within the nursery, targeted preventative maintenance and management can be incorporated into a program's restoration plan.

Coral disease is any harmful deviation from the normal structural or functional state of an organism, generally associated with certain signs and symptoms that do not result from a physical injury (Britannica); it can be caused by bacteria, fungi, viruses, protozoa, or stress, resulting in loss of tissue, reduced growth rates, and/or reduced reproductive abilities. Disease can be observed as a distinct band, jagged edge, or focal, multifocal, linear, and/or diffuse lesion often associated with tissue loss (Figure 51), although not in the case of dark spot disease. Up to 30 coral diseases have been reported on reefs; however, the causal agent or the mechanisms for transmission for a majority have not been fully identified (Harvell et al., 2004; Rosenberg and Loya, 2004; Muller and van Woesik, 2012; Maynard et al., 2015).

Coral predators, which typically include corallivorous snails, worms, crown of thorns, and fish, can have detrimental impacts on corals if not managed (Miller, 2001; Miller et al., 2002; Shafir et al., 2006a; Shantz et al., 2011; Johnston and Miller, 2014; Miller et al., 2014a; Bright et al., 2015; Goergen and Gilliam, 2018). Wounds from predation (Figure 52) can include tissue-denuded branch tips (fireworm predation), scalloped tissue-loss-margin (snail predation), scraping/loss of corallites (fish and urchin predation), and algal garden chimney (fish predation).

Figure 51. Example of coral disease on *Acropora cervicornis* nursery corals.

Figure 52. Examples of predation by fireworms and snails on nursery corals.

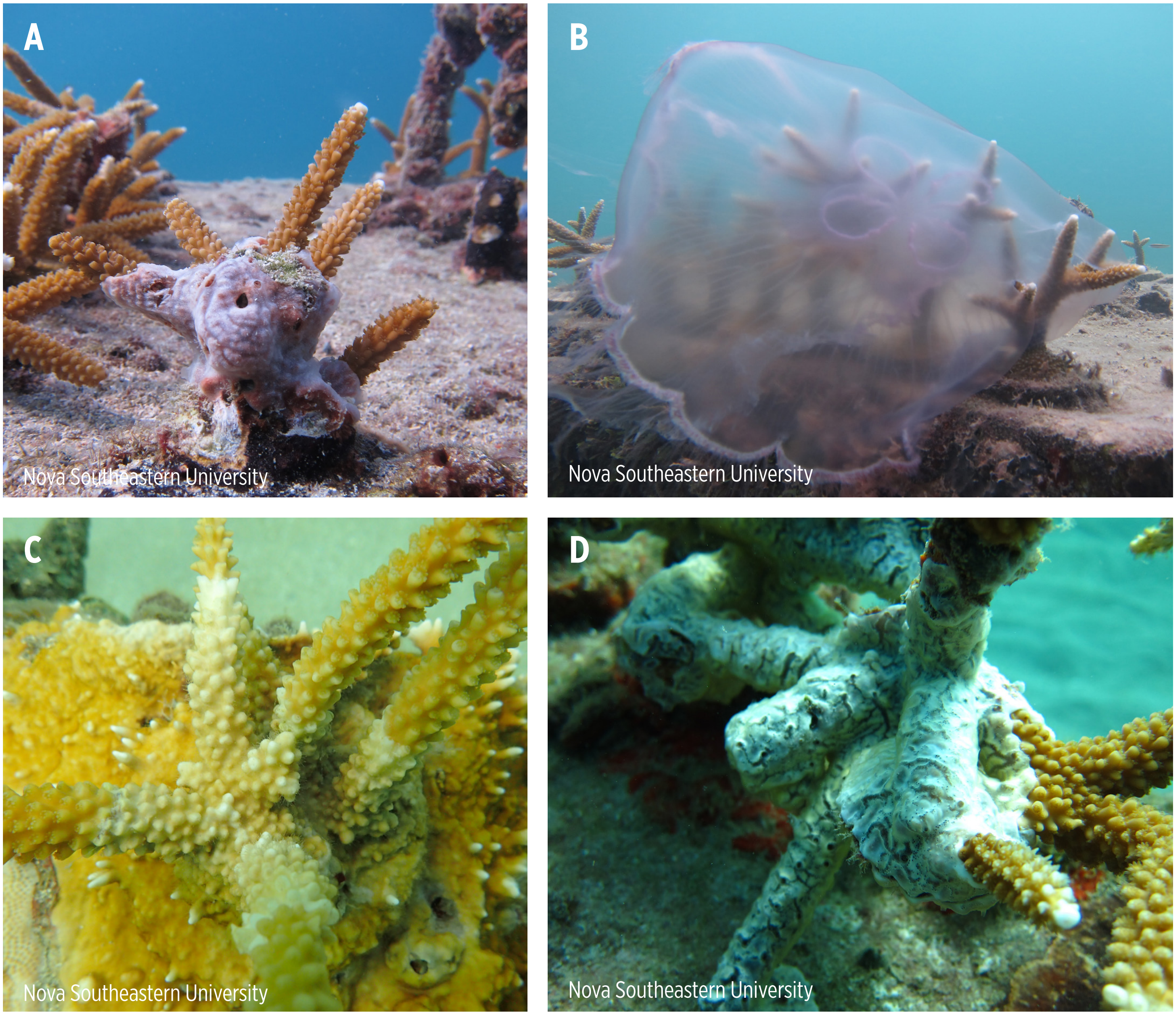

Figure 53. Examples of competitive interactions by sponges (A), jellyfish (B), fire coral (C), and encrusting tunicates (D).

Competitive interactions with algae, hydroids, matting tunicates, jellyfish, and sponges can all result in coral tissue loss (Figure 53).

Coral bleaching may be observed during periods of elevated temperature (Figure 54). Prior to bleaching, corals may become partially bleached or pale, which can be used as a sign that management strategies, such as lowering floating nurseries to cooler water, should be deployed (Figure 55). Coral bleaching reports can be separated as partial bleaching and bleaching (entire colonies bleached). Paling is not considered bleaching but may be an indicator that bleaching may occur in the future.

The presence/absence and prevalence of these signs or the major conditions observed in the nursery should be recorded. By obtaining data on the occurrence of negative interaction within the nursery, targeted preventative maintenance and management can be incorporated into a program's restoration plan. Guidance on data collection methods, monitoring frequency, reporting, and performance criteria are found in Chapter 5: Nursery Monitoring.

Maintenance of Corals

Nursery corals require the following maintenance considerations:

Keep stock manageable — Understanding nursery stock needs can be complicated, particularly for programs with variable funding levels and project goals. There is a fine line between creating too many colonies to handle and letting corals get overgrown by not fragmenting them for extended periods. Some programs maintain broodstock on all nursery structures and outplant fragments from those each year; others outplant from certain structures and restock them from other structures. Learning to manage stock for certain goals may take a few seasons of learning.

Clip corals frequently — Pruning vigor has been shown to have a positive effect on tissue production (Lirman et al., 2014a; Lohr et al., 2015).

Do not overcrowd corals in production — Overcrowding of colonies can lead to breakage and abrasion, creating a place for coral predators and competitors to hide. Give corals room to grow.

Remove dead tissue — Dead and diseased tissue should be removed quickly to avoid impacts to the remaining healthy tissue. Algae will quickly settle on the dead portion of a colony and can start to impact the neighboring healthy tissue. Dead skeleton also adds both weight and drag to the structure. When removing active disease, remove the entire impacted colony or remove the impacted area, leaving a buffer of seemingly unaffected tissue.

Remove predators — Predators such as snails and fireworms may move into the nursery once it is stocked with corals. It is important to relocate these predators from the nursery, and/or remove them from the ecosystem if permitted. Look in the nooks and crannies, between colonies, under blocks, on buoys, etc. With frequent predator removal, many problems can be avoided. However, be aware that there are good coral-associated organisms, such as the coral commensal crabs *Trapezia* spp., which defend corals from some predators (Stier et al., 2010; Rouzé et al., 2014).

Slower growing species — Species such as massive corals, require more attention as they do not outgrow the algae that settle on the attachment materials, such as monofilament lines, which may cause stress and mortality.

Maintenance of Nursery Structures

Maintenance of nursery structures involves both removal of algae and other biofouling organisms and maintenance of the actual structure to ensure that any weak points (e.g., frayed lines, hole-ridden buoys, corroded anchors) are replaced quickly. For additional guidance, see tips in Edwards (2010); Johnson et al. (2011); Frias-Torres et al. (2018).

Figure 54. Example of coral bleaching.

Remove (bio)fouling. — Competitors — algae, encrusting sponges, fire coral, trash, sargassum, etc. — should be removed from corals and the structures that hold them. This cleaning should start closest to the coral and move out from there as time allows, which ensures that the material touching the coral is prioritized and remains the cleanest. Fire coral on structures is not necessarily a bad thing because it prevents algal growth, but it should be removed from the monofilament or any structure that touches coral.

Structures can be cleaned using chisels, brushes (both wire and plastic), hammers, scrub pads, a pick or awl (for cleaning out holes that have been fouled over), and gloves.

Check nursery structures for integrity. — Frequent maintenance helps to keep nursery structures intact and functioning as intended. All nursery structures should be checked for fraying lines, broken buoys, brittle or failed cable ties, corrosion on anchors, and/or metal parts, cracks, or weak epoxy.

Floating structures should always be checked for buoyancy by pulling down on the structure after biofouling organisms have been cleaned from the structure and buoys. If it can easily be pulled down and hangs in the water column before rising, buoys should either be added or existing ones replaced.

If a structure is not being used or will not be used in the coming months, remove it from the nursery. — This is a good time to perform maintenance on the structure and reduce unnecessary wear-and-tear that the structure would endure while being in the water.

Cleaning and maintenance dates should be reported in a program-specific database; tracking these details over time will create a timeline of when structure failures specific to the program may occur, which can assist with preventative maintenance.

Minimizing Surface Area for Fouling Settlement Through Structure Design

Fouling organisms require structure for settlement, so by reducing the structure to coral tissue ratio, the ability for fouling organisms to settle is reduced. For example, on a Coral Tree™, the attachment for the coral is a drop-line, which is arguably the least amount of structure possible to support a coral. This design helps limit the ability of fouling organisms to settle close to the coral tissue. It is important to always cut loose ends of line, wire, and cable ties,

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especially where they are close to the coral, to minimize space for algae to grow and interact with the corals.

It is easier to clean a smooth surface than a rough or porous one. Some fouling organisms, such as hydroids and macroalgae, do not adhere well to smooth surfaces like monofilament, plastic, or metal, making these materials easier to clean. However, knots, gouges, holes, and joints are prime settlement and attachment points for fouling organisms and will require more time for maintenance.

Use of Antifoulants

Some antifouling methods have been used, although not widely, to help mitigate the impacts of fouling in the nursery setting and are described below. Some antifoulants can be environmental toxicants, so we encourage the use of non-toxic methods that are less environmentally invasive for addressing biofouling. Further research is required for all of the methods below, such as the effect on coral reproduction, recruitment, and development, and environmental impacts; therefore, caution should be taken before deploying at large scale.

Copper — Copper (including brass and bronze) is an effective biocide, relatively inexpensive, and readily available as wire. It will kill coral tissue where contact is made, but a nursery structure could be made of copper, brass, or bronze rods/tubing if it does not contact coral tissue directly. Alternatively, a lighter, less costly structure could be wrapped in wire to achieve a similar outcome. However, besides direct contact mortality, copper has been shown to cause coral physiological impairment, symbiont photosynthesis impairment, bleaching, reduced growth, and DNA damage and can negatively affect coral fertilization, larval development, larval swimming behavior, metamorphosis, and larval survival (Rumbold and Snedaker, 1997; Bielmyer et al., 2010; Negri and Hoogenboom, 2011; Kwok and Ang, 2013; Schwarz et al., 2013; Puisay et al., 2015; Reichelt-Brushett and Hudspith, 2016).

Anti-fouling Paint — Anti-fouling paints are widely used on boats because they are effective. These treatments tend to be an ablative mixture of a water-reactive paint and a powdered metal (toxin, usually zinc or copper), with the material cost and strength of the antifouling properties relating to the type and amount of powder. However, some of the ingredients in antifoulant paints can adversely affect corals. Tributyltin (TBT), an active ingredient in some antifoulant paints, has been shown to have negative effects on gamete fertilization, larval metamorphosis, settlement, calcification, juvenile growth, and symbiont concentration (Allemand et al., 1998; Negri and Heyward, 2001; Negri et al., 2002; Watanabe et al., 2006; Watanabe et al., 2007; Bao et al., 2011). Irgarol 1051, a booster biocide in copper-based antifouling paints, has been shown to affect coral symbiont density, photosynthesis and coral settlement (Jones and Kerswell, 2003; Owen et al., 2003; Knutson et al., 2011). Ishibashi et al. (2021) found that Irgarol 1051 has the ability to change coral coloration and disrupt the expression of some coral genes. Shafir et al. (2009) found that Aqua-guard M250 was not toxic to corals if they were more than 2 cm away from the applied paint, and where the paint was used, fouling coverage was reduced by 90%. However, the environmental effects of booster biocides found in antifoulant paints remain poorly understood, have the ability to affect primary producers, including coral zooxanthellae, and can remain persistent in the marine environment (Price and Readman, 2013).

> Antifouling paint trials in Discovery Bay Marine Lab and UWI Mona, Jamaica, circa 2007 (Rachel D’Silva, personal communication) showed immediate reduction in cleaning needed and improvement in fragment health; however, losses were suffered with accelerated decomposition of the galvanized steel nursery trays painted with copper-based paint. In order to avoid this reaction, use such paint on plastic, fiberglass, and other non-metal structures.

Low-resistance Coatings — Coatings such as Teflon make the submerged surface so slippery that fouling organisms are easily removed through waves or minimal grazing or brushing. These coatings tend to be used for racing vessels and military applications, so they are often expensive.

Greases — Greases such as silicone grease, paraffin, petroleum jelly, shea butter, wax, and lithium grease (for short periods, may be toxic) could work to reduce fouling, but are messy to apply and will need occasional replacement. Their effectiveness may be enhanced by adding powdered cayenne pepper (Manov et al., 2003).

Maricultural Recruitment-hindering Paints — Some paints are purported to be nontoxic and food-safe, water-based for easy use and cleanup relative to traditional metallic antifoulants. They do not work with chemical toxicities per se, but catalyze a reaction between sunlight and water to form a boundary microlayer of hydrogen peroxide (H_2O_2) that inhibits initial settlement/recruitment, and maintain an ablative quality for sloughing with either water motion or light brushing. In trials, it has made a particular impact on reducing hydroid recruitment to lines and structures, though established hydroids may send tendrils over the paint; coral will also overgrow the paint. Various tubeworms and bryophytes also are able to colonize the paint, atop which other organisms become established. Informal trials suggest a 75% reduction in cleaning investment over raw glass, galvanized steel, nylon, HDPE, and PVC, likely with related improvements in coral production (Andrew Ross, Seascape Caribbean, 2020, personal observation).

Special Circumstances

Beyond routine, general maintenance, there are seasonal tasks that are recommended during potentially stressful times of the year.

Storm Season

In locations prone to hurricanes, typhoons, or other strong storms, nursery managers should pay particular attention to certain tasks in the lead-up to storm season. Following a number of devastating storms in Florida, nursery managers all indicated that hurricane preparations should not be left until a storm is forming, but that they should be done year-round or at least at the beginning of the season each year. Storm preparation tasks include:

1. Double up on anchors and/or anchor lines on floating structures.
2. Pull lines on floating structures so they have less room to move and interact with other structures.
3. Ensure that all floating structures have sufficient flotation.
4. Check all lines and connections for fraying or corrosion. Replace as needed.
5. Secure any blocks to the sea floor, preferably with more than one anchor and more than one cable tie.
6. Fragment or outplant large corals, particularly on floating structures, to minimize abrasion and breakage caused by corals swinging into each other.
7. Check for loose corals and bases, and stabilize them with additional epoxy/adhesive.
8. Secure (or remove, if possible) spare and unused nursery structures, rebar stakes, pucks, and pedestals that are scattered throughout the nursery so they do not become projectiles.
9. For added strength on rebar tables, add support braces by driving additional legs into the substrate at a 45° angle, and attach them to the rebar table leg and/or set anchor guy-lines.


Reef Ecologic

10. Scan the immediate surroundings, and either secure or remove any flotsam that may be mobilized by waves and currents. Such material may include ghost fishing gear, ropes, plastic bags, and even large reef rubble.
11. If the nursery is sited at a depth where structures can be safely lowered to a deeper depth, this may also be an option for your program (Frias-Torres et al., 2018). Be aware that structures too close to the bottom during a storm can also cause damage.
12. There is also the option of moving the nursery to a safer location; however, this requires certain structures, prior permitting approval, and careful planning (Frias-Torres et al., 2018).

For more information, see the CRC Webinar “Building Restoration Programs to Withstand Hurricanes: Lessons Learned from Irma and Maria,” available both as the taped webinar and slides.

https://reefresilience.org/building-restoration-programs-to-withstand-hurricanes-lessons-learned-from-irma-and-maria/

http://reefresilience.org/wp-content/uploads/Hurricane-and-Restoration-Lessons-Learned-Webinar.pdf

Disease Outbreaks

A severe disease outbreak in a nursery setting can have devastating impacts on stock, so any outbreaks should be managed quickly and frequently. Disease can be managed in a few ways within a nursery. First, corals displaying signs of disease can be moved to a quarantine area far from the other healthy corals until the disease is clearly not active anymore. Second, the diseased tissue can be cut out, leaving a margin of live seemingly healthy tissue on the portion that was removed to increase the likelihood that the entire disease margin is removed. Finally, epoxy or raw copper wire can be used to form a band at the disease margin around/over seemingly healthy tissue to prevent the disease from spreading along the colony. When using any of these techniques, corals should be closely monitored over time to make sure the disease is not spreading and to keep a record of susceptibility to disease for each genotype.

Bleaching and/or Thermoclines

In the event of a severe bleaching event or thermocline, floating structures should be adjusted in the water column, where possible, to avoid significant temperature swings. In the summer, floating structures should be secured closer to the bottom in cooler water; in the winter, they could be extended higher than usual to keep corals in the warmer surface water (Figure 55). Small-scale shading during summer bleaching events could be possible in certain circumstances, as well. A close record of paling and bleaching should be kept as a record of susceptibility of each genotype. Additionally, manipulation (moving, fragmenting, outplanting) of corals should be minimized as much as possible while they are bleaching to avoid any additional stress. For more information, see the CRC's Webinar "Coping with the 2023 Coral Bleaching Event", available as a taped webinar at https://www.crc.world/video-library.


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Figure 55. Coral trees can be raised (left) or lowered (right) in the water column to reduce thermal stress.

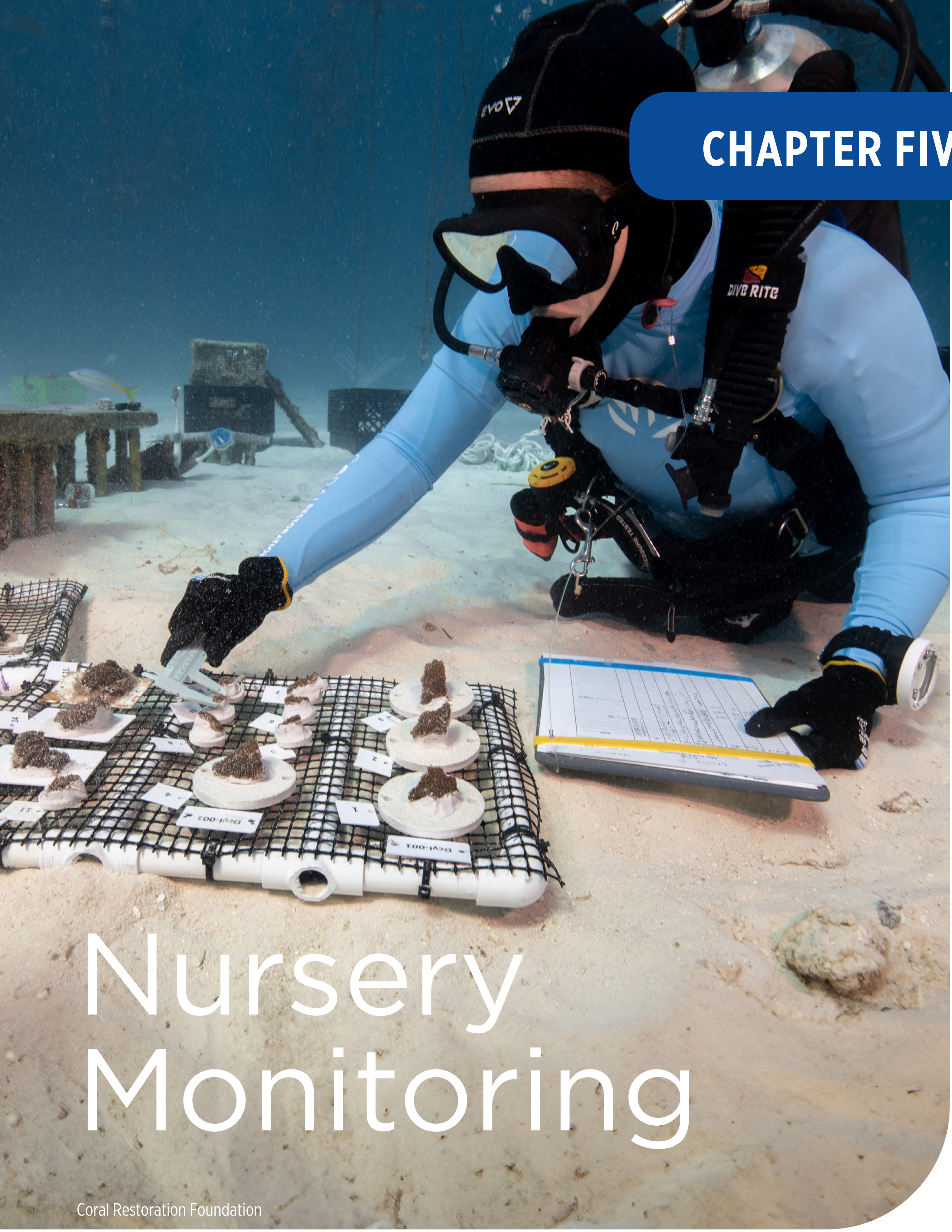

University of Guam Marine Lab

Fishing/Tourist Areas

Nurseries in close proximity to fishing and tourist areas may require more frequent maintenance or visits to check for impacts (anchor drags and fishing traps) and debris (fishing line and nets and trash). This could be an opportunity for partnerships and collaboration with stakeholders who are able to report on disturbances or issues that need addressing. For example, tourism operators in the Whitsundays region of the Great Barrier Reef have been instrumental in providing rapid notification of dislodged floats, degraded coral nursery ropes, and bleaching, enabling researchers to respond sooner than scheduled maintenance trips (Nathan Cook, Reef Ecologic, 2021 personal communication). This may be particularly true after storms as debris tends to move and aggregate during storms, and nursery structures may be entangled in a way that the damage continues over time.

CHAPTER FIVE

Nursery Monitoring



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Monitoring corals during the nursery and outplanting stages allows practitioners, scientists, and managers to assess how a project or program is doing relative to other well-established and successful coral restoration programs. Schopmeyer et al. (2017) compared success rates between restoration programs and proposed a stoplight framework for evaluating overall restoration program success. As programs develop in new regions, benchmarks should be developed that represent success according to local conditions.

In order to make it easy to monitor, report, and analyze data, the CRC has developed several tools (monitoring guide, restoration database, and evaluation tool) that work together and are available for free at crc.world. These products have continuity in the reporting and evaluation; for example, each universal monitoring metric identified in the monitoring guide is represented in the CRC Coral Restoration Database, and the Evaluation Tool (Lirman et al. 2017; Schopmeyer et al., 2024) connects these data collections to programmatic success. **The continuity between these products makes for straightforward data reporting, program evaluation and comparison, and data sharing and collaboration.**

The metrics outlined below provide a standardized framework for the collection of coral nursery data that together evaluate the success of nursery management over time within a program or between programs. For monitoring of coral restoration (outplant) sites, see the CRC Coral Reef Restoration Monitoring Guide (Goergen et al., 2020). For each metric, we provide the following guidance for data collection: a rationale, definition of terms, diagrams, suggested methods, reporting, sampling frequency, and alignment to Evaluation Tool performance criteria.

The **Evaluation Tool for Coral Restoration** (Lirman et al. 2017; Schopmeyer et al., 2024) provides metrics of success for evaluating existing and new restoration projects or programs to assess performance and progress toward restoration goals. Metrics provided within this evaluation tool are designed to evaluate the strength and robustness of each project or program while also identifying specific metrics that may require adaptive management to improve performance. Projects are scored a 1 for achieving the criteria and a 0 for not meeting the presented criteria; the sum of scores can then be evaluated within a program (different nursery and/or restoration sites) or between programs (different regions or techniques; Appendix 3). The evaluation tool is referenced throughout this Guide and aligned within this chapter to specific monitoring techniques and objectives. A few of the criteria presented in the evaluation tool do not require additional monitoring or techniques, but simply suggest that best practices


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and guides are followed in the establishment of the restoration program (see below). This is a voluntary evaluation tool, but highly recommended in order to identify areas of improvement for each program and the restoration community.

Monitoring of corals should occur within one month after placement into a nursery to evaluate the success of methods used, colony survival, and structure security, or sooner if new corals are introduced during a time of stress (e.g., elevated temperatures, disease events, etc.). It is suggested that subsequent monitoring should occur at least once per year to evaluate general coral health and survivorship. However, the length of time between nursery visits should be evaluated within the first year of a nursery program. For example, it is important to understand what seasonal changes — such as periods of increased algae, disease, predation, or jellyfish — may occur in the nursery that would warrant more frequent nursery visits during that time for cleaning and preventative maintenance. More frequent monitoring (quarterly or biannually) may be performed based on individual nursery priorities and budgets. In addition, diligent labeling and/or mapping of corals in each of these phases allows practitioners to track individual genotypes and assess their success in nurseries.

The goals of the program will dictate what data should be collected. However, no matter the goals, a successful nursery program will collect data on the following, especially during the first few years:

- Colony survival (dead, alive, or missing)
- Presence of corallivorous predators
- Presence of partial mortality, breakage, disease, bleaching, and predation
- Colony, lineage, or genet growth rates, including morphology/branching (productivity)

Nursery establishment, maintenance, and management are the three most important criteria that will influence the success of a restoration program. Methods for evaluating each of these metrics have been laid out in detail throughout this document and are referenced within each metric along with the respective evaluation tool criteria.

Evaluation Tool Criteria Alignment: Nursery is established based on best-known methodologies (Chapters 2 and 3); if methods follow published guidance for site selection and deployment, a program will receive a score of 1 (Evaluation Tool Nursery Metric #1).

Evaluation Tool Criteria Alignment: Nursery visits/maintenance are conducted frequently [Chapter 4; minimum quarterly and immediately following stress/disturbance events (disease, bleaching, storms), etc.]; if regular nursery visits/maintenance occurs, a project receives a score of 1 (Evaluation Tool Nursery Metric #15).

Nursery Management Metrics

The following Nursery Management Metrics for coral reef restoration were designed to collect informative, comparable data at all scales of restoration. Three metrics — Nursery Size, Nursery Coral Census, and Genetic and Genotypic Diversity — were designed to be collected at every coral nursery to provide a snapshot of the current condition and status of the nursery. These metrics should be considered a minimum nursery data collection requirement; additional data should be collected according to the program's goals and objectives or following stress events. Similar metrics were also developed for restoration (outplant) sites and can be found on the CRC webpage (Goergen et al., 2020).

Nursery Management Metric #1: Nursery Size

The most important components of nursery management are organization and knowing the program's size and capacity. Once a program is well established, it can be easy for a nursery to become very large and for a practitioner to lose count of what they have or to lose the ability to manage the amount of stock within the nursery. To properly create and manage a successful program, an up-to-date and accurate survey of the nursery area and census of a program's nursery structures (abundance and establishment date) can help the program to 1) evaluate the amount of space (on structures and within the nursery area) available for expansion, 2) determine the time needed for maintenance and data collection, 3) know when structure parts need to be replaced, and 4) easily report out for permit reports and/or other deliverables. This metric is valuable as it provides guidance for reporting standardized sizes and areas of a nursery site. By collecting these data in a standardized way, practitioners, managers, and scientists can compare and evaluate nursery size and production potential. There are three components to this metric: Nursery Area, Structure Footprint, and Structure Census.

In some jurisdictions, defining a program's Nursery Area is beneficial for obtaining a permit, permit reporting, and defining boundaries for the protection of the nursery. The Nursery Area is a rough boundary that includes all nursery structures, or the area permitted to place nursery structures (Figure 56). It is in the program's best interest to reserve a portion of the nursery area for future expansion and/or emergency use following a disease event or storm damage.

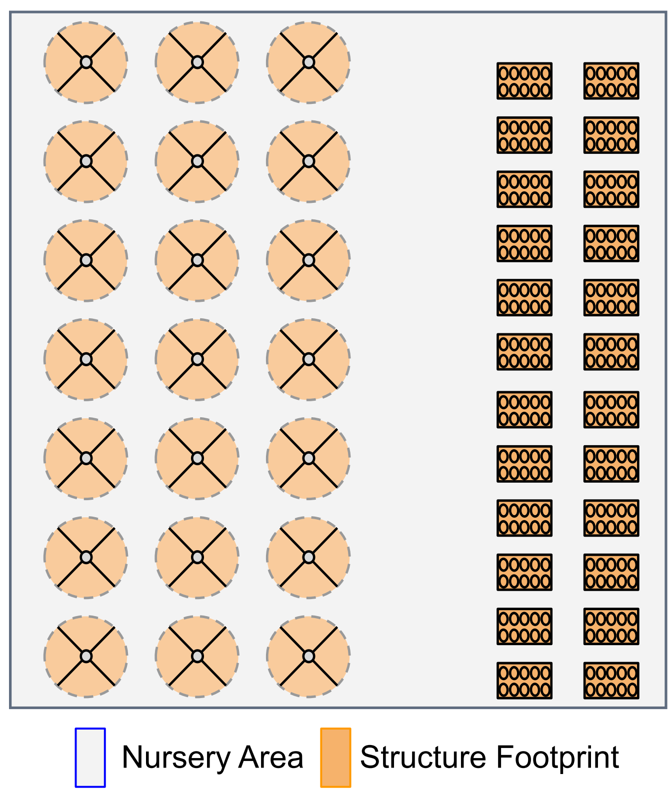

Figure 56. Schematic for determining the area of a nursery.

Structure Footprint is the approximate area that a structure covers from an aerial view. Structures that can spin on a central axis, such as a tree, are to be represented as a circle, with the diameter being its greatest branch length (Figure 57). The measurements taken here will define the approximate surface area of the seafloor (shadow) occupied by a nursery structure. While floating structures move with water flow creating a footprint larger than what is measured here, these movements are difficult to measure and may be unpredictable or seasonal; therefore, this simplified method was chosen for easy data collection and comparison among practitioners.

A Structure Census is a total count of nursery structures by structure type and size. Examples of structure types are defined in Chapter 2. An individual structure is defined by one continuous structure, which may have multiple anchor points or buoys. As a program grows or shrinks, the number of structures could change. If a structure is not being used or will not be used in the coming months, it should be removed from the nursery to complete maintenance and avoid unnecessary structure wear.

When a structure is deployed into the nursery, the **Date of Deployment** should be recorded. This date will inform managers how long a structure has been in the water and when maintenance, such as replacing anchor lines, buoys or cable ties, should be completed (see Chapter 4 for maintenance timeline suggestions).

Required Units: Net area (m²) for Nursery Area and Structure Footprint; number of structures by type and size.

Possible Methods:

Divers or snorkelers will count each of the structures in each nursery area and report them by structure type. During each survey, an evaluation of the structure's components should also be completed following the advice presented in Chapter 4 Nursery Maintenance. Completing the Structure Census will help define nursery area, as the surveyor will know the location of all structures.

The following methods could be used to collect both the Structure Footprint and the Nursery Area. These suggestions are not exhaustive but simply provide examples.

Maximum length and width

Using a flexible survey tape, divers or snorkelers will measure the greatest length and width of the nursery structure and/or area where nursery structures are located. Structure measurement could also be recorded prior to installation of the structure at the nursery.

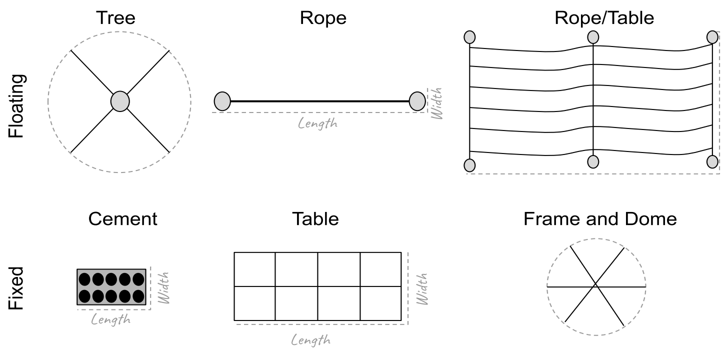

Figure 57. Schematic of structure types for defining structure footprint; Tree and Frame should be calculated as a circle.

In situ tracing

Utilizing a handheld GPS, a surface swimmer (snorkeler or diver) traces the boundary of the nursery (**Nursery Area**) by marking waypoints at the corners or along a polygon surrounding the outer boundary of the nursery structures. Collected waypoints can then be exported into geographic information mapping software such as ArcGIS, QGIS, or Google Earth to create a polygon in which all the structures are located, and the nursery area can be calculated. If nursery structures are large, this method could also be used to trace individual nursery structures (Structure Footprint), or it could be used to mark waypoints over the center of each nursery structure and then estimate the length and width of the structure.

Mapping Software

Aerial imagery captured via drone, plane, satellite, or similar device can be processed using software such as Google Earth, ArcGIS, or QGIS to define Nursery Areal Dimension. The perimeter of the nursery area can be traced to create a polygon from which the area can be calculated.

Reporting:

Structure Footprint and Nursery Area should each be reported as cumulative area (m²) per Nursery site (i.e., all structure footprint areas are summed). The number of structures per type should be reported per nursery. Structure maintenance (when a structure is cleaned and when parts are replaced) should be reported in a program specific database; tracking these details over time will create a timeline of when structure failures may occur to assist with preventative maintenance. Collected data should be reported in program specific databases, as well as uploaded into the CRC Coral Restoration Database (https://www.crc.world/restoration-monitoring).

Sampling Frequency:

Nursery areal dimension should be taken during the establishment of a nursery and any time the structure footprint or nursery area changes substantially (addition or removal of nursery structures). A census of nursery structures should be completed during the establishment of each nursery and continually updated as structures are added or removed. A census prior to and just after storm season is also suggested. Pre-storm, all structures and corals should be checked for stability and integrity. As soon as safely possible following a storm, all structures should be assessed and repaired, if needed (See Chapter 4 for additional guidance).

Performance Criteria:

The Nursery Size metric is used as a management tool to document change in size. Collecting data similarly among practitioners allows for the opportunity to compare program sizes. This metric is not to be used to compare the success of a program, but may be used to look at change of a nursery size over time and assess a program's potential productivity.

Evaluation Tool Criteria Alignment: Nursery Management Metric #1 aligns with two criteria:

1) Nursery Area (dimensions) and Structure Census (#) are available; if the number of structures is recorded, a project will receive a score of 1 (Evaluation Tool Nursery Metric #16).
2) Nursery can be easily expanded/reduced if needed; additional propagation platforms can be installed or removed as needed. If this goal is met, a program will receive a score of 1 (Evaluation Tool Nursery Metric #17).

Further descriptions and supporting research of the Evaluation Tool Criteria can be found in Appendix 3.

Nursery Management Metric #2: Nursery Coral Census

A Nursery Coral Census will estimate the abundance of corals within the nursery, which helps to plan for nursery expansion or outplanting. Nursery coral abundance should be reported by genotype and species. If genetic analysis has not been conducted, it should be made clear that genotypes are assumed and not confirmed. Change in abundance over time can indicate coral survival and health; however, these rates can be influenced by nursery expansion or outplanting and should be considered prior to reporting on this metric.

A **Nursery Coral** is defined as one continuous skeletal unit, which has any live tissue. For a nursery, generally there is one nursery coral per mounting unit: puck, monofilament line, cable, split in twisted line, etc. Isolated tissue areas (isolates) on one skeletal unit are considered part of one coral as long as the skeleton is continuous between the living tissue areas. For the purposes of this metric, a nursery coral with **any living tissue** is considered alive.

Normal operations of the nursery require manipulations of corals such as fragmentation, movement, and removal/outplanting. These operations can happen at any time throughout the year, which can cause major fluctuations in the total number of nursery corals, making an estimate of nursery coral survival difficult. To make these estimates as representative as possible, it is important to track important data for nursery corals including, at a minimum, date established, genotype, and location in the nursery. These three data points will provide, at any given time, the total number of corals per genotype and where they are in the nursery.

This metric does not take into consideration the size or health of a colony, such that a 10 cm coral is represented the same as a 100 cm coral in the database. This method was chosen to reduce the required time spent on data collection and to minimize possible differences between data collectors estimating colony size and partial mortality, but still obtain consistent, comparable, and useful data on the abundance of corals within each nursery program. Further, each restoration program will likely have its own efficient way of determining the biomass of a colony to suit the needs of their program; if not, review Metric #2.2 for suggestions. During the first few years of a nursery, more detailed survival measurements — such as percent mortality, disease susceptibility, and bleaching prevalence — should be collected on nursery corals to indicate site, species, and genotype successes or failures.

Required Units: Total abundance of corals per genotype per species in nursery; percent survival (%) per genotype per species in nursery.

Possible Methods:

The following are methods that could be used to complete a nursery coral census. These suggestions are provided as examples or guidance and are not an exhaustive list. It is important to identify the method used by the program when reporting data.

In situ Coral Count

Divers or snorkelers will evaluate the total number of colonies in the nursery or in a portion of the nursery (see sub-sampling below). This can be done by counting all the living colonies, or if

Figure 58. Example of a nursery image taken at a poor angle (left) versus an image that does not have background obstructions (right). At this angle on the left image, corals on the perpendicular branch are interfering with clearly viewing the corals in front and making it difficult to determine what corals are present and alive.

the structures are kept to near capacity (i.e., 100 of the 100 spaces on a coral tree are occupied by a coral), empty spaces can be counted for more rapid data collection.

If multiple genotypes or species are occupying the same structure, data collectors must take appropriate precautions to know where each genotype or species are located on the structure to ensure accurate abundance counts per genotype and species are reported. This can be identified in the field or within a practitioner's database, depending on the organization of the program's data.

Image Analysis

Divers or snorkelers will take images to be evaluated ex situ for colony abundance. Images should be taken in a systematic way, ensuring nursery, structure, and colony location can be identified later. Images should be taken to include multiple colonies in one image, but need to be taken at an angle where other corals or the structure are not obstructing the view of the entire coral (Figure 58). Following collection of images, images should be renamed, evaluated for colony abundance, and securely stored for any future analysis or data needs.

Thinking ahead: If images are also going to be used to evaluate growth, special measures must be taken to ensure the images are taken from the same angle and include something in the image of known size, like a scale bar or dive knife, that can be used for calibration.

Sub-Sampling

Depending on the size of the nursery, assessment of all corals may not be feasible or advised due to time constraints. In this scenario, surveys can be conducted on a subset of the corals or structures at each nursery site, or surveys can be rotated throughout the year so that only a portion of the nursery is surveyed during each sampling event. For example, if a nursery is being monitored monthly, divide the nursery into sections and only monitor a few sections per monthly event so that each section is evaluated multiple times per year, but not during every sampling event. If sub-sampling, be sure to appropriately represent all species and genotypes each sampling event. In the case of a significant disturbance event, a full nursery sampling event may be warranted. If monitoring using a subset, it is important to **report that only a portion of the area was surveyed**.

Reporting:

Nursery Coral Census data should be reported as abundance or percent of corals per genotype per species. Estimated survival should only be made using corals that were in the nursery for the entire reporting period. Collected data should be reported in program-specific databases, as well as as well as submitted to the CRC Coral Restoration Database using the forms found at https://www.crc.world/resources.

Abundance is a sum of the total number of corals within the nursery. This value over time will provide an estimate of nursery **survival**. Caution must be taken for reporting survival to account for nursery expansion and outplanting. Survival rates must be reported using the same cohort of corals.

Coral Fusion

Coral fusion is when two or more individual corals of the same species and genotype join together as one and may occur (purposely or haphazardly) in nurseries depending on the species or techniques that are used. Fusion often occurs when micro-fragments are placed in very close proximity to each other in the hopes that they fuse together to create a larger colony (Forsman et al., 2015; Rachmilovitz and Rinkevich, 2017; Page et al., 2018; Figure 59). Once the tissue has fused, the result should be considered one colony (Figure 59 C and F).

Sampling Frequency:

A census of corals should be completed following the establishment of the nursery, semi-annually, and following any major change in the nursery (following an outplanting event, nursery expansion, storm event, disease event, or other damaging event).

Performance Criteria:

A coral nursery should maintain a relatively stable, manageable number of healthy corals. The total number of corals and species in a nursery will depend on the available budget and overall programmatic goals. The census of nursery corals should exhibit minimal net loss of corals unless a major outplanting event occurred or there was a planned reduction (decreasing nursery size, meeting program goals, nursery cleaning). If a program experiences large losses of corals for reasons that were not controlled by the program (predation, disease, storm impacts, human impacts), adaptive management strategies listed below should be considered to improve nursery success.

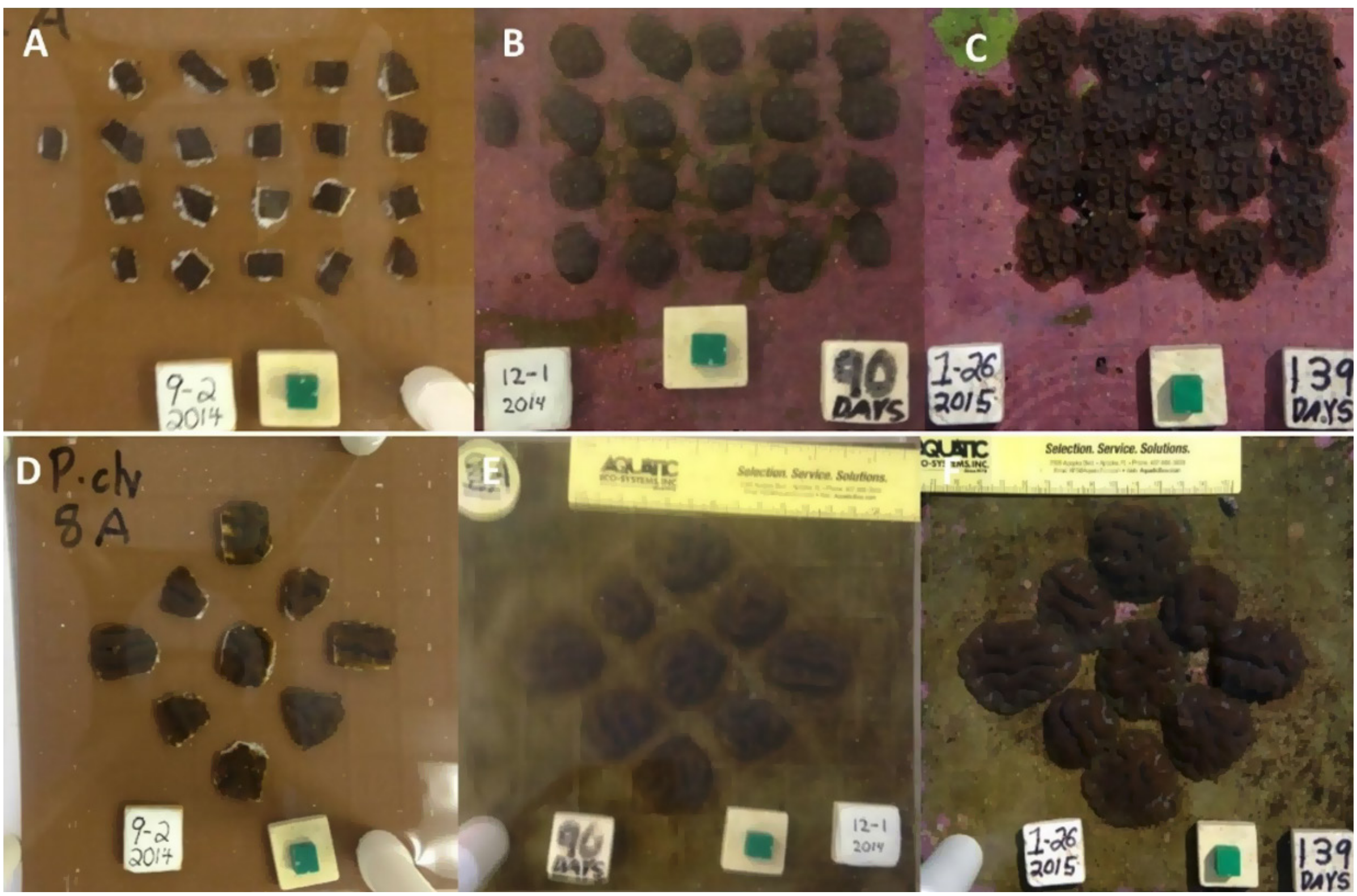

Figure 59. Examples of coral fusion. In A, B, D, and E, we suggest counting each of the corals as individuals, but as they fuse, in C and F, the count would turn to 1 as all the individuals have fused with each other on at least one edge to form one "colony." Figure from Forsman et al., 2015.

Evaluation Tool Criteria Alignment: Nursery Management Metric #2 aligns with three criteria (Appendix 3):

1) A nursery exhibits high coral survivorship per species; if the annual net survival of nursery corals is at least 80% (excludes partial mortality), then a program receives a score of 1 (Evaluation Tool Nursery Metric #8).
2) A nursery contains multiple species; if a nursery contains more than one species, a program receives a score of 1. If a program's goal is single species recovery, this would not be applicable (Evaluation Tool Nursery Metric #3).
3) A nursery program tracks genotype through time (e.g., maps, tags, propagation structure, etc.); if genotype mortality (excludes partial mortality) is tracked within the nursery, a program receives a score of 1 (Evaluation Tool Nursery Metric #7).

Further descriptions and supporting research of the Evaluation Tool Criteria can be found in Appendix 3.

Nursery Management Metric #3: Genetic and Genotypic Diversity

Genotypic Diversity is measured by recording the number of genotypes (genets) and abundance of each (ramets) per species at the nursery. When possible, it is suggested that a minimum of 20 to 25 unique genets per species be hosted in a nursery (Baums et al., 2019). **Replicates of each genotype should be represented at multiple nurseries if the program maintains more than one nursery to prevent the loss of a genotype due to damage at one nursery site (Schopmeyer et al., 2012).**

See Chapter 3: *Coral Collections for additional information and terminology regarding the importance of genetic and genotypic diversity.*

Required Units: Number of genets per species; note the method used to determine coral genotype.

Methods and Reporting:

See Universal Metric #4 Genetic and Genotypic Diversity in Coral Reef Restoration Monitoring Guide (Goergen et al., `2020) for methods for determining diversity and reporting data. Collected data should be reported in program-specific databases, as well as uploaded into the CRC Coral Restoration Database (https://www.crc.world/restoration-monitoring).

Sampling Frequency:

Genetic diversity of the nursery should be recorded immediately following the establishment of the nursery, when new corals/species are added to the nursery, following a large outplanting event, and if a significant mortality event occurs (disease, bleaching, storm, etc.).

Performance Criteria:

Maintain species genetic diversity at 20 to 25 distinct regional genets per species within the nursery.

Evaluation Tool Criteria Alignment: Nursery Management Metric #3 aligns with three criteria:

1) Nursery corals have been genotyped or represent "distinct individuals" based on collection site; if corals have been genotyped or have been collected from colonies at least 100 m apart, a project will receive a score of 1 (Evaluation Tool Nursery Metric #5).
2) Nursery contains a high degree of genotypic diversity (20 to 25 distinct regional "individuals" provide high proportion of standing genetic diversity); if a nursery has at least 20 to 25 genotypes per species, a program will receive a score of 1 (Evaluation Tool Nursery Metric #4).
3) A nursery program tracks genotype provenance (e.g., source location (GPS coordinates of donor), date of collection, depth, number of fragments collected from colony); if corals are tracked, a program will receive a score of 1 (Evaluation Tool Nursery Metric #6).

Further descriptions and supporting research of the Evaluation Tool Criteria can be found in Appendix 3.

Universal Environmental Metric for Coral Nurseries

Coral reefs are sensitive to the environment in which they are found and persist. Important to the existence, conservation, and management of coral reefs is water quality supportive of coral growth and a healthy reef community. While there is a long list of environmental data that would need to be collected to fully understand the effect of water quality on coral restoration, most are out of the scope of many restoration programs, both financially and physically. Therefore, **water temperature** was identified as the universal environmental metric for coral restoration because it is easily obtained, affordable, and comparable across various scales. In addition, water temperature is one of the key environmental metrics that can assist in defining coral growth rates, disease susceptibility, and likelihood of bleaching. Therefore, temperature should also be monitored in coral nurseries.

Methods, Reporting, Frequency, and Performance Criteria:

See Universal Environmental Metric: Water Temperature in Coral Reef Restoration Monitoring Guide (Goergen et al., 2020) for methods for collecting, reporting, and frequency of data collection and metric performance criteria. Collected data should be reported in program-specific databases.

Evaluation Tool Criteria Alignment: This Universal Environmental Metric aligns with one criterion: Environmental parameters (minimum measurement of water temperature required, but may also include light, current, sedimentation, etc.), are measured/monitored; if this goal is met a program will receive a score of 1 (Evaluation Tool Nursery Metric #2). Further descriptions and supporting research of the Evaluation Tool Criteria can be found in Appendix 3.

Nursery Performance Metrics

Nursery performance metrics are designed to evaluate the performance of a nursery program from management to coral production. Without proper management, a restoration program can quickly get out of hand and fail; therefore, we brought together a few key components that should be evaluated to maintain or improve a program's efficiency. Each proposed metric aligns with criteria from the evaluation tool to aid in further project evaluation and adaptive management.

The main objective of any restoration program is to maintain and produce a healthy stock of nursery corals for outplanting in an efficient manner. In order to evaluate the efficiency of a coral nursery, coral survival (Nursery Management Metric #2), growth, and health should be tracked. These data can provide practitioners with the following types of information: 1) how well the nursery is performing, 2) whether some genotypes are more prone to stressors, 3) annual or seasonal differences in survival, growth, and health, and 4) alert if something is going wrong and adaptive management is needed, which can all help improve production performance and inform management decisions.

Nursery Performance Metric #1: Nursery Coral Tissue Production

An estimate of the amount of tissue per nursery coral is necessary when planning for nursery expansion or outplanting and for detailed evaluations of production across seasons, sites, species, and genotypes. These data will help improve program efficiencies. Knowing the performance of a site, species, or genotype can help practitioners make informed decisions about when outplanting should occur or if a nursery should be relocated (low performance). An estimate of coral tissue abundance or biomass should be used to inform outplanting and nursery propagation decisions, such as whether there are: 1) no corals ready for outplanting/pruning, 2) a minimal number of corals ready for outplant/pruning, 3) some corals ready for outplants/pruning, and 4) a large number of corals that need outplanting/pruning. These categories are dynamic throughout a restoration program's tenure and will depend on programmatic factors such as nursery capacity, outplanting goals, time of year, and personnel capacity.

A measurement of coral tissue should be reported for each species per coral or genotype. Reporting the amount of tissue per coral may aid in planning which corals need to be maintained, pruned, or outplanted. By reporting the amount of tissue per genotype, a practitioner will only be able to inform at the genotype level, which may or may not be useful for planning for expansion or outplanting and depends on how the nursery is designed (genotypes grouped vs. randomized across nursery) and maintained. **Coral tissue can be measured in different ways — coral maximum diameter, area, volume, and total linear extension (TLE)**. The pros and cons of each measurement type are detailed below.

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Measurement Types:

Maximum coral diameter defines coral fragment/colony size and should include areas of mainly living tissue and minimal areas of denuded skeleton. If a coral has a lot of partial mortality, multiple estimates of the coral diameter should be taken (Figure 60). These measurements are **meant to be a quick estimate of coral size and do not require precise coral measurements**. Size classes can be used, although depending on the program's goal, more detailed measurements may be included such as TLE, maximum height, number of branches, etc.

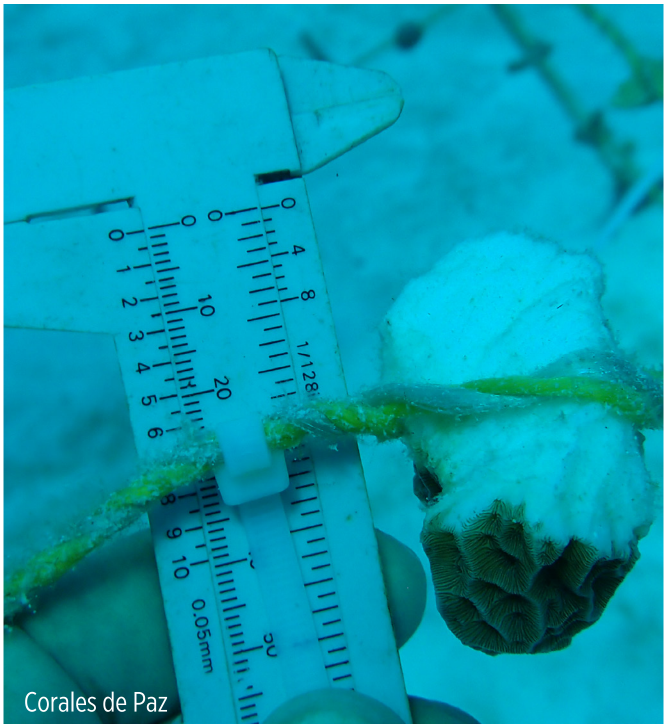
Figure 60. Example of a nursery coral where two measurements of the coral size should be taken because of the amount of mortality separating living tissue areas.

TLE is a detailed method of measurement typically used for branching corals and is a summed measurement of all branches per coral. TLE can be a very time-consuming metric to collect but provides excellent growth and tissue abundance data. However, for *A. cervicornis*, Huntington and Miller (2013) determined that TLE can be approximated from colony length and height (first converted to ellipsoid volume). This approximation can vary by region based on growth rates and should be researched before using as a metric. TLE may also be captured in scaled photographs, though parallax must be accounted for in larger branching corals (Ross, 2012; Goergen and Gilliam, 2018).

Tissue area or volume is a common metric in benthic surveys and can be easily applied to nursery corals. Tissue area is a good representation of tissue abundance for massive corals and can be obtained from the maximum colony diameter if colonies are close to symmetrical and are not tall. If colonies are tall, such as columnar species, colony volume is a better representation of the total tissue. To calculate volume, length and height measurements are necessary, and in some instances, width may be needed.

Possible Methods:

The following methods may be used to estimate the amount of live tissue on a nursery coral. We suggest that measurements such as maximum diameter, tissue area, volume, and TLE be used to describe the total tissue in the nursery. Choosing which measurement to use will be at the discretion of the nursery manager based on their program capacity and experience and program goals. Measurements such as maximum colony diameter or maximum length and height are good for massive coral species, which are uniform in shape, as surface area or volume can be quickly calculated. For branching species, in order to capture the three-dimensionality, additional measurements may need to be reported, such as individual branch measurements, colony length, and height to calculate TLE, or size classes to describe colony size. Below are a few possible methods to use to report the estimation of tissue within the nursery and suggestions for standardizing data collection. These suggestions are provided as examples or guidance and are not an exhaustive list. It is important to identify the method used by a program when reporting data.



In situ Coral Census

Using the same methods as described for abundance (Nursery Management Metric #2), divers or snorkelers can estimate the total tissue for all or a subset of corals within each nursery using a PVC measuring stick, flexible tape, or ruler. An in situ coral count is the most universal method as all measurement types can be collected; however, measurements such as TLE, are more time-consuming. **Therefore, for more efficient data collection, coral tissue could be classified into size classes such as: <5 cm; 5-15; 16-30; 31-50; and >50 cm for colony diameter** (Figure 61). As a note, estimating size classes may not be suitable for volunteers or novice data collectors. As data collectors become more experienced, the use of a measuring device may not be necessary; however, appropriate precautions should be taken to ensure estimates among data collectors are similar and consistent.

To document coral growth, more precise measurements such as TLE, number of branches, exact colony diameter, or maximum height will be necessary. These methods have been thoroughly explained in literature (Yap and Gomez, 1985; Bowden-Kerby, 1997; Soong and Chen, 2003; Johnson et al., 2011; Lirman et al., 2014a; Ross, 2016; Goergen and Gilliam, 2017; Lohr and Patterson, 2017).

Images

To evaluate tissue area from images, divers or snorkelers will take images to be evaluated ex situ for colony size. Images should be taken in a systematic way to ensure that the nursery, structure, and colony location can be identified properly during image analysis. To improve efficiency, images may be taken to include multiple colonies in one image but need to be taken at an angle where other corals or the structure are not obstructing the view of the entire coral (Figure 62). **Images can be used to increase efficiency in the collection of all types of measurements including size classes; however, if using them for very detailed growth measurements, additional steps must be taken**. If the images will be used for precise growth measurements, the images must be consistently taken from the same angle, capturing the same side angle of the colony. Additionally, an object in the image of a known size (e.g., tree branch, ruler, measuring stick) must be used for calibration. For branching corals, multiple images may be necessary to ensure all branches and tissue are measured. Following the collection of images, images should be evaluated using software such as ImageJ, CPCe, or similar image length/area analysis software.

Surveyor:________________ Nursery:____________________

Date:____________________

			Tally in appropriate bin based on maximum coral diameter (cm)					
Structure Name	Species	Geno	<5	5-15	16-30	31-50	>50	Notes
Coral Tree 1	Acerv	2a	////	///	50	//		
Coral Tree 1	Acerv	17						
Coral Tree 1	Acerv	3	/	/////				
FUCA 1	Acerv	2a		75				

Figure 61. Example datasheet for collecting coral tissue data using size classes.

Figure 62. Example images of nursery colonies. The image on the left is an example of a poor angle (overlapping of colonies from other branches). The right image is an example of a good angle where colony size can be estimated using a program such as CPCe; branch diameter of 0.95 cm was used for calibration in this image.

Reporting:

Estimated live coral tissue should be reported as the total tissue per genotype. If using size classes, use the midpoint of each size class bin to calculate total tissue. These data can then be summarized in four ways: 1) total amount of tissue per genotype, 2) total amount of tissue per species, 3) how many corals are available for pruning or outplanting (based on program-defined categories), and 4) biomass remaining following outplanting. By collecting total tissue measurements directly before outplanting, the amount of tissue available for outplanting can be estimated. Estimated size of all outplanted corals should be taken at the time of outplanting, and the difference between these estimates (nursery coral size and outplant colony size) will provide an estimated amount of tissue remaining in the nursery.

Sampling Frequency:

At a minimum, monitoring total live tissue at the nursery should be completed **annually and/or before/after outplanting.** In addition, monitoring after disturbance events (e.g., bleaching, disease, and hurricanes) will provide information on disturbance impacts such as coral loss and colony displacement.

Performance Criteria

Evaluation Tool Criteria Alignment: Nursery Performance Metric #1 aligns with the criteria: Nursery exhibits coral growth (e.g., TLE, size class, maximum diameter or length, volume, etc.); if nursery corals display positive net growth (all species) or if biomass at least doubles each year (*Acropora* only), a project receives a score of 1 (Evaluation Tool Nursery Metric #10).

Nursery Performance Metric #2: Nursery Coral Condition

The condition of a coral can be affected by environmental conditions, disease, physical impacts and interactions, and/or predation by motile organisms, each of which will have a negative impact on the production of coral tissue. Therefore, by obtaining data on the occurrence of negative interaction within the nursery, targeted preventative maintenance and management can be incorporated into a program's restoration plan.

The following are examples of the conditions that could be observed within the nursery:

- Disease
- Predation
- Competitive interactions
- Bleaching
- Physical impacts

Guidance on the impact, importance, and identification of each of these conditions is found in Chapter 4: Nursery Maintenance.

In addition, observations of old partial mortality on nursery coral provide information on longer-term coral tissue loss. It is inevitable that tissue loss will occur in the nursery; however, too much tissue loss means that preventative maintenance, site evaluation, and/or adaptive management should occur.

Often, there are multiple factors affecting your corals, for example, disease and predation. If managers need to prioritize one action (predator control) over another (disease treatment or prevention), **additional data** should be collected. For this example, the additional data would be **percent of each coral colony affected by each condition** (Figure 63).

Required Units: Prevalence of corals with partial mortality, disease, predation, bleaching or competitive interaction (%)

Possible Methods:

The methods, **in situ coral count** and **images**, described above in Nursery Management Metric #2 and Nursery Performance Metric #1 are possible methods for collecting coral health data.

Minimally, presence or absence observations on nursery coral health should be made on a regular basis (Figure 64). The frequency of observations will need to increase during periods of stress or observed increased mortality due to the above, or other, conditions.

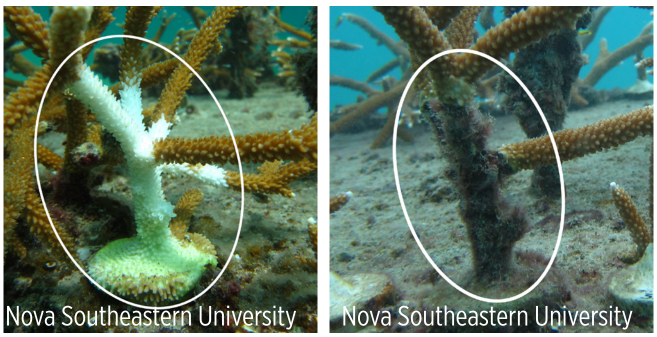


Figure 63. Examples of estimating percent mortality or percent affected by a condition. In this instance, the data recorded estimated 30% recent mortality caused by disease (left) and 15% old partial mortality (right).

To collect more detailed data, such as the percentage of the coral colony affected by each condition, these same data collection techniques could be used with simple modifications to the data sheet such as adding percent mortality rankings.

Data collection considerations due to nursery management strategies:

Some nurseries remove dead skeleton during all monitoring events as a management strategy. If this is a part of your nursery management, first report data on colonies, then remove and clean up the dead skeletons. Collecting data following the cleaning of the nursery will bias results.

Reporting:

Total number of nursery colonies with each condition, in addition to the total number of colonies surveyed, should be reported. All data should be reported by genotype and species to obtain a prevalence of each condition per genotype and species.

Surveyor:________________ Nursery:____________________

Date:______________

			Tally in appropriate bin number of corals with condition												
			Predation				Disease		CI			Bleaching		
Struct. Name	Spec.	Geno	Fw	Sn	F	O	1	2	1	2	PM	PB	B	Notes- Disease and CI codes
Coral Tree 1	Acerv	2a	/				//				5			D1=WBD
Coral Tree 1	Acerv	17	3											
Coral Tree 1	Acerv	3							/		3			C1=Algae
FUCA 1	Acerv	2a												

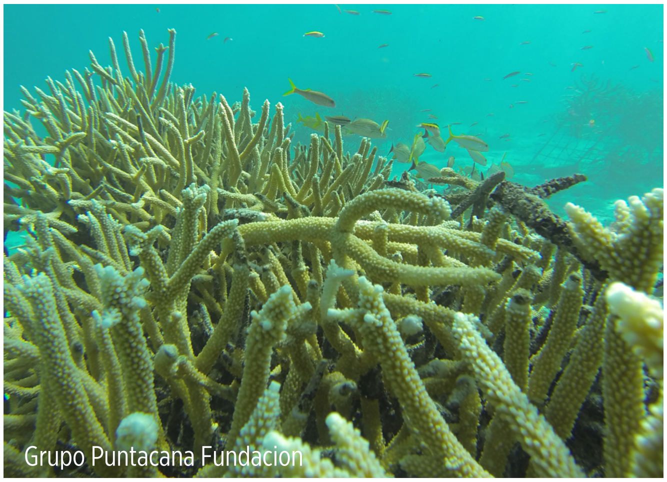
Fw= Fireworm; Sn= Snail; F= Fish; O= Other; CI= Competitive Interaction; PM= Partial Mortality; PB= Partial Bleaching; B= Bleaching

Figure 64. Example datasheet for collecting coral health data. Disease and competitive interactions can be tailored to the location and species.

Table 6. Example coral health assessment data.

Condition	Species	Genotype	Number of Corals Affected	Prevalence
Disease	*A. cervicornis*	2a	5	5/300=2%
Disease	*A. cervicornis*	12	12	4%
Fireworm predation	*A. cervicornis*	2a	0	0%
Fireworm predation	*A. cervicornis*	12	3	1%
Partial Mortality	*A. cervicornis*	2a	14	5%
Partial Mortality	*A. cervicornis*	12	20	7%

For example, 300 *Acropora cervicornis* corals from each of the genotypes 2a and 12 were surveyed. Disease, fireworm predation, and old partial mortality were the three conditions observed. Table 6 provides an example of the data collected and calculated prevalence.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Photographs:

Some disease and predation wounds/lesions can be difficult to identify even by trained observers. Representative photos of the conditions being reported in the nursery will not only help others learn the variability of a condition, but also will help the restoration community become more consistent in identifying conditions. In addition, sharing photos of the condition with the restoration community can help a program identify the condition. Photos can be submitted to the CRC who can share them with the restoration community for discussion.

Sampling Frequency:

At a minimum, coral health data should be collected quarterly and increase in frequency if prevalence levels are high/cause concern. In addition, during stressful times of the year, additional surveys should be completed, especially for bleaching and during disease outbreaks.

Performance Criteria:

Evaluation Tool Criteria Alignment: Nursery Performance Metric #2 aligns with four criteria:

1) Nursery exhibits low prevalence of colony partial mortality; if partial mortality prevalence is <10%, a project receives a score of 1 (Evaluation Tool Nursery Metric #9).
2) Nursery exhibits low prevalence of disease and/or disease within the nursery is mitigated; if annual disease prevalence is < 5% or disease is mitigated to reduce prevalence to <5%, a project receives a score of 1 (Evaluation Tool Nursery Metric #11).
3) Nursery exhibits low impact of coral predators; if annual predation prevalence (whole colony/frag) is < 5%, a project receives a score of 1 (Evaluation Tool Nursery Metric #12).
4) Nursery exhibits limited competition by algae and other competitors (e.g., hydroids, sponges, damselfish); if annual prevalence of whole colony mortality by competition is < 5%, a project receives a score of 1 (Evaluation Tool Nursery Metric #13).

Nursery Performance Metric #3: Outplant Coral Production

The production of outplanted corals is directly related to the health and growth of nursery corals and will typically increase exponentially once a nursery is well established (2+ years). To keep nursery corals healthy and productive, it is best practice to fragment and outplant regularly. See Chapters 6 and 7 for guidance on pruning methods, colony size, and frequency of outplanting. We recommend outplanting at a minimum 25% of the nursery's biomass per year; this still allows for programs to maintain adequate stock material, continued expansion of the nursery if that is the phase of the program, and contribution to the natural reefs through outplanting. During some years, you may choose to outplant substantially more material due to program goals and capacity. Keep in mind that nurseries can become overgrown when left untouched for too long; they can exhibit increased disease and predation prevalence and increased coral loss during a storm.

Knowing how much biomass is outplanted each year is key to describing a restoration program's impact and contribution to reef and species recovery. Therefore, prior to or during outplanting, corals should be measured. This can be completed in three ways: 1) coral size is estimated when they are clipped from the nursery, 2) after outplanting, coral size is surveyed or, 3) immediately before outplanting, a nursery coral tissue production survey is completed (Nursery Performance Metric #1) and then immediately following outplanting, another nursery coral tissue production survey is completed; the difference in measurements will provide total tissue removed for outplanting. Whichever method is chosen, tissue abundance should be reported per outplant site and by species and genotype.

Required Units: number and size of corals to be outplanted per species and genotype.

Possible Methods:

Methods provided in Nursery Performance Metric #1 can be applied here.

Reporting:

Outplant coral production can be reported in two ways: 1) total amount of tissue per genotype and/or 2) if using size classes, a distribution of outplant coral sizes. All reporting should be completed per outplanting event and by site. An outplanting event can span several days, which can be included in one reporting, but if it spans several months, reporting should be split accordingly.

Outplanting Frequency:

Outplanting can occur annually to quarterly depending on location and program capacity. Larger nurseries can outplant more frequently while smaller nurseries may only be able to outplant annually.

Performance Criteria:

Outplanting of nursery fragments should occur on a regular basis if nursery production is efficient.

Evaluation Tool Criteria Alignment: Nursery Performance Metric #3 aligns with one criterion: Nursery provides a sustainable source of healthy coral outplants that are outplanted on a regular basis to prevent overgrowth/ breakage/mortality of corals; if > 25% of biomass is outplanted every year (except during the first year after nursery installation, during the years of expansion, or following nursery reconstruction) to promote healthy nursery management strategies, a project will receive a score of 1 (Evaluation Tool Nursery Metric #14).

CHAPTER SIX

Harvesting and Transporting Corals

Reef Ecologic-Grumpy Turtle Creative

Timing

Timing is an important consideration when planning for manipulation of corals through collections, fragmentation, and/or outplanting, as added stress to the corals can cause mortality (Larson, 2010; Shaish et al., 2010; Hernández-Delgado et al., 2018; Kaufman et al., 2021). In making decisions about timing, it is important to consider both the environmental conditions and the condition of the corals themselves. The length of time a coral remains in the nursery can be variable depending on programmatic goals, species, growth rates, conditions, etc. While a nursery phase can enhance coral growth and health, longer durations in a nursery setting may not affect outplant performance (dela Cruz et al., 2015). Increased mortality upon fragmentation and/or outplanting has been observed during high stress periods (e.g., bleaching events, disease events, increased turbidity due to runoff or following storms, and extreme warm and cold events). In the case of a disease event, colonies can be fragmented to remove diseased tissue, but nursery expansion (fragmentation) or outplanting even seemingly healthy corals should not occur until the event has passed.

Harvesting

Harvesting of nursery corals can happen once or many times per year depending on the restoration program goals. In the first few years of a nursery, coral harvest for outplanting will be minimal, while the focus is mainly on nursery expansion and growth. In the years following, it is best practice to remove a substantial amount of tissue from the nursery each year; at least 25% of the nursery biomass should be outplanted each year (Chapter 5: Nursery Monitoring; Appendix 2). Keeping nursery material to a manageable size, in which corals are not overgrown or overcrowded, will increase nursery production and coral health (Lirman et al., 2014a).

In order to maximize outplanting success, all corals removed from the nursery should show signs of good health and have minimal biofouling organisms attached (Frias-Torres and van de Geer, 2015). The most obvious signs that a coral is unhealthy are lesions, recent mortality, disease margins, and/or discoloration (Chapter 4: Nursery Maintenance). In some cases, a colony may have experienced partial mortality or have discoloration on only a portion of the colony. If the condition is not affecting the entire colony, a judgment call should be made on whether to outplant the healthy-looking portion of the colony. If a colony is bleached, it should not be fragmented to avoid any additional stress.

Coral Size

Corals that are more than 10 to 15 cm in total linear extension (TLE) and/or maximum diameter have high survivorship once outplanted (Yap et al., 1998; Forsman et al., 2006; Brownlee, 2010; Lirman et al., 2014a). This general guidance can help when planning outplant efforts and making decisions about how to collect from the nursery. In contrast, successful outplanting has occurred more recently using small or micro-fragments (1 to 5 cm; Forsman et al., 2015; Page et al., 2018; Suggett et al., 2019). The estimated size of all outplanted corals should be recorded; see Chapter 5: Nursery Monitoring for methods for collecting and reporting outplant coral size.

Methods

There are two equally appropriate methods for collecting branching coral nursery fragments for outplanting, each with their own pros and cons (Table 7). The first is to clip the portions of the colony and leave the base or center in place to continue to grow. On a block or table, this means that the base of each colony would remain, and the branches (or fragments) would be outplanted. On a suspended branching colony, the central point, where the colony is hanging, would remain, and the two ends would be outplanted. The second method is to remove entire corals from the nursery


Reef Ecologic

Table 7. Pros and cons of outplanting whole or portions of nursery colonies.

Removal Method	Pros	Cons
Portions of colony	Reduces the effort to replace the nursery stock for the following outplanting event. May reduce materials used in nursery; for example monofilament won't need to be replaced for stock remaining on a tree. Allows for preservation of genets. More "sustainable" compared to harvesting more wild colonies on the reef. **Outplanting** Easy upright outplanting orientation because a cut end is available for the epoxy or to put against the substrate. Smaller pieces may be easier to work with when outplanting. Able to transport and outplant more colonies.	The effect that multiple fragmentations (over years) from the same fragment have on coral health, growth, and production is unknown. Reduce capacity for sexual maturity to be reached for generation of 1000s of larval propagules each year (biomass and genetic recombination). **Outplanting** Outplanting smaller corals (lower survival and decreased outplanting efficiency). Cutting coral could yield wounds that leave parent colonies (or fragments generated) temporarily open to infection.
Removal Method	**Pros**	**Cons**
Whole colony	Enhance ability to clean and repair trees and blocks thoroughly when temporarily empty. Easy to guide staff or volunteers to remove entire colonies. Potentially produce sexually mature colonies. Produce colonies that may have more resilience to grazing and disease in nursery. **Outplanting** Potentially more flexibility in outplant colony size, attachment technique and transportation methods. Outplanting large colonies may "recover" space faster than smaller fragments (e.g., increased chance of colony survival; sexually mature to kick start broader recovery through larvae).	Substantial time is needed in the nursery to rear to size, and after the outplanting, to fully clean and restock. Extra biomass accrued in nurseries may add engineering challenges (e.g., buoyancy for floating nurseries). Extra biomass accrued may harbor undesirable biota. Must plan to leave stock of all genotypes in the nursery for restocking. More challenging to move material (e.g., requires more boat space to transport larger colonies). **Outplanting** Engineering complexities of outplanting extremely large corals (difficult to secure, can break when outplanting, more space needed when outplanting). Outplanting fewer colonies.

structures, (or in the case of ropes or "carpets", fix the entire structure to the substrate), and restock from remaining structures.

For massive species, the methods used to collect corals from the nursery will depend on the methods used to grow and propagate the corals. If the corals are being grown on plugs or pucks, it will likely be easiest to collect and outplant the coral on that structure. However, if the corals are being grown hanging in the water column (Case Study #2.2), the colonies may need to be cut to create a base for outplanting. Corals could also be fragmented within the nursery and placed on plugs for outplanting with some portion of the colony remaining in the nursery for future grow-out (Case Study #2.3).

It may be helpful, and in some cases necessary, to periodically clear entire nursery structures (Figure 65). In this extreme example, the corals have become too thick to cut easily, dead tissue in the middle of the block causes damage to the remaining live tissue, and drift algae has more surface area to get caught on.

Transport

During collection, corals can be relocated to the restoration site either by creating individual colonies from the nursery and/or transporting full nursery structures.

Transport methods that focus on the harvest and movement of individual colonies should be placed in containers of appropriate size for the corals that are being collected. Some examples of potential containers include milk crates, laundry baskets, mesh/wire baskets, jars, plastic containers, plastic bags, or mesh bags (not ideal for branching corals). Most bins will float when empty, so add a small weight, nail, or lead line to the bottom to reduce buoyancy. Additionally, choose a mesh size large enough that water flows easily through the bin at the surface (makes for easier lifting onto the boat), but small enough that fragments will not fall through (Figure 66). Different size garden netting installed on the bin can help prevent loss of smaller fragments or use screw top jars or fully enclosed containers (Figure 67). It is not recommended to hold corals for long periods of time in smaller, enclosed, transport bins/bags.

Once at the surface, corals should be transferred as quickly as possible to seawater-filled containers on the boat (Figure 69). Whenever possible, have the containers filled just before the corals are brought to the surface to ensure that the water is as close as possible to the temperature the corals were just moved from. It is easiest if collection containers are just smaller than the boat transportation containers so that they can be quickly placed in the seawater. If collection containers are too big for the water bins, corals will have to be individually moved to the seawater bins, taking all necessary steps to keep track of genotypes. Keep the containers in the shade by using lids, towels, or fins, anything that will block direct sunlight. Monitor the water temperature periodically, and if temperatures get too warm, perform a water change.

Figure 65. Example of overgrowth issues that require clearing blocks of all corals.

Figure 66. Examples of bins for transporting corals underwater.

Figure 67. Examples of enclosed containers for smaller fragments.

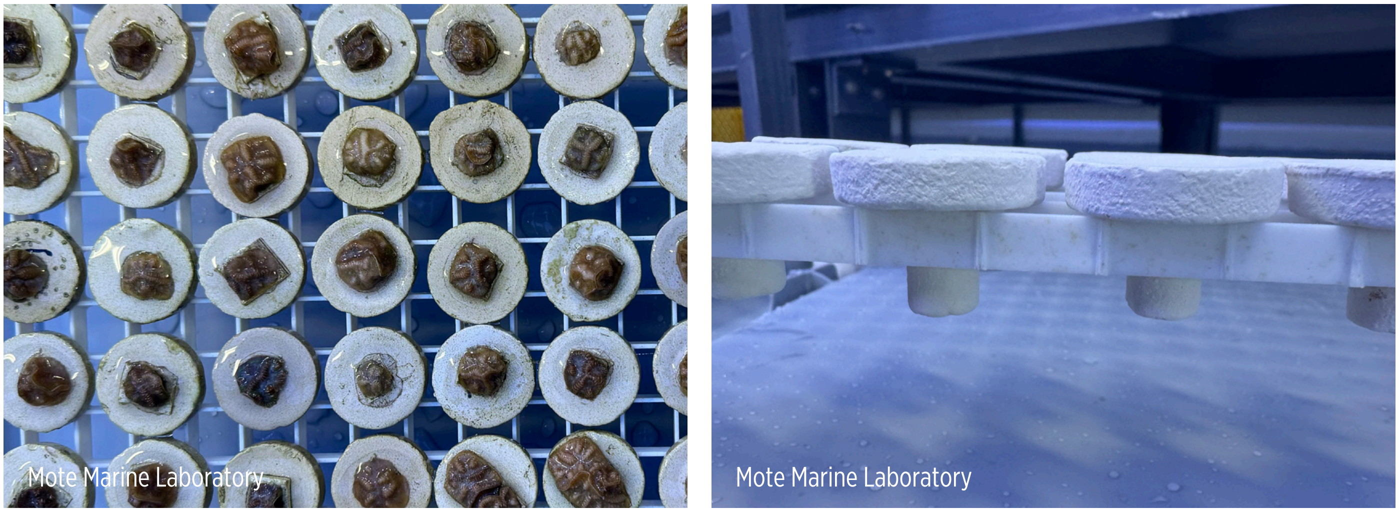


Figure 68. Example of transportation method for coral plugs.

Figure 69. Corals should be kept in seawater containers on the boat.

Corals should be kept at the surface for the shortest amount of time possible; upon arrival at the outplant site, get all the corals in the water as soon as possible. Even if the outplanting will take multiple dives, the corals will fare better for a longer duration on the bottom than on the boat. This takes some logistical planning at the beginning of the day in order to predict how many corals can be outplanted. For example, if there is a high probability of an afternoon storm, plan ahead for a shorter day, outplant fewer corals, or spend time cleaning the nursery to avoid a boat full of corals and unsafe dive conditions.

In the event the nursery location is adjacent to the restoration site, corals can be transported by individual divers directly between areas while remaining submerged. This is common when transporting whole corals grown on ropes from nursery to outplant site. Frias-Torres et al. (2018) address in detail this transport process with an overview described here: when transporting lines/ropes with mature corals to restoration sites, the primary concern is that current-wave action (surge) will have some impact, but it does not prevent this kind of transport from occurring. When no current or a minor current exists, a single diver can transport coral ropes to nearby restoration sites by systematically untying lines and securing lift bags or jerry cans at equal intervals along the rope. In strong current conditions, where a diver can at minimum only maintain their position in the water column, transportation is not recommended unless done so by boat to assist in towing the ropes to the restoration site. More details on this transport method including appropriate knots, diver communication, and safety measures can be found in Frias-Torres et al. (2018).

Genotype Tracking

It is recommended to establish a method to keep track of genotypes within the nursery, from the time of collection until outplanted. This can get complicated when outplanting multiple genotypes in one day, but with proper organization and planning, it is doable. During collection in the nursery, provide the appropriate materials to the divers or snorkelers collecting corals: map of the nursery, guidelines and directions for which genotypes to collect from and how many, datasheet for recording which colonies were collected, labeled containers, and a place on the datasheet for recording genotype and container number.

When outplanting relatively low abundances of coral, take steps such as placing them in numbered containers or wrapping them with wire tags to keep genotypes separate during transport and when outplanting. As restoration efforts scale up and occur across larger spatial scales and in high volumes of corals, tracking the performance of individual genotypes can become so time-consuming that it affects the efficiency and productivity of your program. Therefore, different techniques or a reduced level of data collection can be implemented. For example, simply reporting the total number of colonies per genotype outplanted and tracking them no further may be sufficient for your program's goals and reporting requirements. In this case, tracking restoration efforts by genotype, where a massive amount of coral is placed, becomes less of a priority as a tradeoff to understanding ecosystem function. However, at a minimum for all scales of restoration, maintaining a record of what and how many genotypes were used is encouraged. Tools for monitoring corals and their performance post-outplanting are described in Goergen et al. (2020) for both small- and large-scale restoration efforts.

Long-Distance Transport

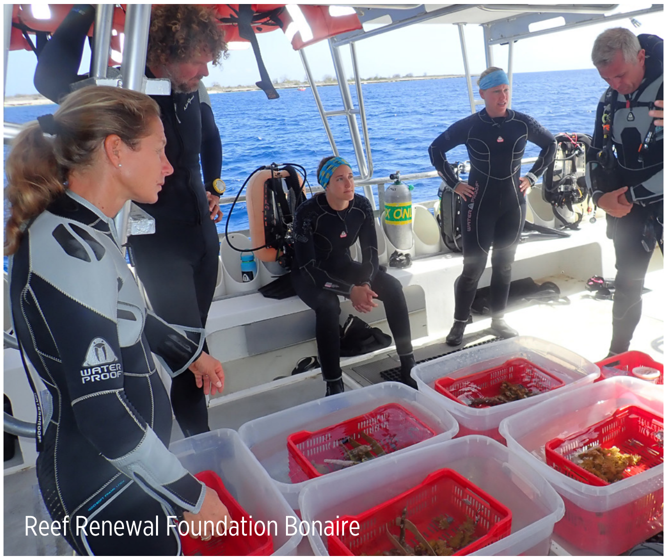
For long-distance transport involving a car or plane, additional considerations must be taken into account, such as permits, weight of the container, oxygen availability for the corals, and coral protection.

Long-distance transportation has been successful in the aquarium business for many years, so before taking on long-distance transportation, a thorough literature review is warranted (Becker and Mueller, 2001; Petersen et al., 2004; Delbeek, 2008). The preferred method is to always use seawater; however, the added weight and possible mess due to seawater sloshing out of the containers into the transport vehicle must be taken into consideration. Corals can be safely wrapped in damp bubble wrap individually or as a group, such as wrapping an entire egg crate filled with coral plugs. When wrapping corals with bubble wrap, place the "bubble" side toward the coral to allow for more circulation around the coral and avoid smothering. Corals can then be stacked/ arranged into coolers or watertight containers. If the corals will be exposed to lethally cold temperatures, either in the plane's cargo or at their final destination, a Uniheat tropical fish shipping warmer packet can be taped inside the lid of the container. Styrofoam or cardboard should be placed between the heat pack and the coral so there is no chance of direct contact; the same can be done with an ice pack for warm climates. Tape the cooler very well to ensure that if the cooler breaks during shipping, it will still arrive in one piece. Place the cooler in a shipping box.

Logistical Concerns

Heat — Corals need to be kept at a relatively steady temperature during transport. Corals should be kept in the shade if possible, but this alone may not maintain the water temperature. Even if the corals are in enclosed holding tanks, shade cloths can offer additional protection. If available, a saltwater hose can be used to flush the containers frequently, maintaining a relatively constant water temperature. Some things to consider when using a hose:

- If it has been sitting on the deck of the boat, the water may be very hot at first. Run the water for a while to bring it back to the ambient water temperature.
- Consider the water pressure of the hose, and aim it toward the wall of the container rather than directly at the corals.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Bubblers can also circulate water to help maintain temperature. If the water gets too warm, freezer packs can be taped to the top of the container, or frozen water bottles can be added to cool the water temperature without affecting salinity. Fans on the deck of the boat also help move air and keep the corals cool. If the holding tanks have a drain plug, drain from the bottom of the tank to flush out sediment and other material that may have settled.

Added weight — When moving large numbers of corals, consider the additional weight that is being placed on the deck of the boat. The corals may be relatively light, but the additional water, containers, tools, people, etc. are not. Large containers of sloshing water can change the way a boat moves, particularly in rough weather. Also, be cognizant of where on the boat the extra weight is placed, and try to distribute it evenly.

Coral abrasion — If corals are being held for any extended period of time, and/or transported over long distances, they should be packed in a way that they are not able to interact with each other or with other objects that could cause abrasion or a reaction by the coral. Corals can be separated using bubble wrap, placed in individual bags filled with water, or mounted on plugs or tiles. If the corals are being mounted on a tile, try to keep any live tissue from touching the tile and the epoxy, and avoid overhang where possible as that will require additional space in the holding tanks to prevent neighboring corals from touching. For short time periods, sargassum could be used as padding between corals to prevent abrasion, as well.

Time to destination — If there is little that can be done to limit transit time, it should be recorded to evaluate whether it influences survivorship.

Holding corals overnight — If corals are held overnight, their containers should be flushed completely at least twice per day with partial flushes throughout. If possible, it is best to leave a hose in the containers so that the water is continually being flushed. In addition, bubblers sitting on the bottom or at the middle of each container are required to continually aerate the water.

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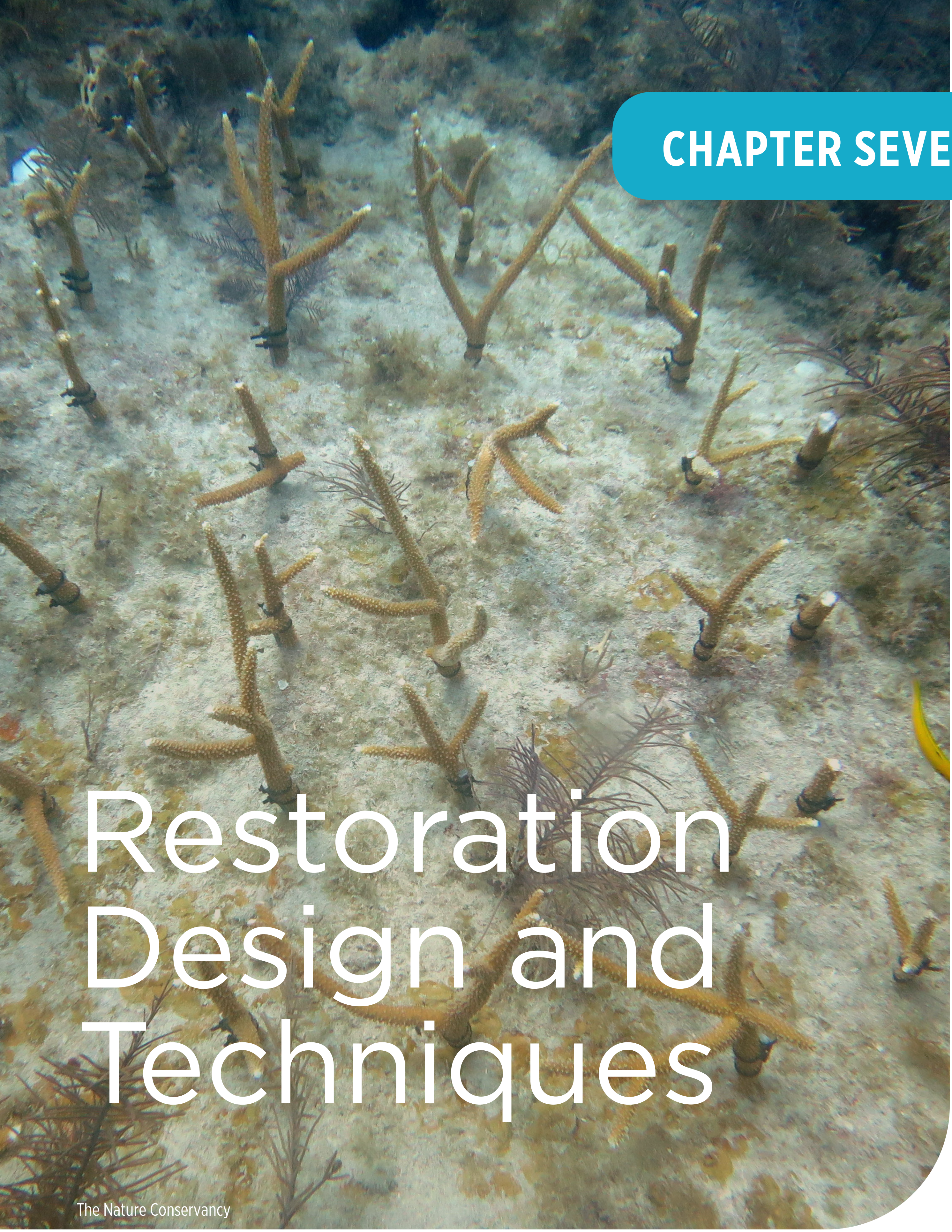
CHAPTER SEVEN

Restoration Design and Techniques



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Many factors will need to be considered when deciding on outplant designs and techniques, most of which will be directed by the restoration goal (e.g., recovery of specific species or ecosystem characteristics such as enhanced structural complexity, live coral cover, etc.), resources available, and site characteristics. The development of an outplanting plan should go hand-in-hand with the selection of a site (discussed in Chapter 1). This chapter lays out the details that should be considered prior to outplanting corals, including programmatic goals, scale, site design, colony size, attachment techniques, and materials.

Chapter 1 of this Guide details the key components to selecting a habitat and further selecting a location within that habitat that may be suitable for outplanting. This chapter will dive into the details behind those factors, including information on how to create a restoration design and details on planting each coral.

Site Design

Restoration design begins with an evaluation of the proposed site, which includes creating a map detailing potential outplant locations (Figure 70) and the development of planting designs. At this point, how many corals will be outplanted, the species that will be planted, and the purpose of this restoration project, all of which will guide the design of a site, should be known. These components will also be key in deciding the total space needed for restoration. Further, replication, reference and control sites, monitoring, permitting requirements, and future restoration (adding more corals to the site in the future) should be considered (see "Coral Reef Restoration Monitoring Guide: Methods to Evaluate Success from Local to Ecosystem Scales" (Goergen et al., 2020). Monitoring needs due to funding, research, and/or permitting requirements can often add additional time and dictate how corals are outplanted to meet the requirements. For example, some permits may require monitoring a percentage of the genotypes outplanted. Therefore, to increase monitoring efficiency, corals may be outplanted in genotype clusters, or a separate monitoring plot may be made. Each of these components should be taken into consideration when designing a restoration site.

During restoration design, it is important to collect site coordinates (latitude and longitude) at a few key points to aid in finding the restoration area during the subsequent visits. These can be obtained with a handheld GPS and snorkeler/diver or by marking the area with a surface buoy tethered securely and safely to the reef and using a boat's GPS by driving close to the buoy.

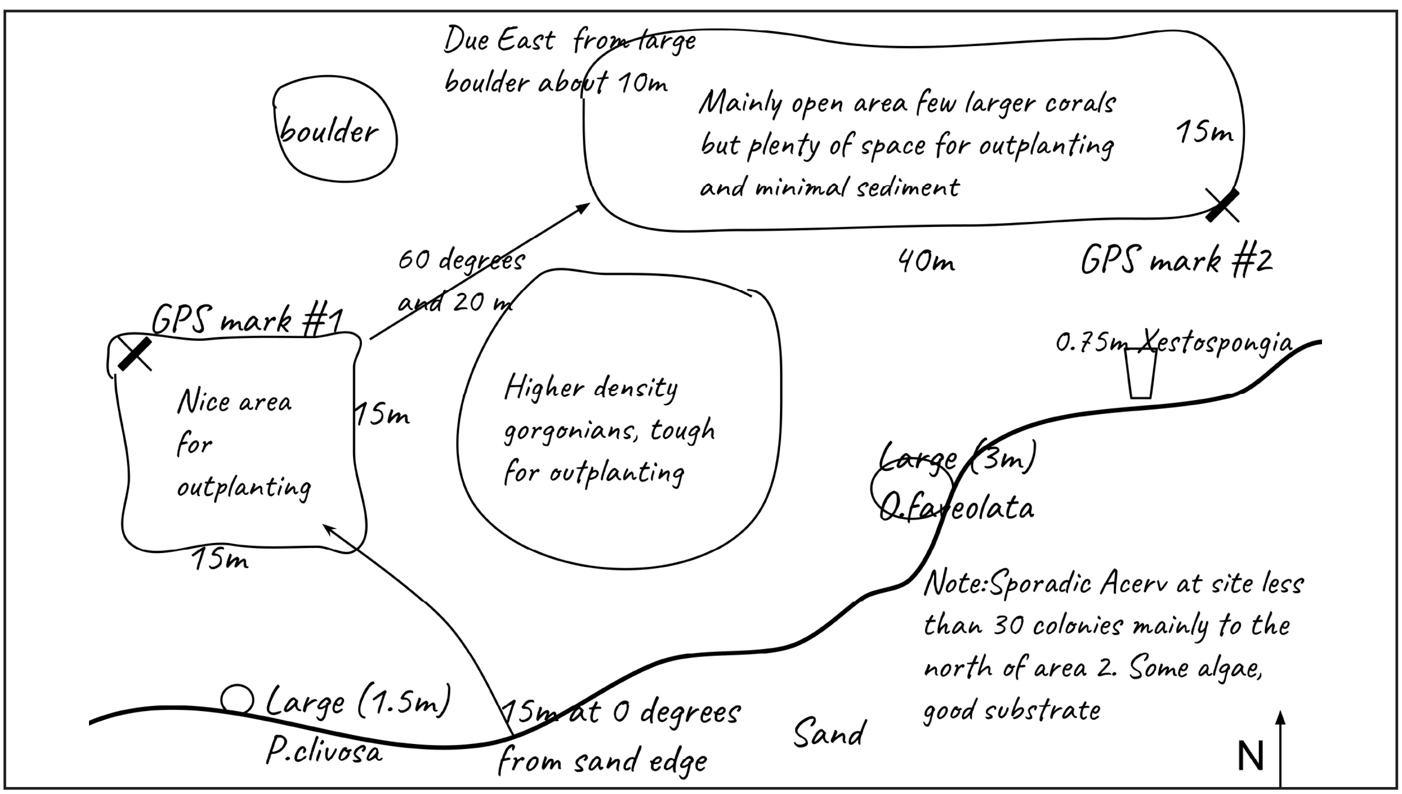


Figure 70. Example of site map detailing areas where outplanting could occur. Map includes location of GPS coordinates, cardinal direction, key features of the site, such as massives, large corals, site notes, and descriptions to help with relocation of the area.

Location on Reef

The location within the reef where colonies are planted may impact overall success of the restoration. **Corals should be planted safe distances away from known negative impacts, such as sediment pockets, reef edges, encrusting sponges, gorgonians, tunicates, zoanthids, other large corals, and mooring lines**. By planting corals close to the reef edge, coral propagation through asexual fragmentation will be limited; corals falling off the reef edge are likely to fall onto unsuitable substrate, reducing the likelihood of survival. Planting colonies away from the reef edge and upstream of the predominant wave direction and current flow will allow for spreading of corals through fragmentation, and in the occurrence of colony dislodgement, this will increase the likelihood the colony will remain on the reef. Avoiding reef edges may also reduce the risk of damage from anchors or anchor lines. Corals should be planted a safe distance from moorings to avoid damage to corals due to routine maintenance work of the line and potential buoy loss causing the line to fall to and damage the substrate in the surrounding area.

Colony Spacing and Density

When choosing outplant colony density and spacing, the ecology of the species and factors that may influence the survival and health of a colony must first be understood. The ultimate objective of coral restoration is to facilitate a species or environment to reach a state where it can function, grow, and provide services without further intervention (ecological restoration). The success of achieving this state will be different depending on location, species, resources, and baseline environment. The density and spacing for which corals are planted will influence how quickly a site or species will recover as colony spacing affects coral health, growth, survival, and reproductive potential (Gomez et al., 2011; Griffin et al., 2015; Schopmeyer and Lirman, 2015; Ladd et al., 2016; Goergen and Gilliam, 2018). Decreased colony survival, health, and growth were reported for higher density designs of 1 colony/m2 or greater (Griffin et al., 2015; Ladd et al., 2016; Goergen and Gilliam, 2018). In contrast, Pacific *Porites* spp. and *Acropora* spp. exhibited an increase in growth with increased density, attributing the increase to possible changes in the near-field flow, which would possibly increase nutrient availability (Shantz et al., 2011; dela Cruz et al., 2014). **Best practices for density of outplanted corals is to mimic what is observed in the wild populations or that has been documented historically for that geographic location and species**.

In addition, **spacing of outplanted corals will affect the reproductive potential** of the restoration site. Broadcast spawning corals need to be in close enough proximity to another unique genotype (hermaphroditic) or a colony of the opposite sex (gonochoric) to successfully cross-fertilize (Table 8). For the reproductive modes of many Indo-Pacific coral species, refer to the summary tables in Baird et al. (2009); Edwards (2010); Baird et al. (2021). For *A. cervicornis* and *A. palmata*, 1.5-2 and 0.5 meter spacing,

Table 8. Mode of reproduction and sexuality of Great Caribbean scleractinian corals from Trnka and Moulding (2008) and Baird et al. (2009).* Listed as threatened under the U.S. Endangered Species Act. †Species may also be hermaphroditic (Neely et al., 2018).

Broadcast Spawning Species		Brooding Species	
Hermaphrodite	**Gonochore**	**Hermaphrodite**	**Gonochore**
*Acropora cervicornis**	*Dendrogyra cylindrus**†	*Favia fragum*	*Agaricia agaricites*
*Acropora palmata**	*Dichocoenia stokesii*	*Madracis* spp.	*Agaricia humilis*
Acropora prolifera	*Meandrina meandrites*	*Manicina areolata*	*Agaricia fragilis*
Colpophyllia natans	*Montastraea cavernosa*	*Mycetophyllia ferox**	*Eusmilia fastigiata*
Diploria labyrinthiformis	*Oculina varicosa*	*Porites astreoides*	*Isophyllia sinuosa*
*Orbicella annularis**	*Siderastrea siderea*		*Porites porites*
*Orbicella faveolata**	*Solenastrea bournoni*		*Porites furcata*
*Orbicella franksi**	*Stephanocoenia intersepta*		*Siderastrea radians*
Pseudodiploria clivosa			
Pseudodiploria strigosa			

respectively, has been recommended (Nicole Fogarty, University of North Carolina Wilmington personal communication, 2012). Similarly, Baums et al. (2019) suggest a 2-3 m distance between outplants of acroporids and orbicellids. Furthermore, if working with gonochoric species, an appropriate sex ratio needs to be achieved (see Szmant, 1986).

Coral Diversity

A restoration site with a high diversity of coral species is ideal for the long-term viability of the reef. For example, Cabaitan et al. (2015) found that some species perform better when mixed with other species, while for others it had no effect. They also found that some species reduced the predation pressure on others. There is evidence of competition between some species, and this should be a consideration when determining colony spacing and diversity (Sheppard, 1979; Rinkevich and Loya, 1985; Tanner, 1997; Abelson and Loya, 1999; Ferriz-Domínguez and Horta-Puga, 2001).

Furthermore, to maintain genetic diversity at a restoration site and to encourage successful sexual reproduction, multiple genotypes should be placed at each site. For example, *A. cervicornis* needs a minimum of five genotypes to reach mean diversity values for an individual reef (Drury et al., 2016), although 10 is preferred (replicating the maximum expected genetic variability; Baums et al., 2019). Because this type of genetic analysis is lacking for most coral species, we suggest using this recommendation as a guiding principle until more species-specific research is completed.

Finally, unique genotypes of the same species may have competitive interactions and should be placed at a distance that accounts for future growth to avoid potential negative interactions (this distance will be based on the growth rate of the coral species being used). This should also be considered when outplanting amid wild colonies of the same or different species, as some species are known to be aggressive toward each other (Sheppard, 1979; Rinkevich and Loya, 1985; Tanner, 1997; Abelson and Loya, 1999; Ferriz-Domínguez and Horta-Puga, 2001).

Colony Health

The initial health of the outplanted colony is a critical component to achieving restoration success and survival of the colony. Prior to outplanting, the health and condition of each colony should be evaluated:

- Colonies that are showing signs of recent mortality (stark white skeleton) or degrading tissue of any kind should not be outplanted until the progression of tissue loss has subsided and no additional adverse health effects are observed.
- Old dead portions of the colony (skeleton overgrown by turf algae but not exhibiting signs of recent tissue loss) should be removed if in a location that will not harm the rest of the colony.
- Fouling organisms (e.g., sponges, hydroids, zoanthids, tunicates, etc.) should be removed to decrease competition and potentially reduce colony dislodgement following outplanting due to organisms grazing on the fouling organisms (Shafir and Rinkevich, 2008; Frias-Torres and van de Geer, 2015; Horoszowski-Fridman et al., 2015).

Colony Size

The size of the outplanted colony is likely to affect efficiency, duration to achieving project goals, and colony survival, growth, and timing of sexual reproduction contribution (Yap et al., 1998; Lirman et al., 2014a; Montoya-Maya et al., 2016; Goergen and Gilliam, 2018). For example, larger outplanted corals (e.g., >15 cm TLE for *A. cervicornis*) have higher survivorship, productivity, and increased ability to overcome adverse conditions such as predation, disease, sedimentation, and physical interactions (Loya, 1976; Sato, 1985; Forsman et al., 2006; Goergen and Gilliam, 2018). In addition, large outplanted corals/ large-scale restoration may have a positive influence on coral recruitment (Montoya-Maya et al., 2016). However, in order to have larger colonies to outplant, corals must be raised longer in a nursery, which can have its limitations within a program due to funding or research goals, capacity of the nursery (more space is needed to grow larger corals), and materials needed for outplanting. Other options such as outplanting in clusters or reskinning may promote growth while reducing the time it takes to produce a larger colony. All such options will be dependent on the program but need to be taken into consideration when developing goals for a restoration program.

Attachment Techniques

There are a number of different methods that can be used to attach outplants to a reef, and the method selected will depend on the species, site conditions (bottom type, currents, and swell), and availability of resources (Table 9). The more common and successful methods presented here are a nail and cable tie for branching corals, and epoxy and concrete mixes for both branching and massive corals. It is always better to secure the coral to the substrate; wedging corals into cracks and crevices may work, but adding cement, epoxy, or nails will yield higher survival rates

Table 9. Comparison of coral outplanting methods. Estimation for cost includes only materials needed for outplanting. It does not include costs for staff time, boat, or materials that are reusable, such as a hammer or brush: $<10 USD /100 corals; $$=10-25USD /100 corals; $$$=25-50USD/100 corals; $$$$ >50USD/100 corals. Estimation for time was based on the time it takes for the average person to outplant one coral using each method including time it takes to mix the adhesive, clean substrate, or pound in a nail: + <=1 min/coral; ++= 1-2 min/coral; +++= 2-3 mins/coral; ++++>3 mins/coral. Branching morphology includes corals that are thicket/arborescent, digitate, and bushy in form. Table adapted from Gomez et al., 2010 and Suggett et al., 2019.

Attachment Method	Time	Advantages	Disadvantages	Branching	Massive/ Columnar	Citations
Nail and Cable Tie $$	++	Widely available materials Immediate stability of coral Nails can be installed days prior to outplanting to increase efficiency Works on vertical surfaces	Plastic footprint	x		Okubo et al., 2005; Johnson et al., 2011; Hollarsmith et al., 2012; Endo et al., 2013; Bowden-Kerby, 2014; Lirman et al., 2014a; Ross, 2014; Goergen and Gilliam, 2018; Forrester et al., 2019
Epoxy $$$$	+++	Applicable to most species Clean and easy to use Can be mixed underwater as needed Quickly overgrown	In situ cure time >10 minutes Best for corals < 10 cm diameter Substrate cleaning is necessary for a good bond Need calm conditions for proper fragment stability and curing	x	x	Birkeland et al., 1979; Yap and Gomez, 1985; Becker and Mueller, 2001; Dizon et al., 2008; Gomez et al., 2010; Williams and Miller, 2010; Forrester et al., 2011; Guest et al., 2011; Johnson et al., 2011; Hollarsmith et al., 2012; Griffin et al., 2015; Goergen and Gilliam, 2018
Cement $	++	Widely available materials Applicable to most species Can be mixed on land or on the deck of the boat and applied underwater Quickly overgrown	Complete cure time 1-2 hours Can be difficult/ messy to handle High product to coral size ratio May need surface support to prepare and dispense usable amounts Need calm conditions for proper fragment stability and curing	x	x	Mayor, 1924; Alcala et al., 1982; Auberson, 1982; Hudson and Diaz, 1988; Clark and Edwards, 1995; Hernández-Delgado et al., 2001; Ortiz-Prosper et al., 2001; Kotb, 2003; Gomez et al., 2010; Forrester et al., 2011; Johnson et al., 2011; Bowden-Kerby, 2014; Kumar et al., 2017; Frias-Torres et al., 2018; Unsworth et al., 2020
Direct Tie-down $-$$	+++	Widely available materials Can be used on days with current or rough conditions Immediate stability of coral	Problematic materials: Some wire materials will corrode and break and cause tissue mortality Monofilament may stretch or loosen Plastic footprint Requires consolidated substrate with holes or knobs to tie coral to	x	x	Mayor, 1924; Maragos, 1974; Birkeland et al., 1979; Alcala et al., 1982; Harriott and Fisk, 1987; Bowden-Kerby, 2001; Bruckner and Bruckner, 2001; Naughton and Jokiel, 2001; Garrison and Ward, 2008; Gomez et al., 2010; Williams and Miller, 2010; Forrester et al., 2011; Forrester et al., 2012; Garrison and Ward, 2012; Hollarsmith et al., 2012; Endo et al., 2013; Ross, 2014; Forrester et al., 2019

* In some instances, holes in the reef could be made with a nail and hammer, which can save costs and possibly time as more people could be making holes at one time.

Attachment Method	Time	Advantages	Disadvantages	Branching	Massive/ Columnar	Citations
Coralclip ® $$	+	Can be used on days with current or rough conditions Immediate stability of coral Works on vertical surfaces	Materials not widely available Requires consolidated substrates Applicable to a limited size range of corals	x	x	Suggett et al., 2019
Pegged/ Coral Rope $	+	Widely available materials Can cover large area quickly Can be used on days with current or rough conditions	Problematic materials: Natural fibers rot and are difficult to clean Synthetic fiber may yield microplastics Corals can be damaged or entangled during transport Low aesthetic appeal of ropes on the reef	x		Lindahl, 2003; Bowden-Kerby, 2014; Frias-Torres et al., 2018
Wedging/ Plug-in $	+++	No additional materials needed	Need complex substrate to hold corals in place Time consuming to find suitable crevices relative to coral size Low survival rates	x		Birkeland et al., 1979; Harriott and Fisk, 1987; Plucer-Rosario and Randall, 1987; Bowden-Kerby, 1997; Smith and Hughes, 1999; Bowden-Kerby, 2001; Lindahl, 2003; Gomez et al., 2010; Williams and Miller, 2010; Villanueva et al., 2012; Mbije et al., 2013; Bowden-Kerby, 2014; Chamberland et al., 2017; Forrester et al., 2019
Drilled Holes $-$$$$*	++++	No need to transfer corals to additional material if plugs were used in the nursery or for larval settlement	Holes need to be pre-drilled and marked at outplant site Additional adhesive needed to ensure stability	x	x	Becker and Mueller, 2001; Gomez et al., 2011; Boch and Morse, 2012; Mbije et al., 2013; Cabaitan et al., 2015; Horoszowski-Fridman et al., 2015; Horoszowski-Fridman and Rinkevich, 2021

* In some instances, holes in the reef could be made with a nail and hammer, which can save costs and possibly time as more people could be making holes at one time.

(Bowden-Kerby, 2001). For all techniques, it is important that the substrate is clean and stable prior to outplanting. Cleaning the attachment location, using a stainless steel brush or scraper, will rid the area of competitive organisms such as algae and hydroids and will ensure proper adhesion to the substrate.

Nail and Cable Tie

The nail and cable tie technique is best for branching corals, such as *A. cervicornis*, on relatively hard substrate such as rock or coral pavement. This method involves driving nails into the reef and attaching corals to the nail using one to two cable ties (Figure 71). The most effective method is to place the knot of the cable tie flush with the nail and tighten it as much as possible. For large corals with many branches, more than one nail should be used (Figure 71). The ends of cable ties should be cut as close to the nail as possible to limit colonization by algae and abrasion of the colony by the loose end. If needed, a small amount of epoxy at the base of the coral can be used to further secure the coral and nail.

Recommended materials

- Hard cut non-galvanized masonry nails minimum of 7.5 cm (3 in) length
- Ultra Violet resistant cable ties between 10-20 cm (4-8 in) length and 40 lb test
- Sledge hammer
- Stainless steel brush for cleaning
- Snips or scissors
- Epoxy/cement (additional/not required)

Important considerations

- The coral should be very tight to the nail as any movement could create lesions in the coral tissue. If the coral can wiggle on the nail, but the nail is solid, a second cable tie should be added; if both the nail and the coral can wiggle, the nail should either be moved to a more secure location, or a bit of epoxy could be added to the base of the nail.
- Certain habitat types may be less conducive to this type of outplanting because the substrate can be either too hard or too crumbly to effectively install a nail. When choosing sites, consider testing the substrate with a nail and hammer.
- An *A. cervicornis* coral can lay tissue over the cable tie within a few months, but they generally take longer to lay tissue over the nail.

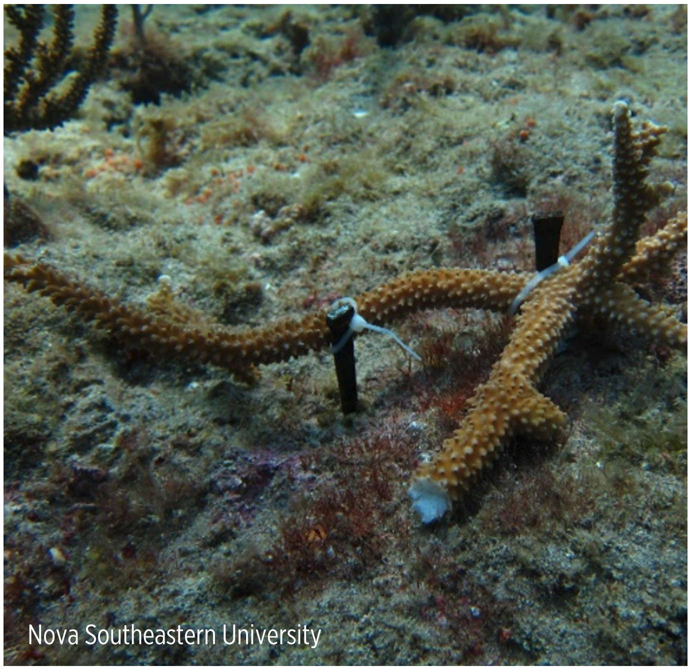


Figure 71. Corals are outplanted to a nail with one to two cable ties securing the coral to the nail. The knot of the cable ties aligns with the nail to create a secure fit. For larger branching corals, multiple attachment points should be used.

Epoxy

For both large branching corals and small massive corals (<10 cm), epoxy can be used to outplant corals (Figure 72). Large branching corals will need more than one attachment point. Epoxy can be relatively expensive, so it is best used when only small amounts are necessary to secure the outplant. When outplanting massive corals, a ring of epoxy equal to the circumference of the coral can be used instead of covering the entire area under the coral to reduce the amount of epoxy. However, the entire edge of the colony should be covered to prevent undercutting or erosion of the skeleton by boring organisms. It is imperative that the substrate and the underside of the coral are thoroughly cleaned prior to using epoxy, as it does not adhere to turf algae or slippery, slimy surfaces.

Recommended materials

- Stainless steel brush for cleaning
- Epoxy putty (Recommended brands: All-Fix, Magic Sculpt, Apoxie Sculpt; Aquamend has been used but does not have as much initial strength to hold fragments upright, thus requiring more time for outplanting)

Important considerations

- Epoxy must be mixed thoroughly; make sure there are no striations visible. If the two parts do not fully mix, the epoxy will not set correctly and the corals may not be secure.
- Epoxy does not adhere to algae, sponges, or slimy/slippery substrates; therefore, the substrate must be cleaned thoroughly.
- Most epoxies take about one hour to set, so plan outplanting with epoxy during times when there is minimal current, waves, and/or surge.
- Larger branching corals need more than one attachment point to be secured with epoxy alone.
- Epoxy should be smoothed around the edges and pressed into the substrate, which limits settlement of competitors and reduces areas that can be lifted by waves and surge.

Cement

A mixture of cement is an effective and inexpensive method for outplanting larger massive and/or branching corals (Figure 73). One benefit of cement is that it can be used to elevate the coral

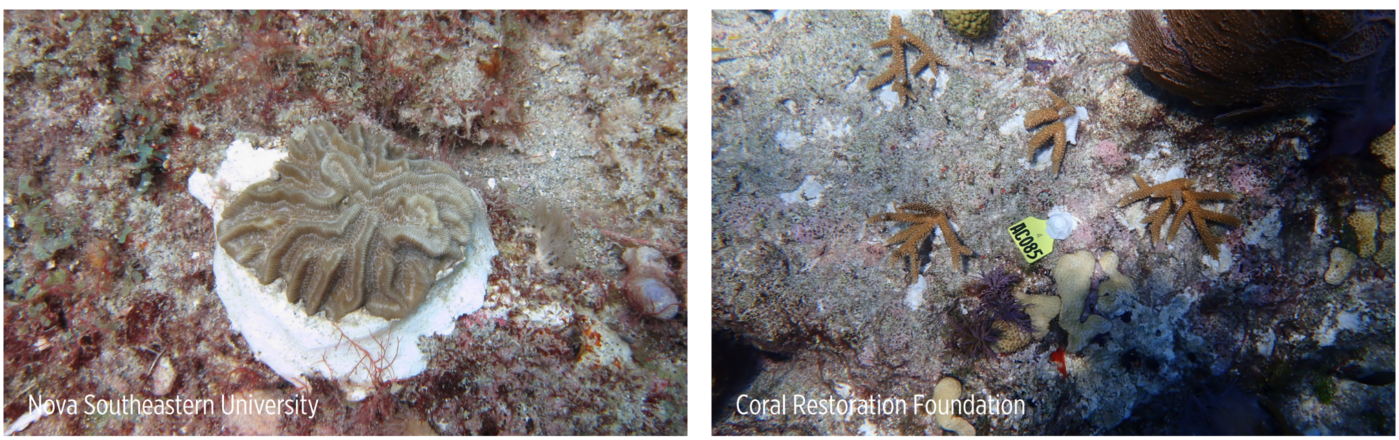


Figure 72. Corals outplanted with epoxy. For larger branching corals, multiple attachment points are recommended.

Figure 73. Corals outplanted with cement.

and gives a clean, stable substrate to fuse to that is initially free of competition by algae and other reef invertebrates. Cement can be mixed in a 2:1 ratio with very fine sand or other plastering mortar aggregate like marl or Marmolina (marble sand). Finer aggregate will reduce the plume. The mortar is mixed with just enough water (salt or fresh) to keep a thick paste consistency to make it easy to use and apply underwater. The mix can be adjusted to set relatively quickly (add Plaster of Paris) or stay soft for longer periods of time to accommodate different outplant methods. Unsworth et al. (2020) completed a comprehensive analysis of various cement mixtures (Appendix 4) and found that the optimal ratio is ten parts type I/II Portland cement to one part undensified silica fume (brand name Sikacrete) as described in Frias-Torres et al. (2018).

A mound of cement about the size of the coral should be first placed on the substrate where the coral will be outplanted. Then, carefully place the coral on the mound of concrete, minimizing contact with coral tissue. Smooth the concrete around the coral ensuring there are no gaps between the cement and the coral base. A few minutes after outplanting, check for any cement that may have settled from the water column onto the coral removing any cement by gently waving your hand over the coral.

Recommended materials

- Cement
- Aggregate (sand or marl)
- Plaster of Paris or similar hardening additive for faster curing (additional/not required)
- Mixing containers — 5-gallon buckets or large containers
- Long-wrist rubber/vinyl/PVC gloves
- Measuring containers or scoops
- Optional mixing tools: Hand concrete mixing tool, cordless drill (high torque and low revolutions per minute (RPM)) with cement mixing bit, or generator and corded drill with MudMixer™
- Underwater transport containers: Ziploc bags, icing/pastry bags, 5-gallon buckets, 1-gallon pails, caulking gun or something to contain the cement on descent

Important considerations

- Cement mixes can be very messy. Take care to keep the cement from settling on the coral and to clean hands off before touching the coral.
- Like with epoxy, create a smooth transition between the outplant and the reef to avoid nooks and crannies where competitors and predators can attach.
- Transport cement powder on the boat in waterproof containers or away from the elements; as soon as it becomes wet, it will begin hardening. Most cement is sold in plastic lined paper bags that are not designed to withstand the elements.

Reef Renewal Foundation Bonaire

Coralclip®

Coralclip® is a manufactured device that in effect integrates “nail and cable tie” and “direct tie-down" approaches for high-throughput outplanting (Figure 74; Suggett et al., 2019). This inexpensive device was conceived as a means to avoid the use of chemicals, but also to better standardize evaluation of outplant success, upon introduction of outplanting into tourism operations on the Great Barrier Reef, Australia. Coralclip® is based around a torsion spring-clip with an integrated masonry nail for easy deployment. It is manufactured from stainless steel to avoid the need for plastics (cable ties, fishing line) and designed to carry “low visual impact” to maintain the aesthetics of reef sites, whereby coral will overgrow the device within several weeks to months, depending on growth rate. Divers can deploy many Coralclip devices in rapid succession for immediate or later coral attachment. If fragments detach (are lost), the devices can be reused.

Recommended Materials

- Masonry nail (37 mm) and Coralclip®
- Sledgehammer
- Stainless steel brush for substrate cleaning

Important Considerations

- Coral fragments should be held tightly by the device’s spring torsion to ensure secure attachment of the coral to the substrate (2+ months, depending on the growing season).
- If the attachment is not secure, or if the device feels loose when first deployed onto the substrate, the device can be removed and reinstalled without damage. Similarly, the coral fragment can be re-secured if it is initially dislodged.
- Multiple clips can be used to attach larger fragments.

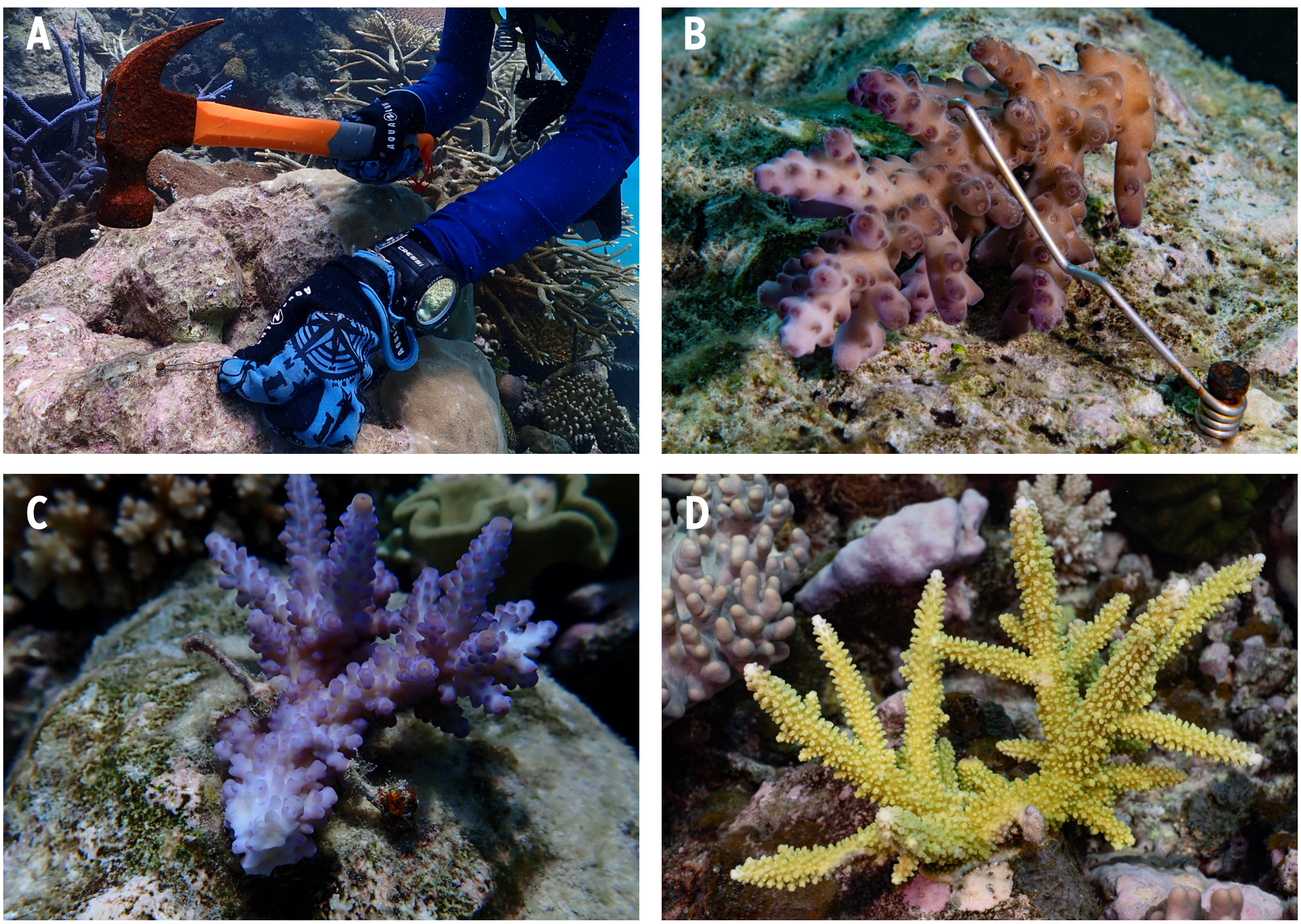


Figure 74. Examples of Coralclip® deployment. Installing Coralclip® (A), a newly outplanted coral (B), an outplant a few months after outplanting (C) and after completely overgrowing the Coralclip® (D). Images provided by John Edmondson/Reef Wavelength Cruises.

- As with other attachment methods, the device is only suited for consolidated (not crumbly) reef substrate, but importantly, it can be used on all substrate aspects (e.g., to attach plating corals to the sides of a rock/reef).
- Device deployment should not be made with the coral fragment in place (it can damage the coral and result in insecure attachment).
- Effective division of labor is achieved by deploying the devices prior to attaching corals.

Direct Tie-down

On reefs where there are many crevasses and nooks and crannies, corals can be tied/attached directly to the reef using wire, cable ties, or monofilament line (Figure 75). This technique is a relatively inexpensive method for outplanting but does require specific site characteristics for it to work (i.e., places that corals can be tied to) and requires time and precision in application. This option is not suggested for volunteers and will likely not be the primary outplanting method but can be used opportunistically in suitable locations.

Direct tie-down can be an efficient way to deal with broken and at-risk coral fragments, as well as within planned outplanting events. This method does immediately secure the coral, though a return visit is recommended to ensure that the coral has grown tissue to adhere to the substrate. Corals are secured to a cleaned spot on the reef with wire, cable ties, or monofilament.

Figure 75. Example of direct tie-down of a coral to the reef using cable ties.

Recommended materials

- Tie down materials: cable ties, wire (plastic coated steel or galvanized wire, stainless steel wire) or monofilament (30 lb test nylon)
- Stainless steel brush for cleaning
- Cutters for tie-down material
- Knot tightening device — side-cut pliers (a dull pair) for line and cable ties, small channel-lock pliers or linesman's pliers for wire, the latter being recommended

Important considerations

- Some wire materials work better than others; some galvanized steel wire has caused coral mortality and should be aged and trialed prior to use. Raw copper is toxic and not recommended, and plastic-coated copper tends to be bulky at larger gauges and stretchy at smaller.
- Nylon cable ties may stretch, allowing wiggle and poor connectivity of the coral to the substrate causing loss or mortality. They are sometimes difficult to tighten enough on the coral without damaging the coral and/or underlying reef. Twist the tightening plier rather than pulling.
- Match the coral to the shape of the intended planting point, and vice versa, to maximize stability without undue contact. For example, branching corals prefer to be in the water rather than on the reef.
- Remove/cut any excessive wire or cable tie as it adds surface area for biofouling organisms such as algae.

Drilling Holes

Colonies propagated on plastic/limestone/cement pegs can be easily cemented into pre-drilled holes in the reef (Figure 76; Horoszowski-Fridman et al., 2015; Horoszowski-Fridman and Rinkevich, 2021). Pneumatic drills, supported by 12 L SCUBA cylinders, can drill 25 to 30 holes per cylinder. A small amount of cement or epoxy is placed on the bottom of the coral peg and then inserted into the pre-drilled hole. This technique allows coral attachment on horizontal and vertical substrates. In a study performed in the Red Sea, 30 corals/hour/worker were transplanted, which is more time-consuming than some other methods presented.

Recommended materials

- Drill — Pneumatic or battery-operated
- Drill bit with a diameter to loosely fit the coral plug
- SCUBA cylinders (for pneumatic drill) and weights for tank as it becomes buoyant when empty
- Cement and/or epoxy

Important considerations

- Time — can be slow; need for multiple SCUBA tanks; corals must be propagated on or pre-glued onto pegs.
- Limited to the tanks' capacity or the battery life of the drill being used.
- Drilling and plugging should be done simultaneously. Pre-drilled holes can be hard to locate on the reef and if left for too long can fill with sediment. Holes can be temporarily plugged with nails/ pegs with flagging tape to aid in hole relocation.

Pegged/Coral Rope

Corals propagated on a rope can be outplanted on that same rope, minimizing time associated with transporting each colony individually. This method works best for branching corals, which can be wedged into the rope either vertically or horizontally. At time of outplanting, the entire rope can be moved to a site and secured in a few places. Different types of rope have been used in different places with varying success. Sisal rope is preferable to polypropylene because it breaks down more quickly, but in some areas, it can last up to a year, enough time for the corals to grow and be outplanted, while in other places it has broken down in just five months. See Case Study #8.1: Outplanting using ropes in an effort to increase efficiency for additional information.

Recommended materials

- Rope
- Nails (optional) — nails may be needed to help secure the rope in places

Important considerations

- Larger corals in areas with high rugosity can often just be placed/wedged without any additional need to secure the rope. Applications will vary by environment and conditions, but corals should be secure enough that they do not move so they can naturally attach to the substrate.
- The substrate should be cleaned where corals make contact to allow them to attach naturally.
- If wedged and secured properly, this method can be used in relatively high-wave energy environments.

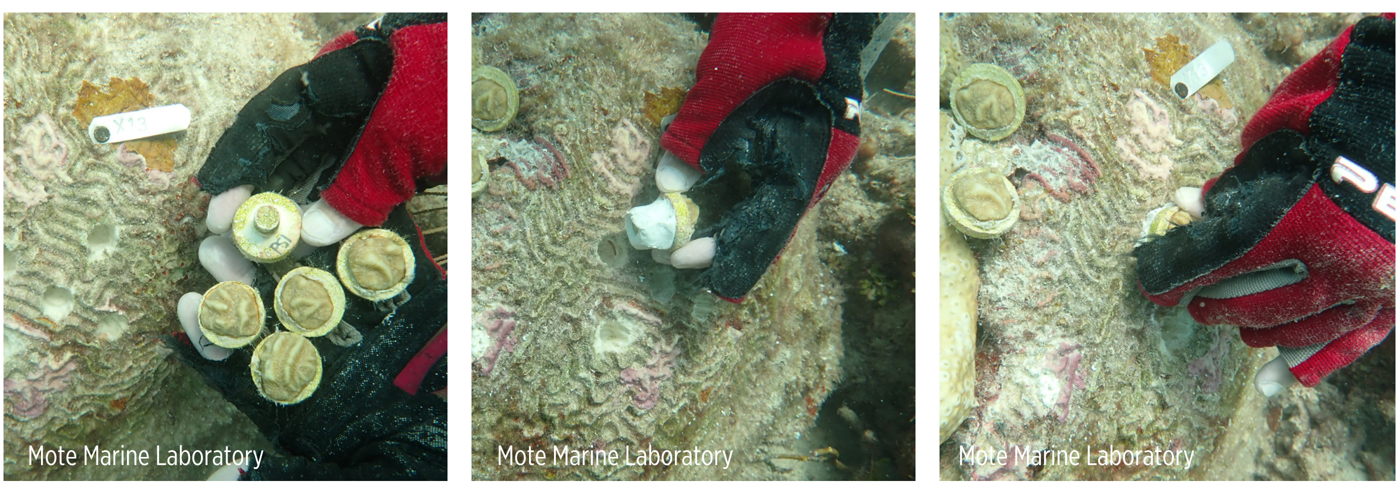


Figure 76. Example of drilling holes to outplant coral plugs.

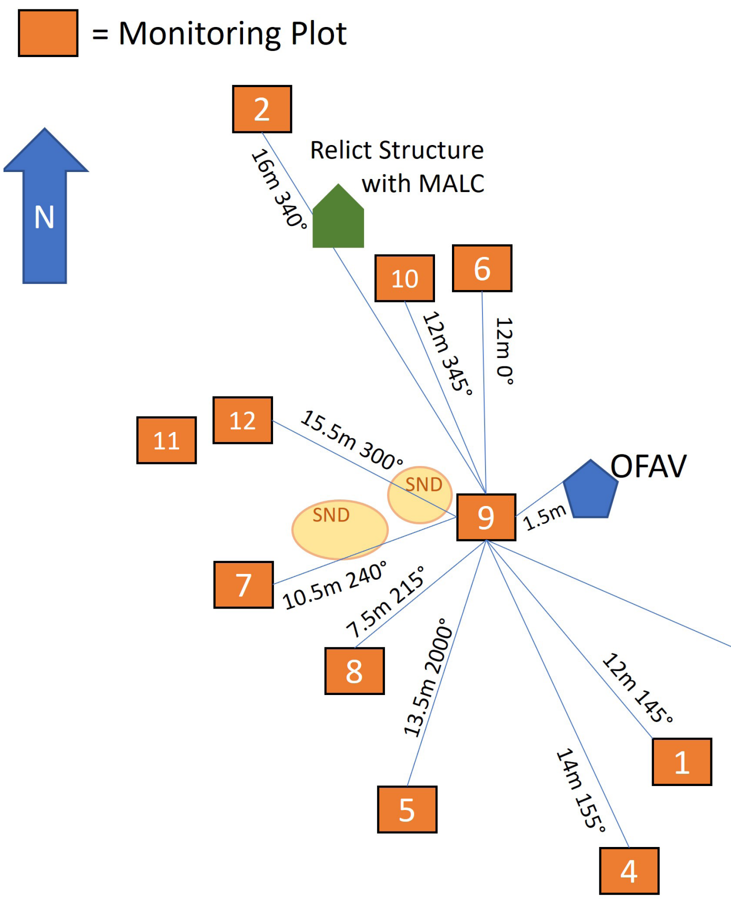
- Some experimentation may be needed to find a type of rope that works best for certain environments and applications. Biodegradable is preferable for short-term nursery grow-out phases, but polypropylene may be necessary if they will be left for longer. Cotton and hemp have not been successful. Sisal works in some applications, and polypropylene has worked best.
- If using a synthetic rope, burn the ends to prevent unraveling over time.

Site Mapping

Monitoring of corals is always easier with a well-designed site map; it will increase data collection efficiency and confidence. Even with designs with tagged corals or groupings, a map can be a good backup in case tags or corals go missing. In addition, site maps are helpful tools for those who are not familiar with the restoration sites, such as volunteers or visitors. There are endless types of site maps, but the key features are: 1) a waypoint of the site (take caution that this is not directly over corals in the case that a marker will be dropped on it), 2) distinguishing features for orientation (e.g., ledge along the east side of the outplants), 3) tag numbers, 4) site name, and 5) location of corals relative to each other or features including distance and bearing. Reefscape features can be subjective, so any feature used should be unambiguously clear to any user. Below are a few examples of sitemaps (Figure 77 and Figure 78).

Site mapping was completed post-outplanting for Figure 77. Once all plots were established, a central location was chosen (monitoring plot 9), and a survey tape and compass were used to map the location of the outplant plots and key features from that central location. Determining a central location may be aided by marking the monitoring plots with a temporary buoy or bright object (dive slate or coral basket), providing an overall look at the site. This is especially helpful in low visibility and during events where many people are outplanting (also a secondary check to make sure all plots are accounted for).

Another way to generate a site map is incorporating it into the restoration design, such as laying out a survey tape of a desired



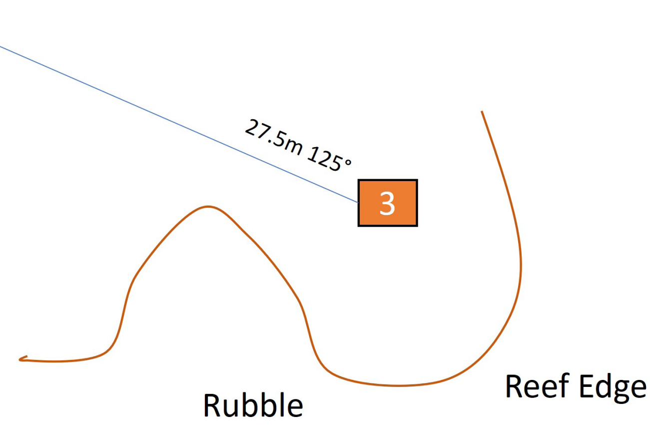


Figure 77. Example of mapping an outplant site from a central location.

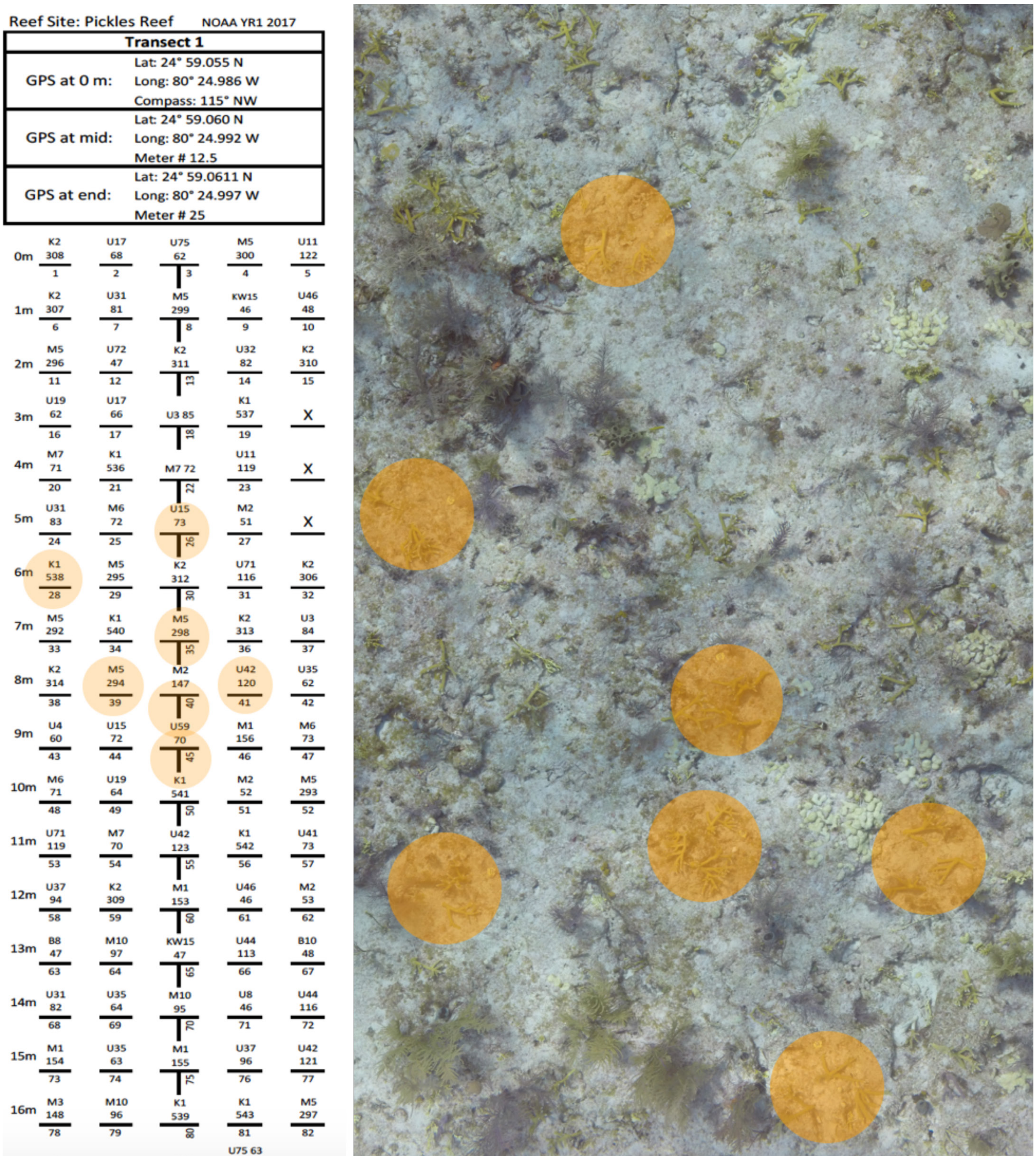
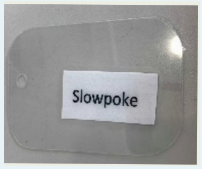
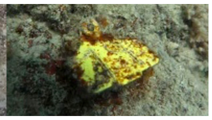


Figure 78. Example site map using a georeferenced grid design.

Table 10. Options of tags that have been used for tagging outplanted corals.

Tag Type	Pros	Cons	Important Notes
Laminated 	Inexpensive Quick to produce Easy to clean Fully customizable Quickly made in remote locations or in the field	Shorter life span Lamination can tear around hole Lamination can split if not sealed well	Cut the paper before laminating so that the edges are sealed on each tag. Rounding the corners of the laminated tag reduces the chances of the lamination splitting. Use 10 mm lamination for long lasting tags. Use a hole punch to make hole for attachment. Use waterproof paper to extend the lifespan.
Metal 	Inexpensive and readily available Fully customizable with metal stamp set or purchase pre-stamped Easily cleaned by bending or gently hitting with a hammer Can be made in remote locations or in the field	Difficult to find among benthic overgrowth  Tags snap with frequent cleaning Cleaning can scratch tag making it difficult to read Stamping takes a long time	If the stamps are too small (less than ¼”), it becomes difficult to read the numbers and letters once the tag is fouled. Glare can make these difficult to read in images.
Livestock 	Flexible and sturdy Come in many different colors and sizes Generally easy to find on the reef Easy to install Long lasting (>2 years)	Less customizable Can be expensive	Similar colors like light blue and white, red and orange, are difficult to differentiate over time due to fading and fouling. Red is a very difficult color to find on the reef. Select high contrast colors. Weight or secure the tags before installation; some brands float. The ink on tags that are made by hot stamping, rather than laser printing, last longer.
Printable ID Cards 	Fully customizable Easy to see on reef Easy to clean by slight bend Quickly made in remote locations or in the field (Power and computer needed)	Relatively expensive Availability of products Cards get brittle and break Need machine for printing	Tags can have very sharp corners, so it is preferable to round the corners.  Attach with short monofilament line to avoid entanglement with other tags or corals.
Engraved Plastic 	Long lasting Fully customizable Easy to find on reef Easy to clean	Expensive Can break with heavy impact-storms Takes time to order and produce	Layered contrasting colors (white over black) make the Tag ID more visible. Use two cable ties (in a chain-see image) to attach to nails on substrate so tag can move around.

length at the restoration site and outplanting corals at set intervals and distance away (perpendicular) from the survey tape creating an outplanting grid (Figure 78). The survey tape location can be geo-referenced (start, middle, and end) so a map can be created using mapping software and even incorporated into photomosaics or other imagery monitoring techniques. The example datasheet in Figure 78 diagrams a site layout for a 16 x 5 m outplant area. Divers lay a tape down the center of the area and collect GPS coordinates at the beginning, middle, and end. Corals are outplanted along the transect in suitable locations. If a location within this area is not suitable, it is marked with an "X." Data such as cluster number, tag number, and genotype are recorded. A mosaic was also completed for this particular area; orange circles on each panel mark matching outplanted coral clusters.

Tagging Corals

Even if restoration goals center on assessing broader ecological outcomes, they also may require "fate tracking" of specific outplants, often through tagged material. While this becomes increasingly difficult with larger scale, fate-tracking at a small scale still enables a means to assess the role of individual fragments or colonies toward the resulting ecological outcomes (and biological mechanisms at play). There are many different materials used to create tags, and the decision about what to use will be based on the available resources, budget, the timeframe of monitoring, and how much information needs to be included on the tags. Some of the more commonly used tags are described below (Table 10).

Restoration Site Maintenance

In some cases, outplant site maintenance may be necessary. Maintenance can be for two different goals: preventative and reparative. Preventative maintenance includes the removal of predators, algae, negative interactions, and quality control after outplanting to check that methods for outplanting were properly executed. Reparative maintenance should occur following events where damage might have occurred, such as a storm or periods of increased tourism, and will likely include the reattachment of corals. In cases where corals are outplanted as mitigation or as a tourist attraction, etc., more maintenance may be required or warranted due to funding and contractual obligations. Additionally, event-driven maintenance may be needed during and following a disease event, which could include removing dead or diseased portions of corals, applying epoxy to prevent the spread of disease, and/or attaching healthy fragmented corals to the substrate. All maintenance activities, especially the removal of organisms (e.g., predators or competitors), should comply with local regulations and permits.

Restoration Site Metrics

The monitoring of a restoration project will require different techniques depending on the goals and objectives of the restoration project and program. The CRC's Monitoring WG has developed a guide for monitoring coral restoration (Goergen et al., 2020). Within this document, there are Universal Metrics, which were designed to be reported for all restoration projects and cover basic metrics ranging from the area of the restoration site to the size distribution of restored corals. There are also Goal-Based Performance Metrics, which tailor monitoring metrics to specific restoration goals such as ecological restoration, restoration for coastal protection, or education, just to name a few. Details and guidance can be found in the "Coral Reef Restoration Monitoring Guide: Methods to Evaluate Success from Local to Ecosystem Scales" found on the CRC Monitoring WG webpage (Goergen et al., 2020).

In addition to the above-mentioned monitoring guide for restoration, we highly recommend following published best management practices, guides, and programmatic evaluation criteria for establishing a restoration site. The three criteria listed below do not require the standard monitoring methods as laid out for other metrics in Chapter 5 but can be used for program development and growth and should be evaluated during the restoration site design phase. Further, if established outplant sites are not performing as desired or meeting programmatic goals, these criteria should be reevaluated; it is best practice to evaluate the beginning stages of restoration such as restoration site selection, outplanting techniques, and community level characteristics to help determine the cause of decreased success. This evaluation can then be followed up with adaptive management strategies (Coral Reef Restoration Monitoring Guide; Goergen et al., 2020).

Evaluation Tool Criteria Alignment:

1) Outplant sites are established based on approved guidelines, practices established within this document, and by the CRC Monitoring and Genetics WGs (Baums et al., 2019); if methods followed published manuals and guides for site selection and deployment, a project will receive a score of 1 (Evaluation Tool Outplanting Metric #1).
2) Sites are surveyed for reef community structure and species abundance prior to outplanting; if baseline surveys are conducted prior to outplanting, a project will receive a score of 1 (Evaluation Tool Outplanting Metric #3).
3) Outplant site contains/has historical presence of outplanted species; if outplant species is present or was historically present at site, a project will receive a score of 1 (Evaluation Tool Outplanting Metric #2).

CHAPTER EIGHT

Scaling up a Restoration Program

Reef Renewal Foundation Bonaire

Coral restoration, as a community of practice, has evolved over many years with practitioners and scientists working closely together to promote successful restoration efforts. Despite significant progress in the field, most active restoration efforts are still not occurring at a scale large enough to make ecosystem-level impacts. Scaling up restoration efforts can occur by increasing the number of small-scale efforts (geographic scale) and/or increasing the scale or scope of an operation (programmatic scale). This chapter presents advice, key points, and challenges for practitioners to consider when planning for scaling up from small to large-scale operations.

Scaling up a restoration program requires a lot of planning to ensure a program has the resources to build additional nursery structures, staff to maintain the restoration program (Chapter 9 provides additional guidance), time devoted to both in situ and ex situ management, an outplanting strategy and management buy-in for the additional coral produced, a monitoring plan, a funding strategy (suggested three- to five-year plan), and an exit strategy. The species being used for restoration will determine how quickly each of these factors will need attention. For example, fast-growing species like *A. cervicornis* will require space, maintenance, and an outplanting plan more quickly than slower-growing species.

A well-thought-out, detailed plan for scaling up a restoration program will go a long way in the success of restoration efforts. Without proper planning, nurseries may become neglected or overgrown, causing an increase in health risks among the corals; nursery and outplant monitoring may not be achievable at the recommended levels, and overall success and production of the restoration program will suffer.

Nursery Considerations

The first consideration for scaling up a nursery is availability of permitted space. Nursery expansion can occur either within the nurseries already maintained or by creating a new nursery location. If the latter is chosen, proper nursery site vetting, following the guidance in Chapter 2, should occur with a small pilot project.

The second consideration is the need for maintenance of the additional corals and planning for exponential growth. For example, a small *A. cervicornis* nursery colony (5 cm) can be expected to produce approximately three to five 5 cm branches within six months to one year. If those branches are fragmented from the nursery colony and planted within the nursery as new colonies, each of those new nursery colonies will also produce three to five new colonies within six months to one year. This growth needs to be accounted for, and additional time will be required for maintenance at each nursery due to the increased number of structures and corals. Workforce and days on the water will likely need to be increased.

Management and organization are key to nursery expansion and will increase program efficiency. Developing a detailed user-friendly database and fragment tracking program will aid in the management and organization of the nursery corals.

Other considerations:

- Create multiple groupings of corals by genotype in the nursery and spread these groupings across the nursery or nurseries to spread risk.
- Invest time in mapping the nursery and where genotypes and species are located.
- Develop a labeling or coding system that is user-friendly so staff can easily double check their work.
- Devise a workflow for nursery structure maintenance and outplanting.
- Use nursery designs that are modular and allow expansion.

Outplant Considerations

The amount of time needed and the success of the restoration are the two most important considerations that go hand-in-hand when scaling up a program. Enough time must be spent outplanting each coral in order to have a successful restoration project. Currently, outplanting efficiency is one of the most challenging bottlenecks in restoration: How can diver-coral interaction be reduced without significantly sacrificing success rates? For restoration efforts to occur at an impactful, ecological scale, novel ways to increase our outplant capacity must be devised, using the same or fewer resources than traditional methods (Suggett et al., 2019).

Some practitioners have tried methods, such as outplanting ropes of corals (corals are intertwined in rope; Case Study #8.1), wedging corals, dispersing loose corals, fragmenting previously outplanted corals (Case Study #8.2), creating novel materials to attach to corals (Case Study #8.3), following a chessboard grid design to increase ecological footprint (Case Study #8.4), and using sexual recruits rather than asexual fragments to increase efficiency, but more research is needed on all methods.

Pre-planning an outplanting event will increase the efficiency of outplanting. Considering factors such as designating and marking specific outplanting locations, pre-installing outplanting substrates such as nails or pucks, and developing detailed site maps could all increase outplanting numbers. Some of these tasks could even occur during non-outplanting times of the year.

Monitoring Considerations

During the scaling up of a program, monitoring is an important but time-consuming task that must be considered. Monitoring should not interfere with or cause a significant reduction in the production of the program, but it must take place in order for programs to evaluate their success, make improvements (adaptive management), and fulfill permitting/regulatory requirements. The CRC Monitoring WG has developed a guide for monitoring restoration (Goergen et al., 2020) in which they have recommended methods for monitoring at larger scales. In addition, in Chapter 5 of this document we have also suggested how to modify nursery monitoring methods as a program grows. Some techniques include monitoring a percentage of the corals, using photos so monitoring can be done ex situ, or expanding monitoring methods to include technologies such as creating a photomosaic.

Reef Ecologic

Funding Strategy

The first few years of a restoration program are likely to be the most expensive due to startup costs such as staffing, materials (e.g., boat, lab, and nursery materials), planning meetings, and reconnaissance diving for both nursery site selection and locations for donor material collections (Spurgeon and Lindahl, 2000; Spurgeon, 2001). During the following few years when the nursery is in the grow-out stage, costs may be reduced as typically maintenance and nursery production is the focus. Once a nursery is well established (generally two to four years), production rates will become consistent; practitioners know what to expect of the nursery. During this time, practitioners should be able to determine an accurate annual programmatic budget (Spurgeon and Lindahl, 2000; Spurgeon, 2001). This budget should be used as a basis for determining the costs that would be needed to scale up to the desired level.

Example Budget Categories:

- Personnel (salary or hourly, overhead, fringe, benefits, contractual/legal, insurances)
- Vessel (usage/rental fees, captains fees, boat maintenance, fuel, slips and dock fees)
- Materials (nursery supplies, office supplies, electronics, SCUBA equipment and maintenance, outplanting supplies, cameras)
- Travel (mileage, ferry fees, airfare)
- Permits (fees)

Exit Strategies

Every program needs to have an exit strategy in place in case they are faced with financial, regulatory, personnel, or other reasons that the restoration program cannot continue. Exit strategies will be unique to each program but should consider the following questions: 1) What needs to be done with corals remaining in the nursery? 2) Do outplanted corals need monitoring or maintenance? 3) Should nursery structures be removed? and 4) What are the costs associated with these operations? If programs are working with threatened coral species, appropriate regulations and laws must be followed, so it is highly recommended that practitioners are in communication with their local regulatory office when developing an exit strategy.

CASE STUDY #8.1

Outplanting using ropes in an effort to increase efficiency

Location: Belize and Puerto Rico

To explore increasing outplanting efficiency of *Acropora* spp., we are highlighting two practitioner groups that have been trialing outplanting using ropes.

Figure 79. Nursery corals grown on ropes.

Corals are grown in a nursery on 2 to 3 m long ¼" rope made of polypropylene, sisal natural fiber, and/or hemp. Corals (approximately 5 cm in length) are inserted into a space in the rope between the three strands with 20 cm between colonies (Figure 79) and grown for about one year or until colonies are 20 to 30 cm in diameter. Polypropylene ropes last up to three years in the nursery, but the natural fiber rope types that have been used do not typically last much more than one year. This rope is then directly outplanted on the reef. Depending on the program's nursery management, prior to rope removal from the nursery, small fragments from the rope could be clipped to populate a new nursery rope or to outplant. Alternatively, ropes could be populated with fragments and directly outplanted on the reef, skipping the nursery phase.

The method used for outplanting the rope to the reef will depend on the habitat, coral size, and genotype being used. High rugosity/relief sites with large, fast-growing, and robust genotypes can be successfully outplanted without attaching the rope to the reef but by placing and wedging corals into a good location. However, lower rugosity sites and sites with higher energy require the rope to be secured to the reef in multiple locations; five to six masonry nails along a 2 m rope (Figure 80). Longer ropes can be used in the nursery and then cut to size for outplanting to meet the needs of the outplant design, e.g., genotype diversity and colony spacing.

Proximity of the nursery to the outplant site will increase efficiency of this method. If close enough, ropes can be swum to the reef for outplanting without leaving the water. Pop-up nurseries (temporary nursery is established, ~1 year, close to the outplant site to increase efficiency) could be considered for this method. If transporting ropes longer distance, large drums filled with water on the boat are a good transportation method. Small fragments will break off the ropes during transport, but they can be wedged back into the lines or in the reef during outplanting.

Rope types:

- **Polypropylene and plastic ropes** work well because they have high durability, low maintenance, and can eventually be incorporated into the reef by overgrowth of coral, crustose coralline algae, and other biota.
- Corals do not seem to overgrow/attach to **natural fiber ropes**, but algae do and cause localized tissue mortality. These ropes are very difficult to clean because the rope turns soft.
- **Sisal rope** degrades faster, so you want to check it regularly while in the nursery during grow-out so the corals do not drop. It has lasted at least one year in the nursery (note: in other places, sisal rope only lasted five months); this probably depends a lot on the movement from waves. The hemp rope trialed in this study was beginning to break down after one year in the nursery.

Outplanting using the rope method increases a practitioner's ability to outplant large colonies in an efficient manner (Figure 81). It is estimated to take one to two minutes per colony when outplanting with the most common method (*Acropora cervicornis*; nail and cable tie). The rope method takes about half the time when not using nails but similar time if using nails to secure the line. An additional advantage to this method is that outplanting is able to occur in conditions (e.g., higher energy, surge, current) that are not suitable for outplanting with cement or epoxy; cement and epoxy require calm conditions to hold the colony stable while the adhesive cures.

Additional research into other types of natural fiber ropes and the methods in which they are used is needed. Perhaps natural fiber ropes could be used for a short-term nursery phase and then for outplanting if a material can be found that does not cause localized tissue mortality.

Case study and images provided by: Lisa Carne, Fragments of Hope, Belize lisasinbelize@gmail.com and Michael Nemeth, NOAA Restoration Center, Aguadilla, PR; michael.nemeth@noaa.gov

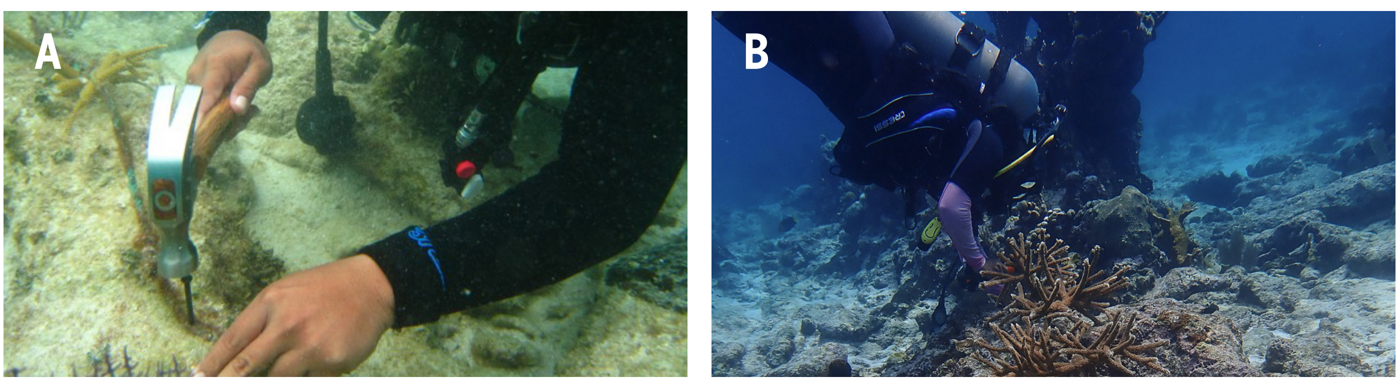


Figure 80. Outplanting ropes to the reef using nails (A) or without direct attachment (B).

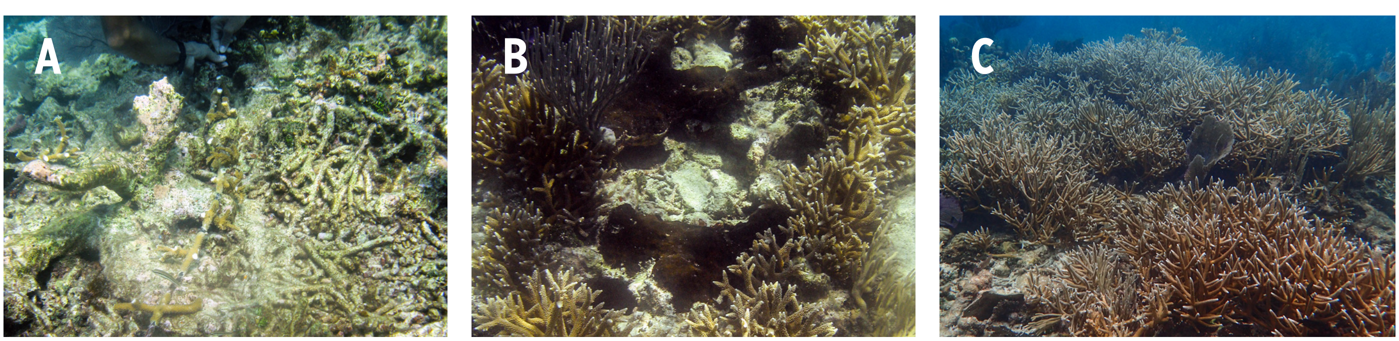


Figure 81. Time series of colonies outplanted on a rope from initial (A), year 2 (B), and year 7 (C).

CASE STUDY #8.2

Scaling up using cuttings from previously outplanted corals

Location: Puerto Rico

In the nursery, one colony can be cut into several fragments, grown out, and the process repeated to produce tens of thousands of corals that are available to help reseed and repopulate reefs. These nursery corals are then outplanted, which usually involves transporting corals to another site and attaching them one at a time by a team of divers. These methods are slow, time intensive, and relatively expensive because they require a lot of diver interaction time. A more novel approach is to use each of our restoration/outplant sites as additional nurseries. Cuttings can be taken from previous outplants to exponentially increase the number of corals outplanted and the size of the restoration footprint (Figure 82). A few years after outplanting, many corals have grown multiple branches, some of which can then be harvested and used for expansion.

For example, if 1,000 corals are initially outplanted to a site, restoration practitioners can return to the site after two to three years, harvest approximately 10 cuttings per coral, and expand the site to approximately 10,000 colonies. After another couple years, divers can return to the same site and harvest again in the same way, producing 100,000 colonies. Results from Puerto Rico show that this method works. Donor colonies heal within a few weeks, and the cuttings survive (100% survival after months). A couple years after the first outplanting, the number of corals at these sites and the restoration footprints were increased by a scale of magnitude. This method reduces the costs per coral and diver interaction times while exponentially increasing production.

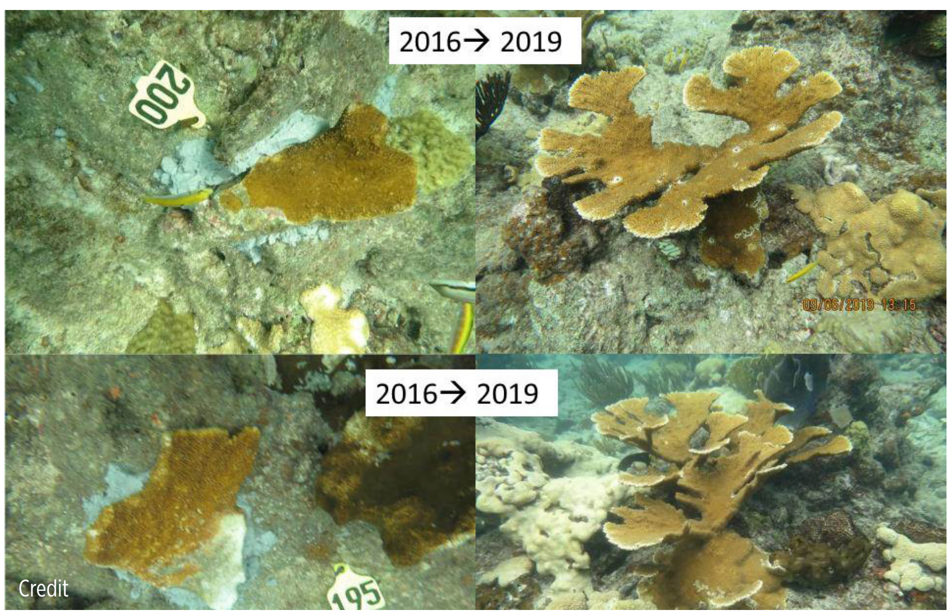


Figure 82. Example of how cuttings can be harvested by collecting branches from previously outplanted corals and cut into smaller pieces to expand restoration sites. The photos on the left are the original storm transplants in 2016. The middle photos are the same colonies in 2019 after two to three years of growth. The photos on the right are cuttings made from branches collected from these colonies.

Case study and images provided by: Sean Griffin, NOAA Restoration Center, Aguadilla, PR; reeftechinternational@gmail.com

CASE STUDY #8.3

Rapid, upright outplanting of nursery-grown staghorn acroporids with the Horticulture Coral Ring Mount (HRM) attachment device

Location: Montego Bay, Jamaica

Culturing corals in an in situ nursery is relatively easy. Outplanting them safely, securely, discretely, and with reasonable expectations of survival is more challenging, often providing a bottleneck to ecosystem (services) scales and leaving excesses on-nursery with resulting losses.

To streamline outplanting, we broke it into a series of quick, discrete actions by employing the physical connectivity of a normal construction screw and the coral's natural propensity to attach and overgrow substrates and attachment materials. In order to use a steel screw with the relative fragility of coral skeleton, we pre-affix a washer to the in-nursery coral so that it can be incorporated into the coral's structure over subsequent weeks. This means the coral is doing the work of securing the device, and not the diver. We have described this proprietary attachment device as the Horticultural Coral Ring Mount, or HRM (patent pending).

How it works?

The practitioner begins with a mature coral nursery, replete with larger branching corals (Figure 83D). On a nursery visit, approximately 10 weeks prior to outplanting date, an appropriate branch on a nursery coral is chosen, and the HRM is secured toward its base with a wrap of the HRM's line and cleat, ensuring that its anchor portions are in contact with the coral's tissues (Figure 83A). This action takes about 15 seconds, and an experienced practitioner may comfortably affix 100 HRM on one S80 SCUBA tank dive at 10 m depth. Initial overgrowth of the line may be notable at 10 days (Figure 83B), with structural incorporation of the anchor portions into the nursery coral's skeleton at eight to 10 weeks (Figure 83C).

At the time of outplanting, the practitioner cuts the planting branch away from the main nursery isolate at ~1-2 mm below the HRM, a distance enough to not impact the overgrowth, but without appreciable overhang. The practitioner now has a discrete branch with the exposed outer portion of the HRM projecting at the bottom of said branch (Figure 83F).

On the outplanting reef, the practitioner finds and/or prepares a planting point with a screw-receiving hole. Natural holes in the reef covered in crustose coralline algae (CCA) may be present and appropriately sized for the screw, and are usually already clean (of turf algae), whereas pre-cast or pre-drilled holes of artificial substrates may require cleaning. If underwater drilling is required, the practitioner finds a small spot of clean bottom, either of CCA or bare, and drills a short 7/32" (bit size) hole. As the coral is planted upright and the contact footprint is small, the clean-bottom spot may be only a few square centimeters.

The practitioner now inserts an off-the-shelf 1/4" x 1.25" masonry screw through the exposed HRM ring and into the receiving hole. The practitioner then turns the screw to tighten with a hand-held screwdriver until secure, with the coral solidly perpendicular to the substrate (Figure 83E). This process takes one diver less than ninety seconds; a buddy-pair may plant 10 in less than six minutes. Over subsequent days and weeks, the coral will overgrow the screw-head and surrounding substrate (Figure 83F).

Case study:

In 2017, Seascape Caribbean was contracted by Sandals Resorts International to set 4,000 cultured *Acropora cervicornis* isolates to 4,000 m^2 of historic staghorn reefscape in Montego Bay, Jamaica. To produce the material, we erected five 200-nubbin Buoyant Drop Line (BDL) systems in clean sand at 8 m depth to the west of the Sangster International Airport, and filled each with a locally sourced wild lineage (N=1000). At seven months, early prototype HRM devices were set to the branches of these nursery corals at five to eight per isolate for a total of approximately 4,500 outplant units. These were left for another eight weeks to overgrow for planting, and then harvested with sharp side-cut pliers as described above. Twenty-four corals were collected by two practitioners from each BDL lineage (N=120) per day, as a comfortable day-rate regardless of weather. Receiving holes were made in the substrate at the outplant location with an underwater battery-operated hammer/masonry drill.

Survivorship at 30 days was somewhat lower than anticipated (~70%) largely due to breakaway in the screw-down process, as rectified in following design iterations. Chronic overfishing and stony coral tissue loss disease (SCTLD) also resulted in an abundance of large bearded fireworms (e.g., *Hermodice carunculata*) including some banding syndrome, both vectored and from the bottom, that were apparently not mitigated by upright planting. Survivorship at eight months remained at approximately 50%; however, through several strong winter storms this was sub-30% at 18 months (18 to 35 isolates per 100 m quadrat). Some of these looked poor and unlikely to persist, though a majority were attached or reattached and strong. Storm-breakaways were partial as the overgrown screw made a very secure base, and the remnants are expected to regrow. Further information on the development and use of the HRM, planting point choice and this project generally are in Ross et al. (in prep).

Case study and images provided by: Andrew Ross, Seascape Caribbean, Suzanne Palmer, UWI Mona, Bernadette Charpentier, Duwatech. Contact: ross.andrew@mac.com

Patent Pending: Coral Nursery and Planting System based on a ring or washer mount. Andrew MacKay Ross.

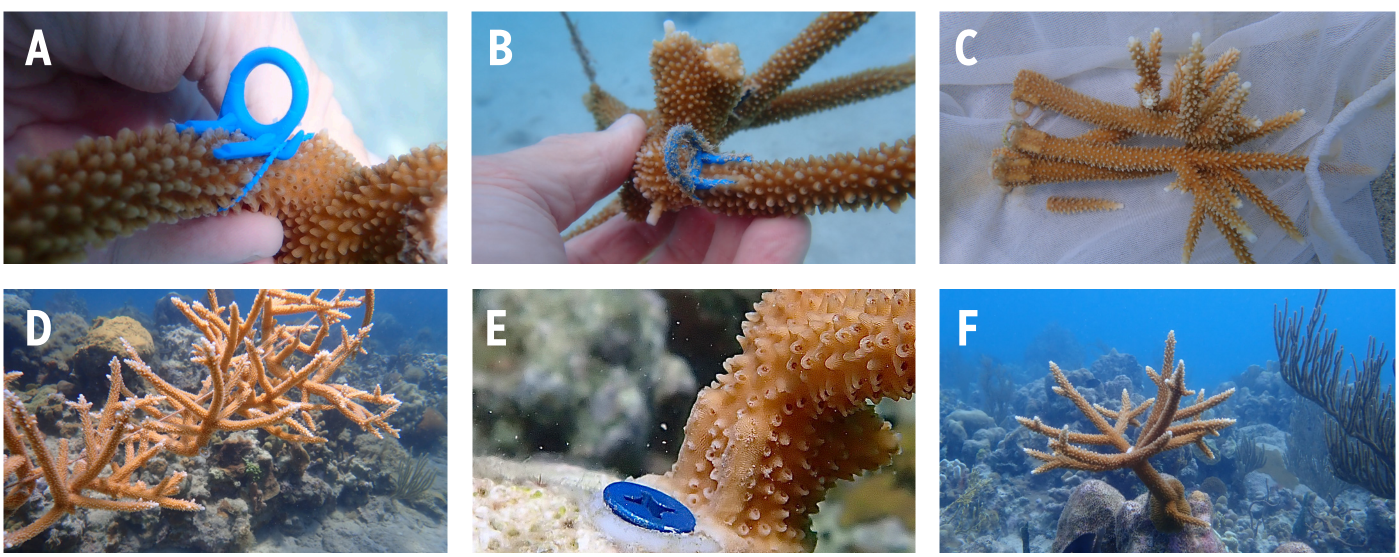


Figure 83. Stages of the HRM: A) at setting to the coral branch noting the post and base anchoring elements of the current device, B) commencing overgrowth, C) harvest, noting the polyp formation over posts, D) BDL nursery nearly ready for harvest, E) recently planted smaller coral noting upright orientation F) secure coral at 12 months, noting discrete, elevated planting position and benthic overgrowth. Note: D and F are of the above case project's early prototype; whereas A, B, C and E are of the current design, also in Montego Bay.

CASE STUDY #8.4

Scaling up following a chessboard outplanting design

Location: Colombia

This project implemented an innovative chessboard-style outplanting approach, achieving live coral cover increases between 25% to 41%. A total of 48 *Acropora cervicornis* colonies, each 15 cm in diameter, were outplanted within 16 m^2 patches at a density of 3-4 colonies per m^2. To maximize the ecosystem benefits of spacing, four outplanted patches were placed within a 400 m^2 area, interspersed with non-outplanted 16 m^2 patches to create a chessboard pattern. This structured layout was replicated 25 times to rehabilitate one hectare of degraded reef, with a total of 4,800 coral outplants enhancing coral growth and ecosystem resilience over a larger area compared to traditional, contiguous planting methods.

Why Chessboard Outplanting is Beneficial

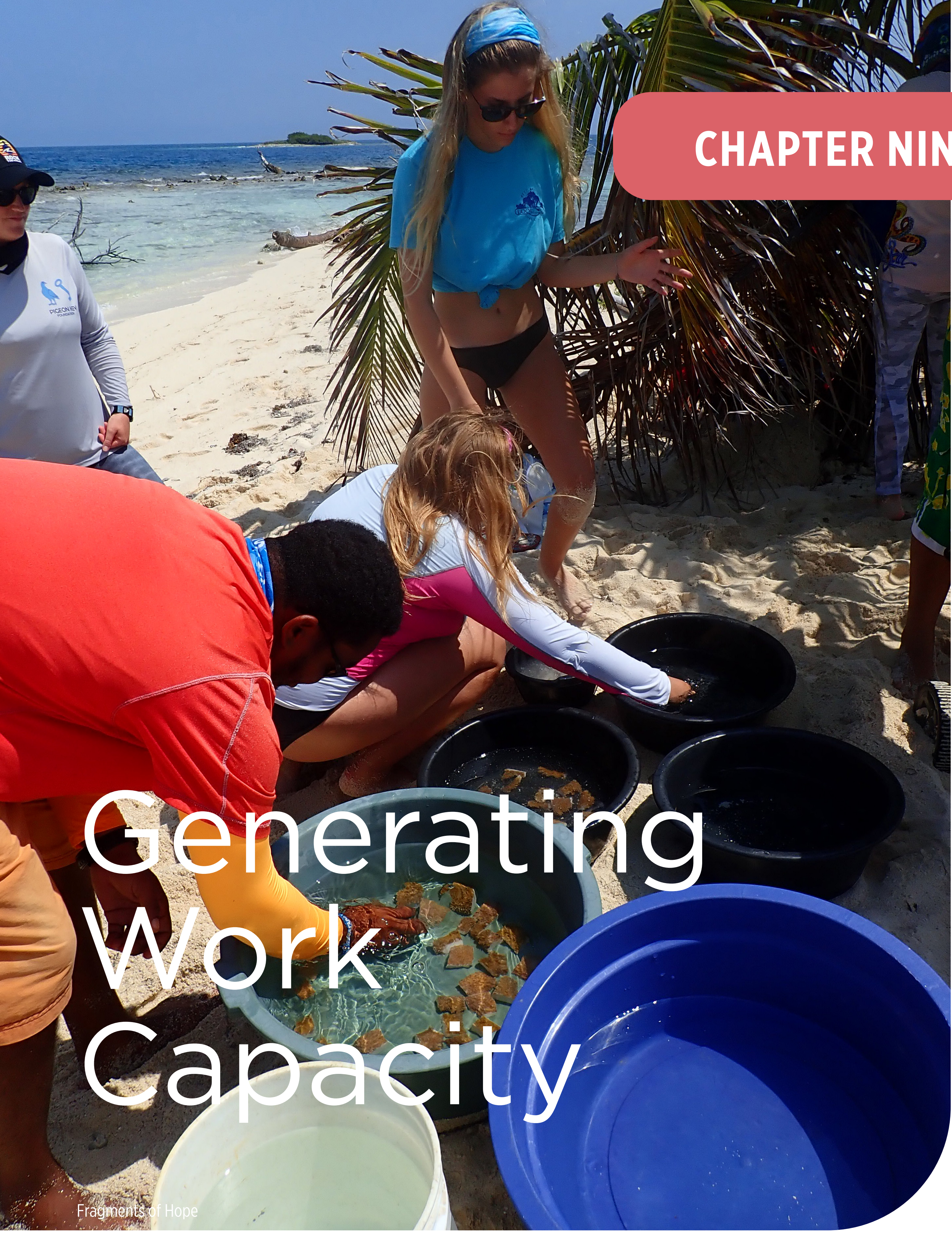
Unlike continuous outplanting, the chessboard configuration minimizes competitive stress by creating buffer zones between patches. This spacing reduces crowding, allowing each coral colony to expand more effectively without direct competition, promoting faster tissue spread and higher survival rates. The configuration also fosters ecological connectivity across the reef, which supports natural processes like fish recruitment and coral larval dispersal, enhancing overall reef resilience.

Outcomes

Within six months of outplanting, this method resulted in a 25% increase in live coral tissue area, as documented by Bayraktarov et al. (2020). The rapid increase in live coral cover highlights the efficacy of this design over traditional, densely-packed approaches, which often take longer to achieve comparable coverage levels.

Case study and images provided by: Phanor H. Montoya-Maya, Corales de Paz Colombia; Coral Restoration Foundation; phanor@coralrestoration.org.

Figure 84. Schematic of the outplanting and upscaling approach used by Corales de Paz in Colombia.



CHAPTER NINE

Generating Work Capacity

Fragments of Hope

Restoration projects take an enormous amount of capacity in terms of materials, resources, and staff. As a restoration program expands, the work capacity must also grow. Generating greater work capacity is a key element for restoration programs that want to: 1) run an efficient coral restoration program, 2) increase gross production, 3) generate greater public awareness, and 4) increase the ecological impact of their restoration efforts. However, this can often be a programmatic bottleneck in which there are not enough divers and researchers to complete the work necessary to maintain or grow the restoration program. In addition, funding is often a limiting factor in a program's ability to hire enough paid staff to accommodate its growing needs.

Programs have overcome this capacity problem by the development and use of volunteer, internship, citizen science, and outreach programs. In addition, local dive shops and ecotourism companies have developed partnerships with restoration practitioners to aid in restoration activities such as nursery maintenance and outplanting. These activities have broadened the reach of restoration by involving a broader audience, encouraging greater ocean stewardship, creating awareness, and exposing locals and tourists to a unique experience.

Alternatively, advancements in approaches, materials, and equipment have increased per-technician efficiency and therefore net productivity, reducing the need for staff per se and the logistical costs and constraints associated with more staff.

Training

Proper education, training, and guidance must be an integral part of building work capacity. Restoration programs who are partnering with local dive shops or ecotourism programs should begin with training workshops or presentations where participants receive guidance on important aspects of coral reef ecology and restoration methodologies. It is important that these workshops are attended by representatives from all stakeholder groups involved in coral restoration to ensure consistency and good communication among partners. Such training, followed by in situ training for responsible diving techniques and restoration practices, will enhance the experience of dive tourists and provide them with the knowledge needed to promote good coral reef stewardship.

Planning

If the growth of a restoration program (or project) is a goal, there are several ways to generate a workforce to help programs achieve their objectives. Increasing the size of a restoration program is not always in the best interest of the practitioner; staying within a program's means will likely be more successful than growing without the appropriate capacity to support the growth. Plans must be made to manage the growth in multiple years to come, including an exit strategy if funding or capacity is lost. More importantly, expansion and growth should not interfere with the success, growth, and survival of nursery or outplanted corals. If

KAUST Coral Restoration Initiative

monitoring results show a decrease in health or survivorship of the corals, a program should evaluate what is driving this result.

This chapter explores several types of ancillary support programs that have been generated to help restoration practitioners.

Types of Workforces

There are numerous types of workforce that could be utilized when growing a program's capacity.

Paid Staff — Paid by the hour, day, or on salary, these staff complete a majority of the work within a program. Some programs may choose to bring in seasonal staff during busy times of the year, such as during outplanting.

Intern — A person or student who is participating in restoration activities to gain work experience or to fulfill requirements. Could be paid or unpaid.

Volunteer — A participant who is trained by the organization to partake in assigned tasks without pay. Land-based or diver.

Citizen Scientist — Non-professional scientist (diver or snorkeler) who is trained in participating in the collection of data for a research project.

Working Diver — SCUBA diver who performs work underwater associated with the assigned tasks such as cleaning, collecting data, or clipping corals. Working divers should be well trained, proficient in SCUBA, and able to take on the challenges of completing tasks while underwater. Could be paid or volunteer.

Contractual — person under hire by the restoration program to perform assigned tasks. These can be divers, boat drivers, or other operations. Commercial divers may be contracted to complete more advanced, labor-intensive diving skills such as installing nurseries.

Monitoring Program Growth

In order to evaluate the success and efficiency of an increased work capacity, corals should be monitored as described in Chapter 5 and the Coral Reef Restoration Monitoring Guide (Goergen et al., 2020), with a focus on who completed the work. For example, corals outplanted by the volunteer workforce should be evaluated against those outplanted by the experienced workforce to determine if training is sufficient and if volunteers are fulfilling their role. If corals outplanted by volunteers are not performing as well, the training offered to them should be evaluated and those tasks possibly re-assigned to other workforce groups.

Fragments of Hope

CASE STUDY #9.1

Expanding programmatic capacity through a working-diver volunteer program

Location: Key Largo, Florida, USA

The volunteer program at the CRF™ has evolved into three types of non-staff, volunteer-centralized roles: 1) a long-term working diver volunteer program, 2) an internship, and 3) a short-term recreational volunteer. These classifications of volunteers complement each other but are independent from one another in their purpose and management. This case study explores the impact of the formal, long-term working-diver volunteer program and internship program.

The goal of the working diver program is to facilitate the educational and restoration goals of CRF™. The working-diver volunteer requires training and time investment but provides beneficial returns with regard to restoration work achieved, educational outreach, and financial returns (donations). The quantifiable measurements of these returns are different for the formal volunteer and internship programs. For example, the internship program supplies a financial reimbursement to interns whereas long-term volunteers may provide financial donations to the organization.

In 2018, more than 23,000 corals were outplanted to reefs in the Florida Keys, and, of these, a quarter (about 5,750 corals) were outplanted by working diver volunteers and more than 40% (about 9,660 corals) by the internship program. Figure 85 illustrates the impact of each of the three non-staff volunteer types to CRF's outplant goals in 2018.

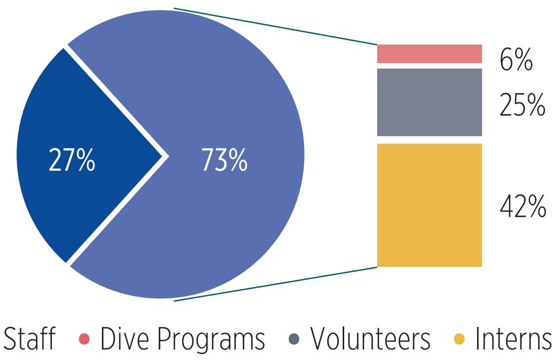


Figure 85. Results of the amount of coral outplanted by each of the three non-staff volunteer-types. Of the 23,000 corals outplanted in the 2018 operating year, at least 73% of the outplants were completed by non-staff. In total, at least 25% (or approximately 5,750 corals) were outplanted by long-term working diver volunteers and more than 40% (or approximately 9,660 corals) were outplanted through the internship program.

The working diver volunteers represent a diversity of interest, background, skill level, and availability and vary throughout the year between 100 and 180 individual working divers for CRF™. The working diver internship primarily consists of students currently matriculating or post-matriculation at a university.

Training

Since the availability for scheduling of the formal volunteer program and the interns differ, the training programs are tailored accordingly. For the formal working-diver volunteer program, initial inquiries are evaluated for suitable applicants using an online application and survey. Once approved, the working diver applicant will begin the documentation process, which includes multiple release forms, as well as proof of dive history and dive/safety certifications.

Once past the initial vetting process and into the document pipeline, training occurs in a multistep process:

Step 1: **Orientation level 1:** An introduction to CRF™ expectations and logistics; includes dives that focus on safety and essential nursery skills.

Step 2: **Nursery diver:** Once evaluated in situ, the working diver is approved for basic nursery work.

Step 3: **Orientation level 2:** An in-depth discussion of outplant methodology; includes dives focusing on necessary harvest and outplant skills.

Step 4: **Outplant diver:** Upon completion of an outplant orientation, the working diver may be approved to work alongside staff for outplant restoration work. Initially, they will be paired with restoration staff and/or experienced outplant divers to ensure outplant standards.

Step 5: **Continuing Education:** A working diver volunteer can join on any orientation again for skill and concepts review, as well as work with any staff or experienced working diver for extra skill development.

Upon acceptance into the internship program, interns immediately have a two-week training period. During this time, they will be exposed to all facets of the organization including in situ restoration work, social media, and operating the visitor location, with the heaviest focus on in situ training. Their experience is similar to the formal volunteer experience, with initial training in the nursery followed by outplant and coral monitoring training. Interns are then internally scheduled for working dives on a daily basis.

Benefits

Long-Term Working-Diver Volunteer Position

- Working divers add additional support to your field-based efforts and increase your programmatic capacity while easing staff resource allocation between different needs and projects.
- Volunteers represent a valuable source of funding matches for grants.
- Volunteers bring an influx of new energy, diversity, and background within an organization and can act as long-term ambassadors.

Working-Diver Internship Position

- While volunteers are available pending their personal schedules, interns are available and on-site for this educational experience and purpose. They provide a steady availability on days when volunteer availability may be low.
- Interns represent a valuable source of funding matches for grants.
- As interns move forward in their careers, they can act as lifelong ambassadors for an organization.

Challenges

Long-Term Working-Diver Volunteer Position

- A volunteer can easily be viewed as free labor; however, they are an investment and so require time and energy to succeed. Training is an ever-evolving process.

- All volunteers carry personal expectations and need for appreciation. If the expectations of the volunteer applicant and those of the organization do not align or if an organization falls short of meeting the needs of its volunteers, volunteer attrition will result.

- The amount of paperwork and safety documentation increases significantly with volunteers. Internal resource allocation for the maintenance of these documents can be significant; constant re-development of pipelines and in-take is necessary for growth.

Working-Diver Internship Position

- An educational stipend used for reimbursement, whether in financial support, housing, or food while volunteering through an educational experience can represent a costly investment that not all organizations can afford.
- The laws governing non-paid internships may be complex regarding the boundaries of what an intern can or cannot do in a more rigid position than formal volunteering.
- With most internship opportunities attracting younger individuals, it can be challenging and time consuming to train interns at a potentially lower maturity level.

Case study and images provided by: Roxane Boonstra, CRF, Key Largo, FL, USA; Roxane@coralrestoration.org

CASE STUDY #9.2

Enlisting the Recreational Diver in Coral Restoration Efforts.

Location: Kralendijk, Bonaire, Dutch Caribbean

Since its beginning in 2012, Reef Renewal Foundation Bonaire (RRFB) has expanded its capacity by building a recreational dive program model to assist in accomplishing its mission of restoring Bonaire's coral reefs.

In this model, local dive operators are members of the Foundation and execute a practical restoration program with oversight from RRFB staff. Dive shop members serve as educational ambassadors for Reef Renewal Bonaire's restoration program as well as training centers for Reef Renewal divers. By offering the Reef Renewal Diver distinctive specialty course, recognized by PADI, dive shop members are able to build their businesses and elevate their brand, while simultaneously restoring reef areas and supporting the RRFB project.

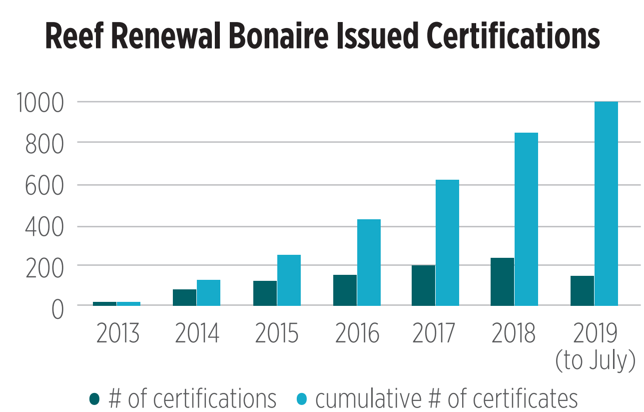


Figure 86. Number of divers trained by Reef Renewal Bonaire between 2013 and 2019. More than 1,000 divers have been trained since 2013.

Through this successful recreational dive program model, since 2013, more than 1,000 divers (residents, tourists, researchers, interns, and local youth) have been trained by Reef Renewal Bonaire and its five dive shop members. Figure 86 shows the number of issued certifications by year as well as the growth of the cumulative number of certifications issued (Note: graph was compiled July 2019).

Training

The Reef Renewal Diver specialty course is designed to give basic training in coral nursery maintenance and outplanting to divers looking to participate in coral restoration. The course is taught by instructors trained by RRFB but who work for the dive shop members. It is structured as three modules comprised of three training dives with a knowledge development presentation and a hands-on skill session to be completed on land prior to each dive. Each module of the course has a different learning objective focused on a basic restoration skill, with each dive also building upon and improving basic diving skills.

Module 1: Topics covered include conducting nursery surveys and recognizing coral competitors, coral predators, and coral disease. Hands-on demonstration of using nursery maintenance tools and discussion of nursery etiquette. Dive 1: Divers clean coral nursery trees under direct supervision from the instructor.

Module 2: Topics covered include basic coral anatomy, coral bleaching, and asexual reproduction. Hands-on demonstration and practice of tying and hanging techniques and discussions of considerations when working as a team underwater. Dive 2: Divers tie and hang coral under direct supervision of the instructor.

Module 3: Topics covered include sexual reproduction, genetic diversity, and various outplanting techniques. Hands-on demonstration and practice of outplanting coral on a structure or on hard substrate. Dive 3: Divers practice outplanting coral under direct supervision of the instructor.

After receiving their Reef Renewal Diver certifications, divers are qualified to join RRFB staff as volunteers. Volunteers not only help with day-to-day activities, but are also pivotal in sharing RRFB's vision with the wider community.

Benefits

- Dive shop members naturally become educational centers for Reef Renewal Bonaire's restoration program promoting the project to a wider audience and thereby increasing program exposure.
- Dive shop operators generate financial support for RRFB through paying their membership fee, placing an open donation box, selling RRFB merchandise, and teaching courses (a portion of the course fee goes to RRFB as a donation).
- Training is outsourced to the dive shop operators, allowing for the core RRFB staff to focus time and resources elsewhere.
- Specialty courses accomplish various restoration activities, expanding the work capacity of the Foundation and aiding in achieving annual outplant goals.
- Specialty courses promote awareness and educate a large number of people about the RRFB project, as well as aid in volunteer recruitment and donor generation.

Challenges

- Trained divers are mainly short-term tourists, leading to less continuity of individual volunteers and inhibiting opportunities for further higher-level training.
- Responsibility for training and dive shop nursery maintenance is given to dive shop operators but requires an initial investment of RRFB time and resources through the training of specialty instructors at each dive shop as well as additional training during turnovers.
- Dive shops can be hesitant about the initial project buy-in as they can see it as a big commitment, do not perceive the benefits, and are unwilling/unable to allocate their own resources.

Case study and figures provided by: Francesca Virdis, Reef Renewal Bonaire, Bonaire, Dutch Caribbean; francesca@reefrenewalbonaire.org

CASE STUDY #9.3

Contractor Support

Location: Puerto Rico (PR) and the U.S. Virgin Islands (USVI)

Response to physical impacts is a jurisdictional priority in both PR and the USVI, an identified capacity gap in both jurisdictions, and a priority element of the draft Acropora recovery plan. PR and the USVI have acknowledged that because of internal limitations and the need for quick and flexible response, more robust action on the part of NOAA was necessary to help stem the unchecked and unnecessary coral losses that were occurring after physical impacts. In 2009, an emergency response support contract with a local firm was set up. This, in combination with NOAA's Restoration Center establishing an on-the-ground presence in the region, has enabled NOAA to address the numerous impacts that were occurring annually.

This support contract provides NOAA, PR Department of Environmental Resources, and USVI Department of Natural Resources support to have a functional emergency restoration operation, but also provides a mechanism to accomplish other tasks needed for coral propagation like construction of coral nurseries, maintenance, and outplanting. Tasks can be set up under this contract to fit a variety of needs and timeframes, from a couple days of work needed for maintenance or site checks, to longer term efforts that may take weeks or months. Based on a schedule of services provided by the contractor, individual task requirements can be customized from the size of vessel needed to the type of divers required (scientific, dive master, safety diver, commercial, or restoration technician).

Benefits

- Can be cost-efficient because only paying for specific tasks when they are needed (construction of nurseries, quarterly maintenance, outplanting events, etc.). There is not as much overhead.
- Allows for flexibility during unforeseen events (storm damage, disease outbreaks, etc.).

Challenges

- There may be long periods (weeks to months) between tasks. If there is not enough work to create full-time jobs, divers may have to look for other part-time work, or they may move on to other job opportunities altogether, which will require training a new set of divers.

Case study provided by: Sean Griffin, NOAA Restoration Center, Aguadilla, PR; reeftechinternational@gmail,com

CASE STUDY #9.4

Local Youth

Location: Fiji

Since it began in 2006, Reef Explorer Fiji's coral restoration program has been embedded in community-based marine management efforts. As such, involving resource owners from local communities in the efforts has been an integral part of our coral restoration activities.

Local community members play various roles in the restoration efforts, from assisting with establishing new nursery and restoration sites, propagating corals to stock nurseries, transplanting cultured corals from nurseries back to the reef, and ensuring the safety of nurseries and restoration sites from snorkeler damage (Figure 87). While community elders were involved in the establishment of coral nursery and restoration sites, generally it has been village youth (18 to 35 years old) who have been involved with field activities associated with the program (i.e., propagating and transplanting corals).

Figure 87. Youth divers assisting with coral nursery work.

Training

Before their involvement with field activities, village youth are first given a briefing about the coral restoration program that covers how and why the restoration is being conducted and how they will assist with the effort. Generally, this briefing has been conducted in advance of any field activities, and village elders accompany the youth during the program.

All other training is provided on-site in the field as the methodologies used are simple and conducive to hands-on training.

Benefits

The involvement of village youth in the restoration program

- Provides a range of educational opportunities including many active learning experiences
- Increases stakeholder understanding and support for the restoration initiative
- Creates further intergenerational support for marine resource management efforts that are being spearheaded by village elders

Challenges

- Village youth groups often have a range of responsibilities in the community and may not always be available to assist with field activities when Reef Explorer staff are ready to conduct them.
- Involving too many people in the effort at once, particularly when transporting corals, does not necessarily expedite the work but rather can make the field work harder to manage and less efficient.
- Providing snorkeling equipment and wetsuits for groups of village youth is an additional expense for the effort.

Case study and images provided by: Victor Bonito, Reef Explorer Fiji, Fiji Islands, staghorncoral@hotmail.com

CASE STUDY #9.5

Scaling through tour operator partnerships: Coral Nurture Program

Location: Great Barrier Reef, Australia

In 2018, a unique partnership between researchers and tourism operators was established on the northern Great Barrier Reef, the Coral Nurture Program (CNP; www.coralnurtureprogram.org), to develop novel "stewardship-based" management of economically high-value Great Barrier Reef reef locations. The tour operator industry largely sustains the Great Barrier Reef's $6.5 billion-per-year asset value and has a strong desire to maintain and restore the quality of their "high-value" reef sites. Back-to-back mass coral bleaching events of the northern Great Barrier Reef in 2016/2017, in particular, left this industry vulnerable to further stressors, and the CNP was established to work alongside the Government (including the Great Barrier Reef Marine Park Authority, GBRMPA) to develop site-tailored coral propagation and outplanting approaches to rehabilitate coral abundance and diversity.

Phase 1 of the CNP activities (February 2018 to February 2019) focused on a single flagship reef site (Opal Reef), which is characteristic of many northern Great Barrier Reef sites after 2017, where coral health remained high for some within-site locations but not others (thereby ensuring donor colonies without the need for inter-reef translocation effects). The goal was to implement low-cost coral propagation and outplanting approaches that could dovetail into existing operations and thus be cost-effective but also be easily adapted to existing business models. Importantly, the early workflow was to adapt what had already been learned from more than a decade of work in the Caribbean into the unique ecology and governance/management structure of the Great Barrier Reef. This was particularly central to establishing novel permitting for activities never previously conducted; for example, implementing capacity to re-plant naturally fragmented material (fragments of opportunity), which until 2018 had not been permissible, thereby restricting site maintenance to activities such as pest corallivore removal. Important outcomes included establishing low-cost nurseries (carrying >2,500 corals) and developing a new reef attachment device, Coralclip®, that transformed the ability to replant coral by one to two orders of magnitude faster (and hence more cost-effectively) than was previously possible via conventional methods used to date. Using Coralclip®, the CNP outplanted nearly 5,000 corals to Opal Reef in the space of a few weeks (see Suggett et al., 2019), largely through routine vessel operations but out-sourcing operator staff to outplant.

Phase 2 of the CNP activities (April 2019 to April 2020) examined how the approach developed for a single site and tourism operator via Phase 1 could be applied to multiple reefs of different environments/conditions and across multiple tourism operators of different business models (Figure 88). During this phase, CNP also assessed how Coralclip® could be adopted by existing restoration practitioners worldwide. Efforts focused on ensuring standardized workflows for establishing nurseries and outplanting, including training, site evaluations, and data reporting (in part for ecological trajectory assessments, as well as permit compliance). Initial installation of nursery platforms at all sites provided very visible demonstrations relatively quickly to operators and their tourist customer base of active site rehabilitation practices. Active outplanting was slower to adopt, and ultimately was best executed in targeted "campaigns" when staff were available without impacting their regular operation.

Capacity clearly rested on feasible business operations, uniquely tested during this phase by a "perfect storm" of an unprecedented summer heat wave event immediately post-spawning (reducing capacity to fragment and outplant) and COVID19 travel restrictions. As of March 2020, >50 nursery platforms were established and >15,000 corals were outplanted across five major high-value tourism sites. Planning has begun toward Phase 3 of CNP, which includes broader (regional) adoption among the tourism industry and full tracking ecological responses of the outplanting sites.

Case study and images provided by: John Edmondson, Wavelength Reef Cruises & Coral Nurture Program; info@coralnurtureprogram.org; and David Suggett and Emma Camp, University of Technology Sydney; david.suggett@kaust.edu.sa and Emma.Camp@uts.edu.au

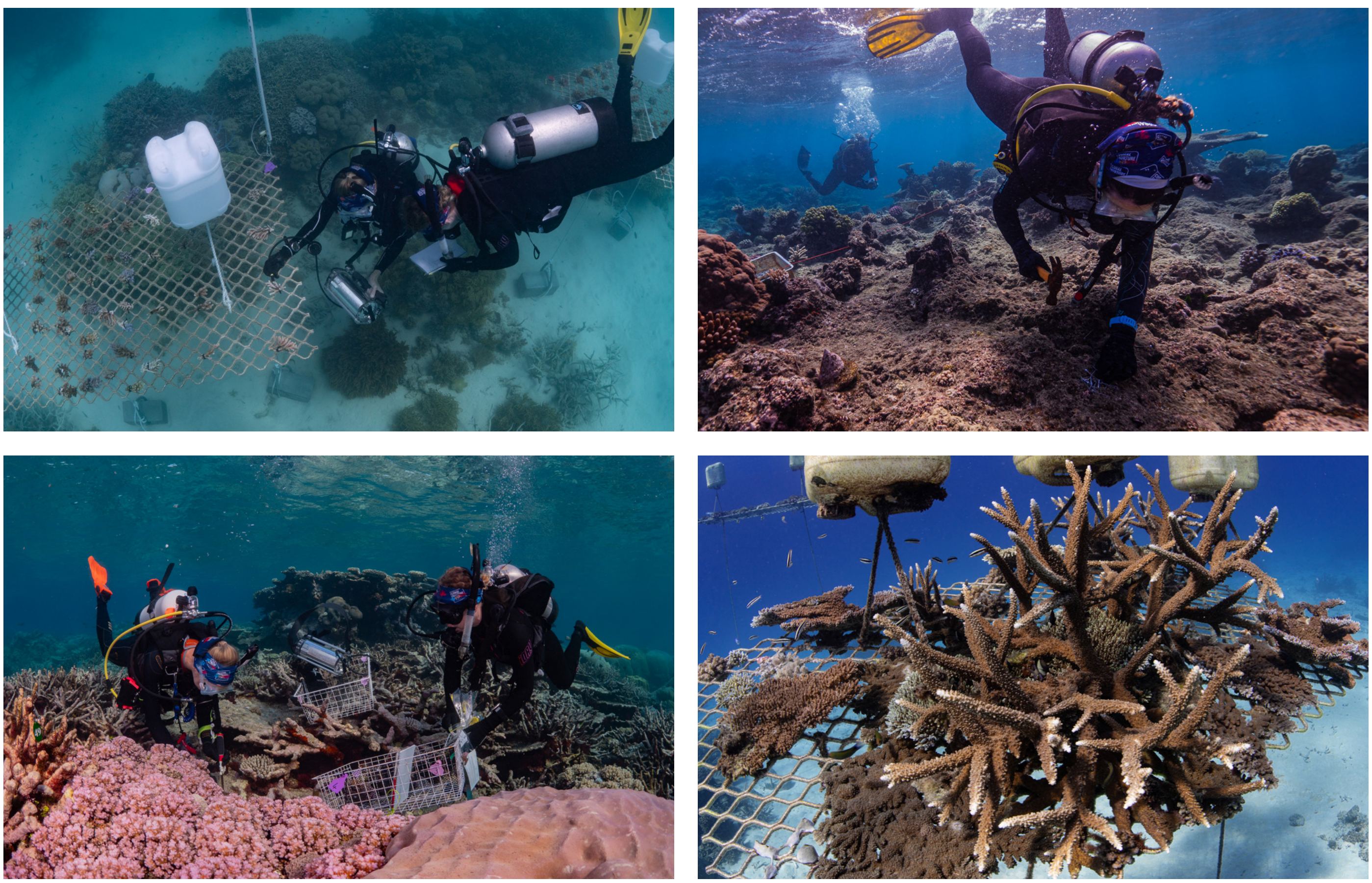


Figure 88. Coral Nurture Program at work. Top: Operators tending to nurseries and out planting using Coralclip®. Bottom: outplanting corals to a reef site and corals growing in a nursery.

CLOSING REMARKS

Coral Restoration Foundation

This Guide is a representation of recent work, findings, and ideas from restoration practitioners, researchers, and managers from all over the globe. These were gathered from conferences, interviews, workshops, publications, and grey literature in hopes of providing the most comprehensive Guide to implementing in situ coral reef restoration from the planning of a restoration program through the outplanting of corals from a nursery setting. Included at the end of the Guide is an introduction to how programs are approaching scaling up of their restoration programs to scales that are more ecologically relevant. While every effort was made to include all potential topics and techniques, we recognize that not everything could fit, but hope it provides guidance to start a well-rounded informed program with a good base to grow from. As more restoration programs find efficient, reliable ways to do restoration at a large scale, we suggest that the CRC update this Guide or create a new version to keep products relevant to and representative of the field.

Not included in this Guide is the use of sexual reproduction in coral restoration, although it is a very important aspect for the longevity and diversity of a program. However, this topic was out of the document's initial scope and is a field that requires additional research on how to best incorporate it at scale into a restoration program. The CRC Larval propagation working group is developing strategies to predict, capture, record, and settle coral larvae. We urge you to become familiar with their guidance and start integrating a mixed approach to your restoration program if resources allow. Further, we did not include guidance on the use of artificial structures in restoration. This topic also needs further development and was out of the scope of this document.

During the development of this Guide, we were asked to provide guidance for building nursery structures. After multiple versions of how to best include this request, in a usable manner, we chose to create one-page documents of the most used and tested nursery designs. These one-page documents provide a detailed diagram with an associated materials list, step-by-step illustrated construction and installation instructions, and a few lessons learned that were gathered from users of the designs. Each design will be an individual PDF that can be taken with you to the store and workshop as you work through the building of your nursery structure. At the time of publication, eight designs were published and posted to the CRC website (crc.world) with the idea that more will be added as more designs become more widely used in the future.

We expect and hope that practitioners, managers, and researchers from around the globe use this Guide as a starting point to develop and grow their programs or inform their research. Following the use of the Guide, we welcome feedback and ideas to incorporate into future versions to advance the field of restoration.


Fragments of Hope

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APPENDICES

APPENDIX 1 Detailed Designs of Coral Nursery Structures

Details of the construction, materials, and lessons learned for many nursery structures are provided here as guidance for building each structure type. These "one-pagers" do not include every single structure design but provide the basics as a starting point. For example, we know not everyone builds their trees the same, but in general, most are the same with minor tweaks based on preference and available materials; however, if there is a design with major structural or design changes, those could be incorporated into a new design page.

The purpose behind these documents is to provide a practitioner with a paper that they could bring to the store to buy the materials and have in the area where the structure will be assembled without having to carry around this entire Guide. Each page is available as a PDF for easy printing and viewing on the CRC webpage.

Structures for which we have assembled detail plans thus far:

1. Coral Tree
2. Floating Underwater Coral Array (FUCA)
3. Floating Underwater Platform
4. Vertically Tensioned Line (VTL)
5. Pyramid
6. Grid

Coral Restoration Database

The Coral Restoration Database was developed by the CRC's Monitoring WG. The CRC identified a need to track coral nurseries and restoration efforts to better demonstrate the collective impact of individual efforts. The input fields were developed to reflect information desired by researchers, nursery operators, and managers and were developed in conjunction with the universal monitoring metrics identified in the Monitoring WG's Monitoring Guide and the restoration evaluation tool (Appendix 3). A map of coral nursery and outplant locations can be found at: https://bit.ly/CRCRestorationMap. Datasheets can be downloaded from https://www.crc.world/restoration-monitoring and submitted for inclusion in the database. For more information, contact Alison.Moulding@noaa.gov.

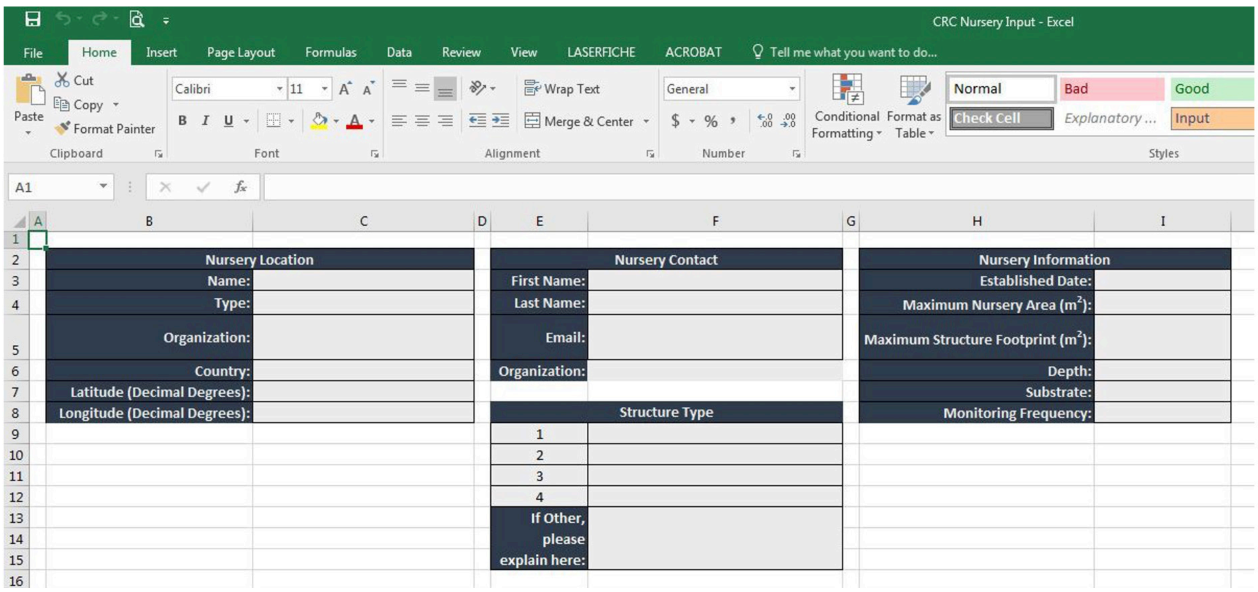

Figure A2.1 . Coral Restoration Database spreadsheet for reporting coral nursery census information. This datasheet should be filled out annually to update how many colonies of each species and genotype (if known) are housed in each nursery.

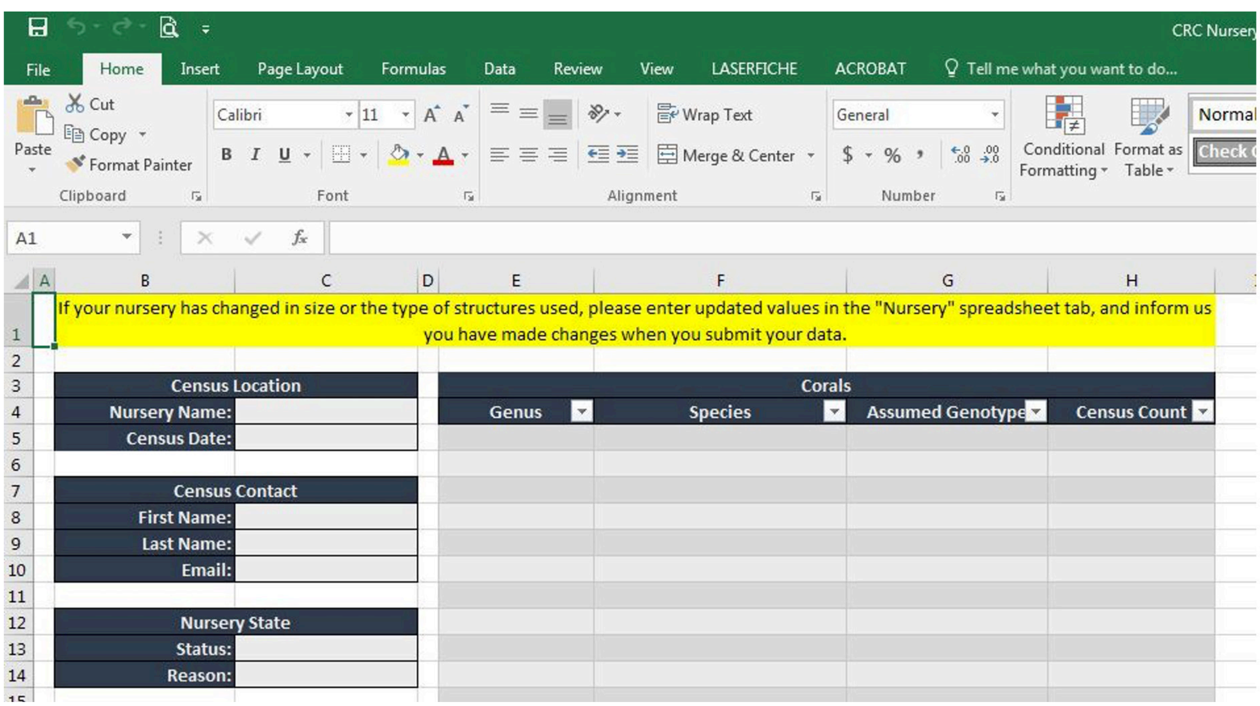

Figure A2.2. CRC Coral Restoration Database spreadsheet for reporting coral restoration site locations. This datasheet should be filled out once for each restoration site.

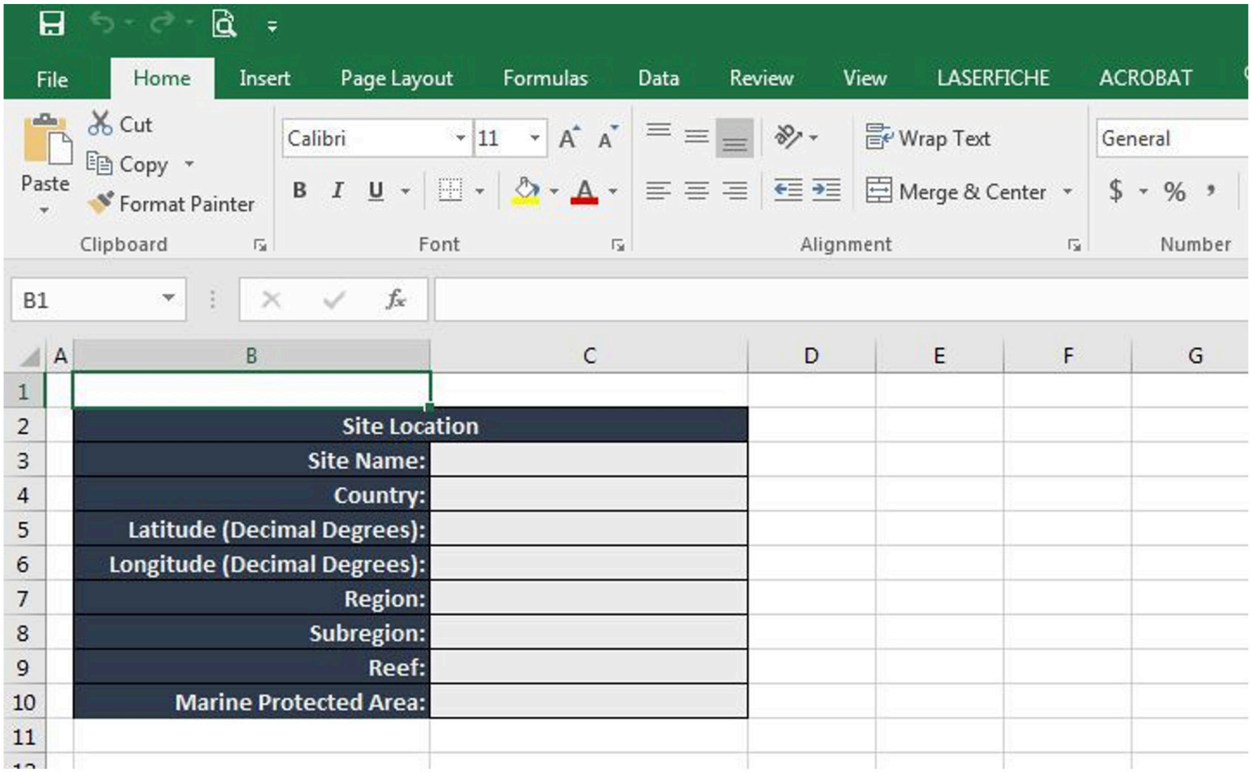

Figure A2.3. Coral Restoration Database spreadsheet for reporting coral restoration site locations. This datasheet should be filled out once for each restoration site.

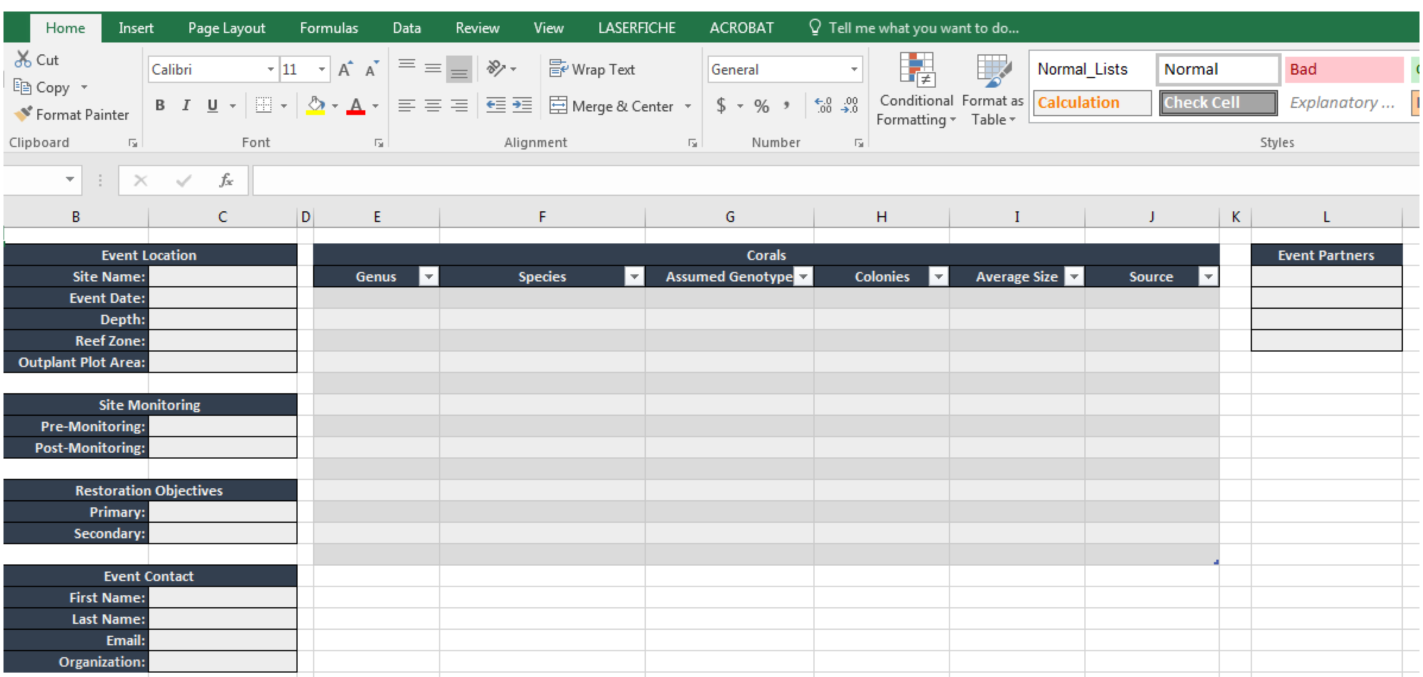

Figure A2.4. CRC Coral Restoration Database spreadsheet for reporting coral restoration sites species, genotype (if know), and colony count information.. This datasheet should be filled out once for each restoration site.

Evaluation Tool for Coral Restoration

The objective of this tool is to provide metrics of success for evaluating existing and new restoration projects or programs to assess performance and progress toward restoration goals. Metrics provided within this evaluation tool are designed to evaluate the strength and robustness of each project or program while also identifying specific metrics that may require adaptive management to improve performance. This tool follows the recovery goals, objectives, and criteria outlined with the Recovery Plan for Elkhorn and Staghorn Corals (National Marine Fisheries Service, 2015) which may also be applied to additional species which are now listed within the Endangered Species Act or have recently suffered dramatic losses in abundance and cover due to severe bleaching and disease events. Specific goals set forth by the Recovery Plan include increasing the abundance of and protecting the genetic diversity of coral populations throughout their geographical ranges through restoration, restocking, and active management. Therefore, the metrics outlined within this evaluation tool focus on best management practices or results from restoration-based research conducted by experts in the field of coral propagation and outplanting. This tool should be used to evaluate the current status of restoration techniques, outline positive attributes of productive projects and programs, and promote the development of successful strategies to achieve population-based recovery for coral reefs. For additional information, see Chapter 4 of the Coral Reef Restoration Monitoring Guide (Goergen et al., 2020) and the CRC Monitoring WG webpage: http://crc.reefresilience.org/working-groups/monitoring/

Coral Restoration Consortium Monitoring Working Group Evaluation Tool for Coral Restoration

	Nursery	Scoring	References
1	Nursery is established based on best known methodologies and Field-based and Genetics Guides	if methods follow Best Management Practices for site selection and deployment = 1	Field-based, Genetics, and Monitoring WG Guides
2	Environmental parameters are measured at nursery locations (e.g., water temperature, light, current, sedimentation, etc.)	if environmental parameters, in particular water temperature, are measured/monitored = 1	Spieler et al., 2001; Baums, 2008; Young et al., 2012
3	Nursery contains multiple species	if nursery propagates > 1 species = 1	Edwards and Clark, 1999; Abelson, 2006; Rinkevich, 2014
4	Nursery contains a high degree of genotypic diversity (20 distinct regional "individuals" provide high proportion of standing genetic diversity)	> 20 genotypes per species will get a score = 1	Baums, 2008; Drury et al., 2017; Genetics WG
5	Nursery corals have been genotyped or represent "distinct individuals" based on collection site	if all potential source corals have been genotyped = 1	Baums, 2008; Shearer et al., 2009
6	Nursery tracks genotype provenance (e.g., source location, date, depth, number of corals)	if metadata exists for collections = 1	Field-based and Genetics WG Guides
7	Nursery tracks genotype through time (e.g., maps, tags, propagation structure, etc.)	if genotype mortality is tracked within nursery = 1 (excludes partial mortality)	Baums, 2008; Shearer et al., 2009
8	Nursery exhibits high coral survivorship (per species)	if annual net nursery survival >80% per species = 1 (excludes partial mortality)	Field-based WG Guide; Schopmeyer et al., 2017
9	Nursery exhibits low prevalence of colony partial mortality	if partial mortality prevalence is <10% =1	Field-based WG Guide; Lewis 1997; Lirman et al., 2014b
10	Nursery exhibits net coral growth (e.g., TLE, size class, maximum diameter or length, volume, etc.)	if nursery corals display positive net growth (all species) or if biomass at least doubles each year (Acropora only) = 1	Field-based and Genetics WG Guides

Coral Restoration Consortium Monitoring Working Group Evaluation Tool for Coral Restoration			
	Nursery	Scoring	References
11	Nursery exhibits low prevalence of disease and/or disease within nursery is mitigated	if annual disease prevalence is < 5% or disease is mitigated to reduce prevalence to <5%= 1	Vega Thurber et al., 2014(7.7-8.4% Caribbean); Pollock et al., 2014(3.1 + 0.6% Western Australia); Ruiz-Moreno et al., 2012(0.3-4.1% Caribbean, 0-2.1% Pacific including GBR, Hawaii, Philippines); Myers and Raymundo, 2009 (0.2-12.6% Guam); Harvell et al., 2007(<5% Austria, Palau and E Africa; 8% Philippines; up to 20% Yucatan and Caribbean)
12	Nursery exhibits low impact of coral predators	if annual predation prevalence (whole colony/frag) is < 5% = 1	Rotjan and Lewis, 2008
13	Nursery exhibits limited competition by algae and other competitors (e.g., hydroids, sponges, damselfish)	if annual mortality by competition (whole colony/frag) is < 5% = 1	Field-based WG Guide
14	Nursery provides a sustainable source of healthy coral outplants that are outplanted on a regular basis to prevent overgrowth/breakage/mortality of corals	if > 25% of biomass is outplanted every year (except during the first year after nursery installation, during years of expansion, or following nursery reconstruction) to promote healthy nursery management strategies = 1	Lirman and Schopmeyer, 2016
15	Nursery visits/maintenance based on published guidance (minimum quarterly and immediately following stress/disturbance events (disease, bleaching, storms), etc.)	if regular nursery visits/maintenance occurs based on Guides (minimum quarterly and immediately following stress/disturbance events (disease, bleaching, storms), etc.) = 1	Field-based and Monitoring WG Guides
16	Nursery dimensions (area) and structure census (#) are available	if the size of the nursery and #/type of structures are monitored/calculated = 1	Field-based WG Guide
17	Nursery can be easily expanded/reduced if needed	if additional propagation platforms can be installed or removed as needed = 1	Johnson et al., 2011; Field-based WG Guide

Below are a supplemental figure and table from Unsworth et al., 2020, displaying the success of specific concrete mixes used in the study. These are provided to help with the decision-making process of choosing which cement mix would be the best for the products available to your program.

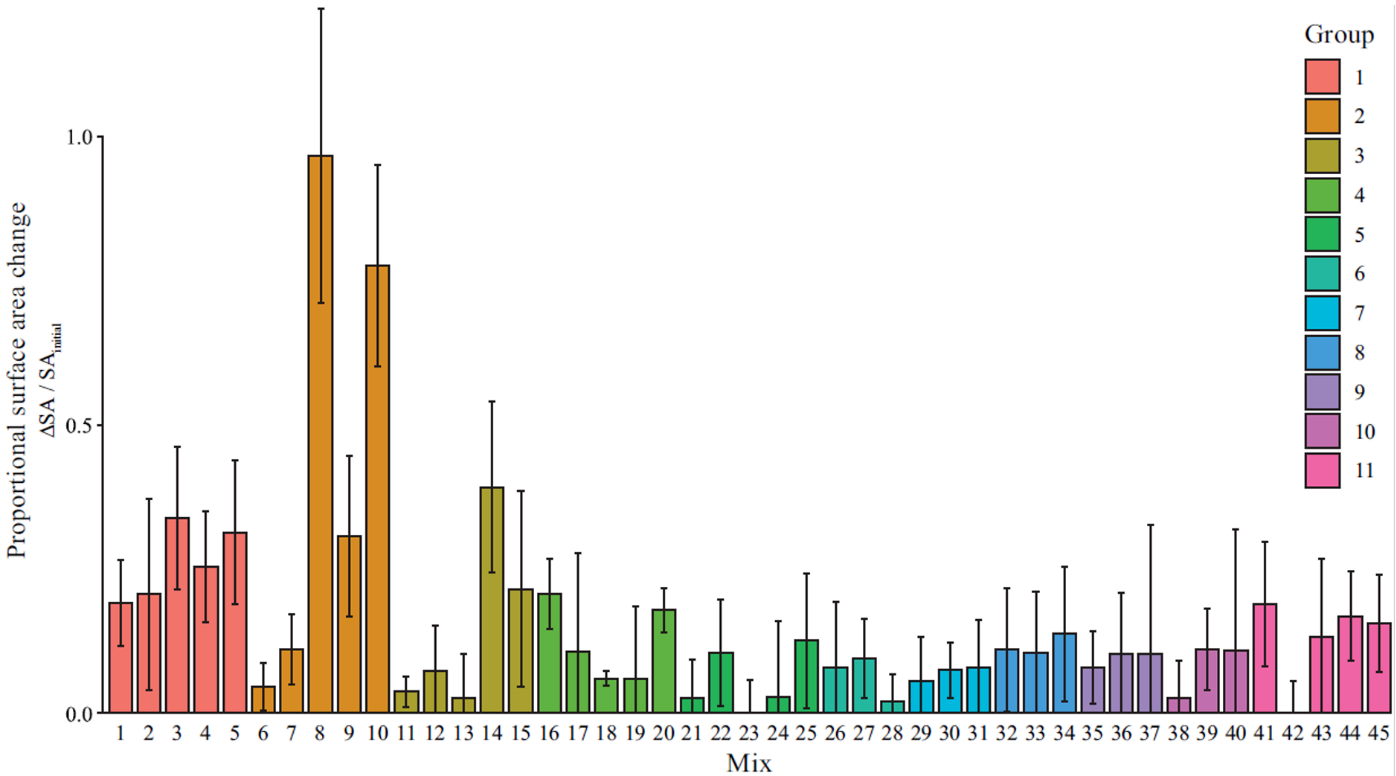

Figure A4.1. Comparison of mean proportional surface area change (a proxy for cohesiveness) between 45 initial candidate mixes. From Unsworth et al., 2020.

Table A4.1. Mass proportions of eight ingredients used in 45 initial candidate mixes. From Unsworth et al., 2020.

		Ingredient								
Group	Mix	Portland cement	30-60 grain silica sand	50-140 grain silica sand	30-60 grain limestone sand	Lincoln 60 fireclay	Silica microfiber	Silica fume (microsilica)	Fumed silica	Fresh water
1	1	1	4	0	0	0	0	0	0	0.8
	2	1	2	0	0	0	0	0	0	0.45
	3	1	1	0	0	0	0	0	0	0.35
	4	2	1	0	0	0	0	0	0	0.62
	5	4	1	0	0	0	0	0	0	1.36
2	6	1	0	0	4	0	0	0	0	0.84
	7	1	0	0	2	0	0	0	0	0.4
	8	1	0	0	1	0	0	0	0	0.33
	9	2	0	0	1	0	0	0	0	0.56
	10	4	0	0	1	0	0	0	0	1.12
3	11	1	0	4	0	0	0	0	0	0.96
	12	1	0	2	0	0	0	0	0	0.53
	13	1	0	1	0	0	0	0	0	0.35
	14	2	0	1	0	0	0	0	0	0.62
	15	4	0	1	0	0	0	0	0	1.4

Ingredient										
Group	Mix	Portland cement	30-60 grain silica sand	50-140 grain silica sand	30-60 grain limestone sand	Lincoln 60 fireclay	Silica microfiber	Silica fume (microsilica)	Fumed silica	Fresh water
4	16	1	0	4	0	0	0	0.1	0	0.8
	17	1	0	2	0	0	0	0.1	0	0.48
	18*	1	0	1	0	0	0	0.1	0	0.33
	19	2	0	1	0	0	0	0.2	0	0.52
	20	4	0	1	0	0	0	0.4	0	1.04
5	21	1	0	0	0	4	0	0	0	1.92
	22	1	0	0	0	2	0	0	0	1.1
	23*	1	0	0	0	1	0	0	0	0.67
	24	2	0	0	0	1	0	0	0	0.9
	25	4	0	0	0	1	0	0	0	1.28
6	26	1	0	0	0	2	0	0.1	0	1.13
	27	1	0	0	0	1	0	0.1	0	0.72
	28*†	2	0	0	0	1	0	0.2	0	1.06
7	29	1	0	0	0	2	0.2	0	0	1.1
	30	1	0	0	0	1	0.2	0	0	0.7
	31	2	0	0	0	1	0.4	0	0	0.96
8	32	1	0	0	0	2	0	0	0.01	1.15
	33	1	0	0	0	1	0	0	0.01	0.72
	34	2	0	0	0	1	0	0	0.02	1.06
9	35*†	1	0	0	0	2	0.2	0	0.01	1.1
	36	1	0	0	0	1	0.2	0	0.01	0.7
	37	2	0	0	0	1	0.4	0	0.02	0.98
10	38*†	1	0	0	0	2	0.2	0.1	0.01	1.2
	39	1	0	0	0	1	0.2	0.1	0.01	0.72
	40	2	0	0	0	1	0.4	0.2	0.02	1.06
11	41	1	0	0	0	0	0.2	0	0	0.23
	42	1	0	0	0	0	0	0.1	0	0.3
	43	1	0	0	0	0	0	0	0.01	0.27
	44	1	0	0	0	0	0.2	0.1	0	0.3
	45	1	0	0	0	0	0.2	0.1	0.01	0.3

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