Restoration Implementation and Monitoring Plan
National Fish and Wildlife Foundation Project #69532: Strengthening Coastal Resilience through Coral Reef Restoration (VI)

August 2023

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RESTORATION SITE SELECTION AND STRATEGY

The location and coral reef habitat restoration strategy of this project have been prioritized through planning processes at territorial and regional levels to contribute to coastal and community resilience goals, aimed at enhancing ecosystem services within the St. Croix East End Marine Park (EEMP) and protecting adjacent shoreline communities. Our restoration strategy uses an ecosystem-based adaptation framework guided by the principles of NOAA's A Manager's Guide to Coral Reef Restoration Planning and Design (Shaver et al., 2020), Restoring Seven Iconic Reefs: A Mission to Recover the Coral Reefs of the Florida Keys, and the Coral Reef Restoration Monitoring Guide (Goergen et al., 2020), referred to in this document as the CRRMG.

Site Selection

The project will be implemented in the St. Croix East End Marine Park (EEMP), in the U.S. Virgin Islands (USVI). The EEMP has been selected as a priority area for coral reef restoration, by both the National Oceanic and Atmospheric Administration (NOAA) and the USVI Department of Planning and Natural Resources (DPNR). The project aims to restore coral reef habitat within a 150-acre *Geographic Focus Area*[1]. The Geographic Focus Area encompasses a variety of habitats, including reef, seagrass, and sandy bottom. This area within the EEMP was selected after being identified as highly likely to reduce exposure to erosion and flooding from storms and future sea levels, and to protect vulnerable people and property by Coastal Vulnerability and Coastal Protection models created using the software Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) (Natural Capital Project, 2022). The 50-acre *Restoration Focus Site* is the area within the Geographic Focus Area that contains coral reef habitat. The Geographic Focus Area and Restoration Focus Site were both adjusted from the maps submitted in the grant proposal after baseline surveys revealed that much of the area mapped as *Fringing and Patch Reef* did not contain reef habitat; the encompassed areas (150 acres and 50 acres, respectively) remain the same. The *Restorable Reef Area*[2] within the *Restoration Focus Site* (area where restoration activities will be carried out) is 76,511 m^2 and consists of two reef types: *Forereef* and *Workable Reef Crest (*referred to as simply *Reef Crest* in the implementation and monitoring sections of this document). The third reef type in the Restoration Focus Site, *Unworkable Reef Crest*, was deemed unrestorable because its shallow depth and high wave energy make it unsafe for divers. However, restoration of coral in the adjacent Workable Reef Crest, namely of *Acropora palmata*, is anticipated to directly benefit the Unworkable Reef Crest through the natural spread of this species via fragmentation. Reef types were delineated in ArcGIS Pro using benthic habitat maps produced from Planet Dove imagery (Schill et al. 2021) as a baseline and further refining using bathymetry data produced by the Global Airborne Observatory Network (Asner 2020), high resolution drone imagery, and *in situ* diver surveys. Reef types were defined as having the following depth zones: Unworkable Reef Crest (<2 m), Workable Reef Crest (2-3 m), Forereef (3-9 m). Restorable reef within the two workable reef types was calculated using benthic cover

[1] According to the Manager's Guide to Coral Reef Restoration Planning and Design, a Geographic Focus Area (GFA) is defined as "…a broad area where conducting restoration interventions would be most appropriate or relevant to achieving your goal. This could be the northeastern side of an island or multiple islands that are experiencing similar issues and where coral reef restoration might be needed and appropriate."

[2] According to Restoring Seven Iconic Reefs, Restorable Reef Area is defined as, "the proportion of reef habitat that is devoid of desirable species and otherwise suitable for restoration, or that can be prepared for restoration."

data collected via *in situ* diver surveys in October 2022 (survey methods detailed in Ecological Goal-based Performance Metrics). Any hard substrate not already occupied by coral, sponges, gorgonians, zoanthids, *Peysonnelia* spp., or *Ramicrusta* spp. was considered restorable reef. Finally, the restorable reef area was divided into four zones for easier implementation and tracking of restoration activities (Figure 1).

Restoration Strategy

Restoration targets for the Restorable Reef Area, including target percent cover and species composition, were calculated by reef type using the Restoring Seven Iconic Reefs methodology. To maintain and enhance ecological and geological features that provide coastal resilience, coral species groups selected represent a diversity of life history traits and morphotypes, including fast-growing framework-builders (elkhorn coral (*Acropora palmata*) and staghorn coral (*Acropora cervicornis*)), as well as slower growing reef-building groups (star corals (*Orbicella* spp.) and brain corals (*Diploria* and *Pseudodiploria* spp.)) appropriate to the reef type and habitat conditions. Additionally, an 'other' species category includes locally-important branching *Porites* spp. and *Agaricia* species, as well as locally rare species (e.g., *Dendrogyra cylindrus* and *M. meandrites*). Percent cover targets by species group were developed considering estimated historic species composition and cover in the area, gathered from a literature review and local expert consultations, as well as current geomorphological and environmental site characteristics. Existing coral cover by species was estimated for the preliminary targets submitted in the proposal using benthic cover data collected in nearby reef sites in 2017 and 2018 as part of NOAA's National Coral Reef Monitoring Program (NCRMP) (Edwards 2021) and the University of the Virgin Island's Territorial Coral Reef Monitoring Program (TCRMP) (Ennis 2020). Number of outplants needed by species was then calculated based on outplant size and predicted growth and mortality rates of outplants during the four-year project period (**Table 1**). The target percent cover numbers presented here (**Table 1**) differ from those estimated for the proposal largely due to a sizable decrease in starting coral cover, as coral cover data mined from NCRMP and TCRMP was collected prior to the emergence of Stony Coral Tissue Loss Disease (SCTLD) around St. Croix in May 2020. In the year following the emergence of SCTLD, declines in relative coral cover of up to 53% were documented at reefs around the USVI (Brandt et al. 2021). Existing coral cover used for final target calculations was determined from the baseline *in situ* diver benthic cover surveys conducted in October 2022. Target number of outplants remains the same to keep coral production goals the same as originally proposed.

While both asexual and sexual propagation techniques will be applied in this project, these four-year estimates of percent cover are calculated from number of asexual outplants. Juvenile corals produced sexually will mature after the project period and contribute to the long-term coral cover, genetic diversity, and resilience of the restoration effort. Targets for the number of juvenile seeding units planted were determined based on the current capacity of the larval rearing raceways in the land-based nursery.

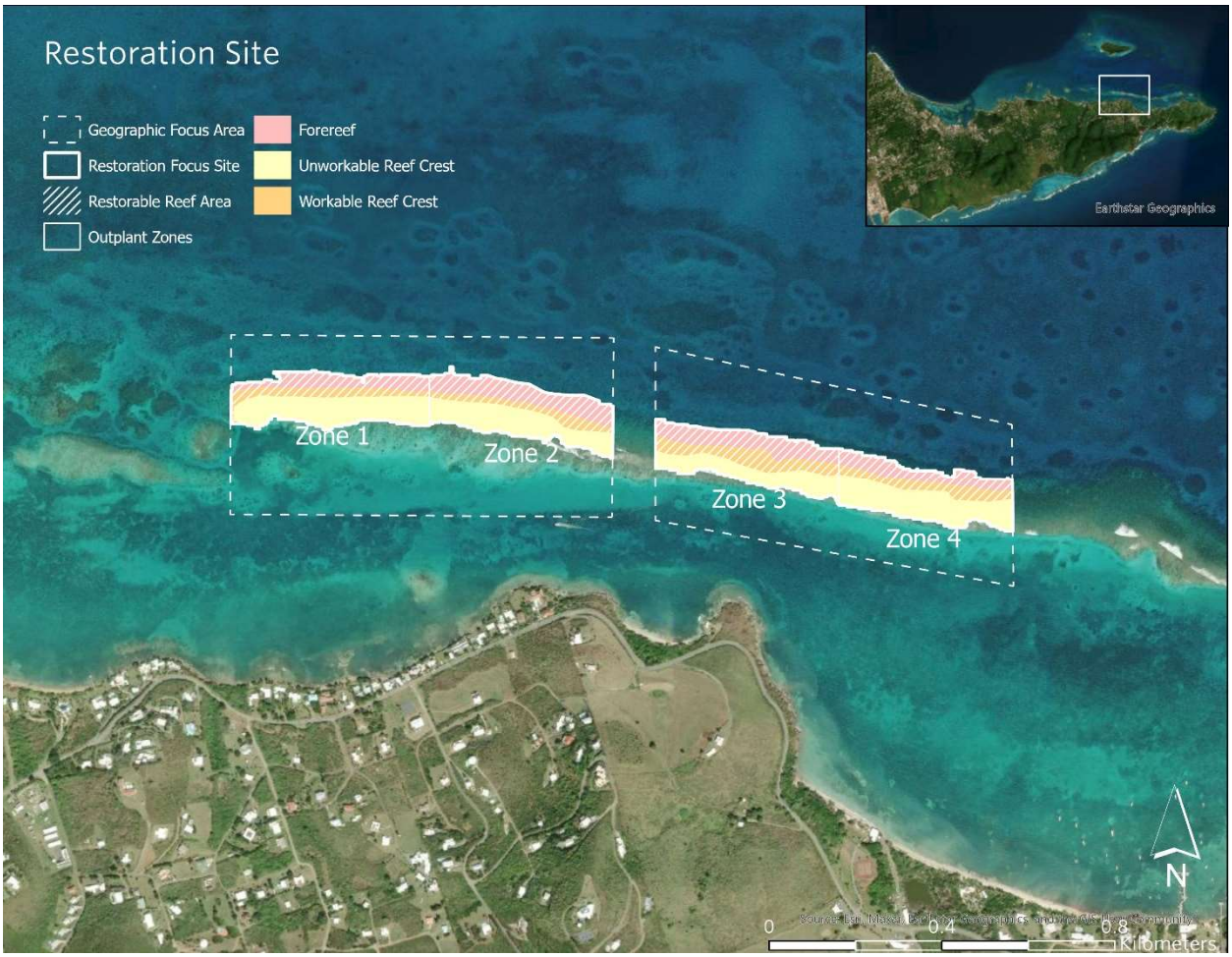

Figure 1. Map of Geographic Focus Area, Restoration Focus Site, and Restorable Reef Area within the East End Marine Park in St. Croix, USVI. Benthic habitat map shows distribution of reef types, and Restoration Focus Site is divided into four zones for restoration implementation and tracking.

Table 1. Restorable reef area, target outplant numbers for each species group (staghorn, elkhorn, star, and brain, and 'other'), and estimated cover resulting from outplanting efforts at the end of the four-year performance period. Target percent cover values were calculated using the target outplant numbers from the original proposal and extrapolating out four years from the baseline cover values surveyed in 2022. Note: The goal number of seeding units holding at least one coral juvenile to be planted is also included but does not contribute to the calculation of target percent cover.

Reef Type	Restoration Area (m^2)	Target % Elkhorn Coral Cover	No. Elkhorn Outplants	Target % Staghorn Coral Cover	No. Staghorn Outplants	Target % Star Coral Cover	No. Star Coral Outplants	Target % Brain Coral Cover	No. Brain Coral Outplants	Target % Other Stony Coral	No. Other Coral Outplants	No. Seeding Units	Total Target % Cover
Workable Reef Crest	30,239	6%	14,400	0%	0	0.2%	0	0.23%	300	4%	0	4,800	**10.4%**
Forereef	46,272	0%	0	1.3%	9,000	0.1%	992	0.04%	692	6%	500	7,200	**7.4%**
Total	76,511		14,400		9,000		992		992		500	12,000	

RESTORATION IMPLEMENTATION

Coral Propagation

Coral Collections

Corals will be collected from a minimum of six geographically distant and environmentally distinct reefs (**Table 2**) to maximize genetic diversity and adaptive potential of outplants (Baums et al. 2019) and to minimize impacts to donor sites. Fragments will be collected from four to six donor colonies of each species at each site to capture intraspecies genetic diversity (Baums et al. 2019), and donor colonies will be a minimum of 10 m apart to maximize chances of collecting distinct genets. Where available, coral fragments of opportunity will be collected. If fragments of opportunity are not present, material will be collected from mature and healthy donor colonies. Divers will collect no more than 10% of the biomass of a colony and will collect from no more than 10% of colonies of a species on a reef, as per USVI DPNR permit conditions (DFW20052X). Donor colonies of the primary target species (up to ten colonies per

species per site) from at least two environmentally distinct reefs will be tagged for monitoring of lesion recovery. Health metrics (size; percent old and new mortality; percent of colony affected by bleaching/paling, disease, and predation; and size of collection lesion) will be collected at the time of collection and one year later, and scaled photos will be taken of the colony and the lesion at each timepoint.

Approximately 30% of fragments produced from each collected coral will be retained as nursery stock. All genets that are part of the stock will be sampled for genetic analysis to determine genetic variability within the stock. Survival, health, and growth of the stock and a subset of outplants will be monitored, and genets displaying positive phenotypic traits (e.g., low partial mortality, fast growth) and/or resilience to stressors (e.g., sea surface temperature anomalies, disease) will be prioritized for propagation and restoration. However, less successful genets will also be propagated as they may have traits that make them resilient to yet unknown future stressors.

Fifteen putative genets of staghorn coral, representing four geographically distant sites, are currently in stock in the nursery. Because there are currently no known healthy staghorn stands around St. Croix, additional collections of this species will only be made if needed due to poor performance of existing stock. These genets will be included in genetic analysis sampling.

Table 2. Collection target sites and number of genets by species. Targets are based on recommendations to maximize genetic diversity and adaptive potential of nursery stock.

Site	Elkhorn	*C. natans*	*D. labyrinthiformis*	*Pseudodiploria* spp.	Total Brain	*M. cavernosa*	*O. annularis*	*O. faveolata*/*O. franski*	Total Star	*Agaricia* spp.	*D. cylindrus*	*Porites* spp.	Total Other
Butler Bay/West	5	5	5	5	15	5	5	5	15	5	2	5	12
Cane Bay/North Star	5	5	5	5	15	5	5	5	15	5	2	5	12
Channel Rock	5	5	5	5	15	5	5	5	15	5	2	5	12
Deep End	0	0	0	5	5	5	5	5	15	5	2	5	12
Green Cay	5	0	0	5	5	0	0	0	0	0	0	5	5
Llew's Reef	5	5	5	5	15	5	5	5	15	5	2	5	12
Long Reef	5	5	5	5	15	5	5	5	15	5	2	5	12
Total	**30**	**25**	**25**	**35**	**85**	**30**	**30**	**30**	**90**	**30**	**12**	**35**	**77**

Land-based Coral Propagation

In 2020, TNC established a land-based coral nursery that houses 24 650-L outdoor raceways, a wet lab with nine 150-L raceways for larval rearing and 24 individually-controlled tanks for research activities, a dry lab, and a coral life-support system module. The nursery is operated as semi-closed system, with water exchanges provided via an offshore intake. Infrastructure improvements are on-going to upgrade the system to flow-through. The outdoor nursery consists of four autonomous systems (six raceways each), each with its own filtration, UV/ozone sterilization and heating/cooling units. One spatially separated system (system A) is dedicated to holding incoming coral colonies for a three-month

quarantine period to ensure no disease or pests enter the propagation systems. The three remaining propagation systems are delegated to grow-out of recently cut fragments, nursery stock and long-term grow-out, and acclimation in preparation for outplanting or transfer to field-based nurseries. Once improvements to the land-based nursery are complete, the wet lab will serve as a quarantine facility. Following the quarantine period, corals are cut using diamond bandsaws into 'microfragments' ranging from 1-2 cm^2 (depending on species) to promote rapid growth (Page et al. 2019). Fragments are then attached to different grow-out substrates depending on the species and their outplant destination. Approximately 30% of fragments will be allocated to arrays on ceramic tiles to retain as parent stock in land-based and field-based nurseries for grow-out and re-fragmentation, and 70% will be allocated to arrays on manufactured substrates to grow-out, fuse, and be outplanted to the reef. Arrays on substrates will be grown out in the land-based nursery for approximately four months followed by an acclimation phase, and subsequently transferred to field-based nurseries for the remainder of the grow-out period (estimated to be ~six months). Arrays will be made up of a single genet and fragments will be spaced to promote rapid fusion into a single colony. The substrate size (~100cm^2) was chosen because colonies of this size are likely to have reached reproductive capacity (St. Gelais 2016; Szmant 1991; Weil & Vargas 2010), and because generally as coral colonies increase in size, changes of whole colony mortality decrease (Madin et al 2020), with significant increases in probability of survival at 30-50 cm^2 (Edmunds 2015; Foster & Foster 2018).

Field-based Coral Propagation

Corals propagated in our offshore nurseries are placed on holding structures designed to be low-maintenance, long-lasting, and storm resistant and include welded-rebar domes for branching species and welded-rebar tables for bouldering, brain, and other species. The domes are used to grow out staghorn coral until ramets have reached a size of at least 20 cm total linear extension (TLE; target outplant size). The tables are used to grow out microfragment arrays of brain, boulder, and other coral species until they have fused to reach a total size of ~100 cm^2 live tissue area (target outplant size).

Additionally, an elkhorn 'orchard' was installed adjacent to one of the shallow field-based nurseries within the restoration area. The orchard was created by cementing ramets of genetically diverse colonies (five colonies from each of six collection sites) to the reef and is used to grow stock for outplanting. Once elkhorn outplants have grown multiple branches, these will be pruned every three years (tentatively) to use in outplanting. This three-year time period has been shown to allow for adequate recovery and regrowth (Griffin et al. 2022).

Coral Outplanting

Outplanting will be carried out by zone and reef type, guided by the targets in **Table 1,** and will occur in phases by species group based on growth rates and expected time needed for propagation. The first phase of outplanting will focus on fast-growing (and SCTLD-resistant) elkhorn and staghorn corals, while the second phase includes outplanting of slower growing brain, star, and 'other' species. Outplant methods will be adapted and refined based on success of monitored outplants and small-scale experimental plantings occurring concurrently under separate grants to directly compare multiple outplant methods in terms of outplant success (survival, growth, and health), and time and financial costs. Outplant methods detailed below are starting points based on methods that have been used

successfully in other restoration programs and will be adapted as needed throughout the restoration project.

Outplant Plot Site Selection and Design

Within each reef type and outplant zone, exact locations for outplant sites were randomly selected using ArcGIS Pro, with a minimum of 30 m between plots (Figure 2). The number of plots per reef type was determined by dividing the target outplant number by the number of outplants needed per site to achieve desired outplant density. An equal number of plots were allocated to each outplant zone, with the exception of staghorn plots. Staghorn plots were limited to depths greater than 6 m, and plots were allocated to zones based on the area of forereef meeting the depth requirement. Elkhorn plots were distributed throughout the Reef Crest. Brain, star, and other corals will be planted primarily in the mid-forereef (3-6 m). A total of 27 outplant plots were selected. Three plots for each species group within each zone were randomly designated as monitoring plots. Four monitored Reef Crest plots include both elkhorn and brain corals, and four monitored deep (>6 m) Forereef plots include both staghorn and star/other corals. This design allows managers to assess whether outplant plots that include multiple species groups exhibit greater success than those with only one species group. Additionally, seeding units holding coral juveniles produced via sexual propagation will be planted at two monitoring plots in the Forereef and one monitoring plot in the Reef Crest of each zone.

Each outplant plot consists of three 10 x 10-m subplots: east (A), central (B) and west (C) with 5 m between subplots. This design allows for the measurement of the expansion of the ecological footprint[3] (area of outplanted coral) as corals grow and naturally spread through asexual reproduction, particularly for elkhorn and staghorn corals. Subplot B of three randomly chosen plots for each species group within each outplant zone will be prepared for Structure from Motion (SfM) monitoring by installing fouling-resistant targets in each corner. The central plot of those three monitored plots will also receive a HOBO® pendant temperature/light 64K data logger to log temperature from the time of outplanting to the end of the project period.

[3] Per the Coral Reef Restoration Monitoring Guide, “The Ecological Footprint is the maximum areal extent of reef which encompasses all Outplant Plots using the shortest contiguous boundary. This area could be very similar to or the same as the Outplant Plot during the initial survey depending on your restoration design.”

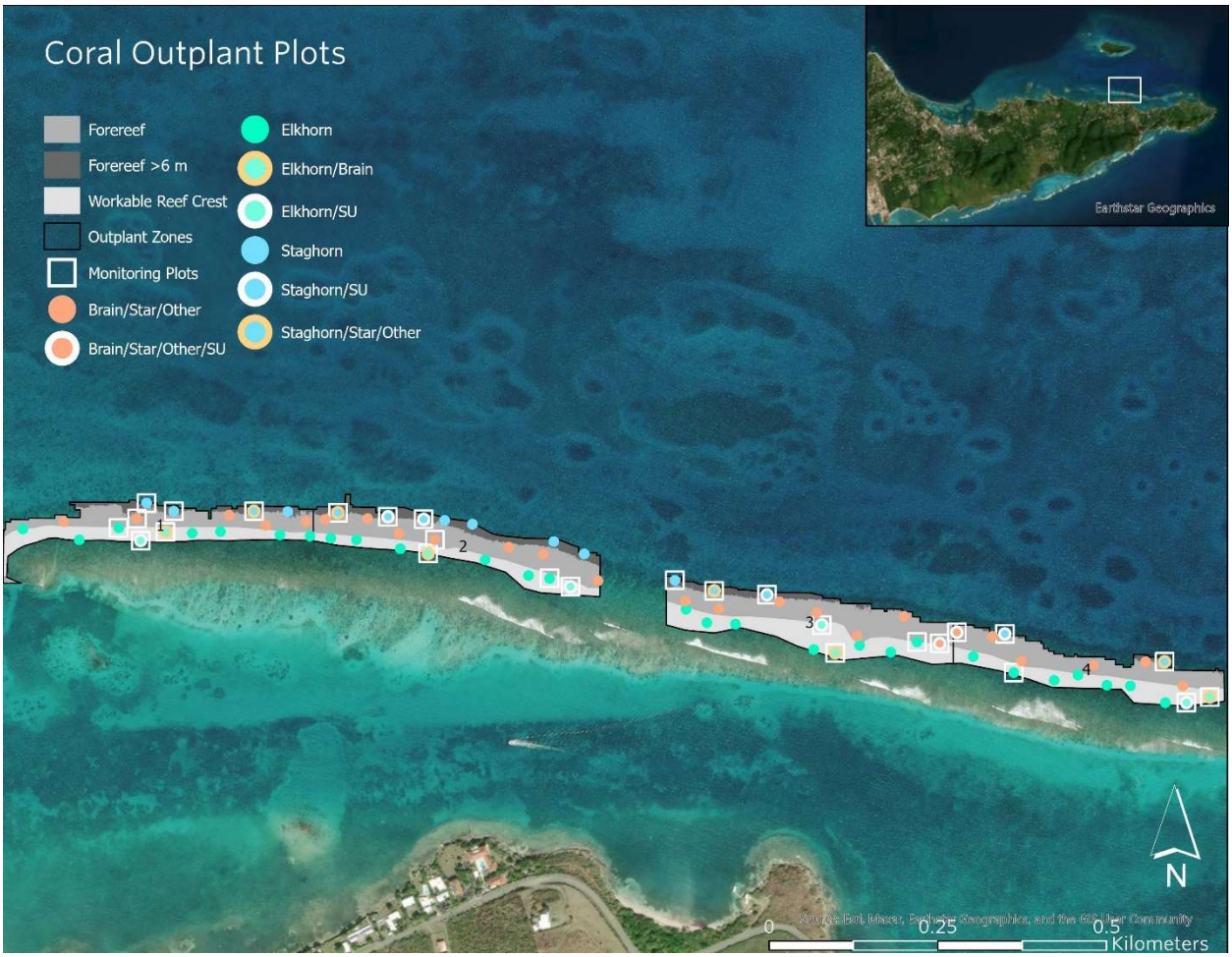

Figure 2. Outplant plots were distributed across each reef type and zone with a minimum of 30 m between plots. Three plots of each species group within each zone were randomly designated as monitoring plots. Elkhorn plots are in the Reef Crest, staghorn plots are in Forereef >6 m depth, and brain, star, and other coral plots are primarily in the mid Forereef (3-6 m depth) with a smaller number of brain coral plots in the Reef Crest and star and other coral plots in the deep Forereef (>6 m depth). Additionally, seeding units (SU) holding juvenile corals will be planted at two monitoring plots in the Forereef and one monitoring plot in the Reef Crest of each zone.

Elkhorn Outplanting

Elkhorn (*A. palmata*) is outplanted within the Reef Crest reef type using direct outplanting techniques. Outplant material is sourced from the field-based nursery orchard, additional collections from wild colonies, and/or past outplants once they obtain large enough size, as detailed in Field-based Propagation. All outplant material, regardless of its source, will be staged at the outplant sites at least one week prior to outplanting provide an acclimation period. Source material is cached at the outplant site 1-2 weeks ahead of outplanting for acclimation. The ramets are fragmented *in situ* at the time of outplanting using bone cutters, mallets, and chisels into small fragments approximately 3 cm x3 cm pieces (sizes are an approximation as fragmenting is done underwater by hand, not bandsaw, and not exact)) Fragments are outplanted in arrays of five fragments approximately 1-3 cm apart. Arrays are comprised of fragments from one genet to promote fusion and rapid maturity to sizes that are at reduced risk of whole colony mortality and can reproduce sexually. Fragments are attached to the reef

substrate using cement, epoxy, Coral Clips©, or other methods conceived based on the latest available restoration research or conditions at the time of outplanting (Figure 3). Arrays will be planted at a density of one per 4m^2 (approximately every 2 m) across each outplant plot. When possible, five or more genets will be planted at each site, with a minimum of two genets per subplot to promote natural sexual reproduction and genetic diversity (Baums 2019).

Figure 3. Coral clips are used for quick and easy outplanting. One diver nails the clip into the substrate, and another slips a coral fragment underneath the clip.

Staghorn Outplanting

Staghorn coral (*A. cervicornis*) will be outplanted within the Forereef at a depth >6 m using fragments propagated in the field-based nurseries and will be outplanted either via direct attachment to the substrate or using artificial structures, depending on the substrate type. In areas of reef where sufficient consolidated substrate is available, fragments with 20-cm total linear extension (TLE) fragments will be attached directly to the substrate in arrays of six fragments. As with the elkhorn arrays, staghorn arrays will be made up of fragments from one genet to promote fusion and rapid maturity to sizes that are at reduced risk of whole colony mortality and can reproduce sexually. Fragments will be attached to the reef substrate using cement, epoxy, Coral Clips©, masonry nails with cable ties, or other methods conceived based on the latest available restoration research or conditions at the time of outplanting. Arrays will be planted at a density of one per 4 m^2 (approximately every 2 m) across each outplant plot.

When possible, five or more genets will be planted in each plot to promote natural sexual reproduction (Baums 2019); if planting five genets is not logistically feasible, a minimum of three genets will be planted in each plot.

Where feasibile, staghorn coral will be planted in areas of rubble using the Mars Assisted Reef Restoration System (**Figure 4**). This system utilizes a web of welded and coated steel structures called 'reef stars' to stabilize rubble substrate and provide a platform for coral fragments to grow. The interlocking stars form a secure web that is highly resistant to wave energy and are additionally anchored with angled steel stakes. Between fifteen and twenty 10-cm fragments are attached to each reef star, allowing fragments to grow into a dense thicket.

Figure 4. Staghorn coral outplanted using the Mars Assisted Reef Restoration System. Fragments are attached to 'reef stars' that form an interlocking web to stabilize consolidated rubble.

Brain and Star Coral Outplanting

Approximately two-thirds of brain and star corals will be outplanted within the mid-depth Forereef (3-6 m). The remaining third of brain coral arrays will be planted on the Reef Crest, and the remaining third of star coral arrays will be planted in the deep Forereef (>6 m). Microfragments will be grown out in the field-based and/or land-based nurseries in arrays on cone-shaped cement structures. Once the fragments have fused and the total live tissue is at least ~100 cm^2, the arrays will be outplanted to the

reef. Arrays will be planted using marine epoxy or cement and will be planted at a density of one per 4 m^2(approximately every 2 m) across each outplant plot.

'Other' Species Outplanting

Species in the 'Other' category include branching *Porites* species, *Agaricia* species, *Dendrogyra cylindrus* if available, and potentially small numbers of other less common species when available. *Agaricia* species microfragments will be grown-out in the field-based and/or land-based nurseries in arrays on cone-shaped artificial structures using the methodology for brain and star corals, above. As branching *Porites* are not commonly used in restoration efforts and little research has been conducted to determine the most effective outplant method for this species, a variety of methods will be tested and iterated to determine the most effective outplant method locally. Methods may include microfragmentation and grow-out on artificial substrates; attachment to 'reef stars' using Mars Assisted Reef Restoration System (described above in Staghorn Outplanting); or direct outplanting onto reef substrate using epoxy, cement, Coral Clips©, masonry nails with cable ties, or other methods conceived based on the latest available restoration research. Similarly, *D. cylindrus* and other less common species are not often targets for coral restoration and will be planted by testing and iterating a variety of methods to determine the most effective outplant method for each species.

Sexual Propagation

Sexual propagation techniques are conducted in parallel with asexual propagation to produce thousands of genetically diverse coral recruits from one or more species each year. Gametes are collected from wild parent colonies by placing a gamete collection net over selected donor corals on the reef during spawning times, which are predicted for individual species using the lunar cycle and timing of sunset. Once gametes are collected, they are brought to shore, and gametes from multiple parents combined to promote fertilization. Resulting coral larvae are reared in the land-based nursery and settled onto conditioned recruitment seeding units in both the land-based and field-based nurseries. Recruits aregrown-out in a nursery for one year, and then planted onto the reef. Seeding units are designed to allow rapid outplanting by wedging units into natural crevices in the reef.

Outplant Timeline

Timelines for outplanting following sexual and asexual propagation can be found in Tables 3 and 4.

Table 3. Schedule of asexually propagated outplant activities.

	2021-2022		2022-2023						2023-2024						2024-2025					
	Nov	Apr	Nov	Dec	Jan	Feb	Mar	Apr	Nov	Dec	Jan	Feb	Mar	Apr	Nov	Dec	Jan	Feb	Mar	Apr
Species Group	Elkhorn	Staghorn	Elkhorn		Elkhorn		Staghorn		Elkhorn		Elkhorn		Staghorn		Brain, Star, Other		Brain, Star, Other		Brain	
Reef Zone	2	2	1		2		1&2		3		4		3&4		1&2		3&4		1-4	
Reef Type	Reef Crest	Fore-reef	Reef Crest		Reef Crest		Fore-reef		Reef Crest		Reef Crest		Fore-reef		Fore-reef		Fore-reef		Reef Crest	
No. Outplants	835	1425	3400		3400		5000		3400		3400		2575		1100		1100		300	

Table 4. Schedule of sexually propagated outplant activities.

	2020	2021		2023		2024	2025
	Fall	Spring	Fall	Spring	Fall	Spring	Spring
Species Group	Brain	Star	Brain/Star	Brain	Brain	Brain	Brain
Reef Zone	1	2	1	2	3	4	1-4
Reef Type	Forereef	Forereef	Forereef	Forereef	Forereef	Forereef	Reefcrest
No. Seeding Units	590	420	80/230	2040	1450	2400	4800

RESTORATION MONITORING

The monitoring outlined below follows the guidelines published in the CRRMG and measures universal metrics to assess ecological goal-based performance and restoration project performance. Monitoring for both ecological goal-based performance metrics, as well as project performance metrics will be conducted.

ECOLOGICAL GOAL-BASED PERFORMANCE METRICS

This project uses an ecosystem-based adaptation framework. Ecological goal-based performance metrics will be measured to examine changes in the overall ecological community across the Restoration Focus Site.

Sampling Design

A Before-After-Control-Impact (BACI) experimental design will be used to make comparisons between restoration sites and control sites and between pre- and post-restoration conditions. Chosen control sites are geographically close to restoration sites, have similar starting benthic covers and fish communities to those of the restoration sites, and experience similar environmental conditions to those of the restoration sites. No reference sites are available as all local reefs have suffered major declines in coral abundance and cover in the past several decades and no local reef currently represents the reef conditions that this restoration project strives to achieve.

Because this project aims to restore a 50-acre area of reef, a stratified random sampling design was adopted to collect spatially representative ecological data and to reduce sampling bias. Prior to each survey, , six random points will be selected within each reef type (Workable Reef Crest, Forereef) in the restoration outplant Zones 1-4, and three random points in the Control areas serving as the start of each temporary transect. Control areas with similar reef conditions were identified between outplant Zones 2 and 3 and to the east of Zone 4 of the restoration area. Each Control area contains approximately three acres of restorable reef habitat. Points will be overlayed on the restoration area using ArcGIS Pro for each ecological sampling time point. Points will be a minimum distance of 50 m apart to avoid pseudoreplication.

Ecological monitoring was conducted pre-restoration (October 2022) to collect baseline data. Post-restoration ecological monitoring will be conducted in summer 2024 and at the end of the project period (summer 2025).

Survey Methods

The following presents methods for each survey type.

Coral Demographic Surveys

Coral demographic data will be collected using the National Coral Reef Monitoring Program (NCRMP) 2022 Coral Demographics Survey Field Protocols for U.S. Atlantic (CRCP, 2022b). The coral demographic survey records abundance of coral colonies by species within a 10-m x 1-m belt transect and records size and condition of each colony.

Reporting metrics:

- Coral abundance will be reported as the average density (number corals per 1 m^2) by reef type for all species combined and for individual species and the total number of restored corals per reef type by species.
- Coral health will be reported as mean percent old mortality, mean percent new mortality and prevalence of bleaching and disease by reef type for all corals.
- Species richness, species diversity, and species evenness will be reported by reef type.

Benthic Community Assessment Surveys

Benthic community will be assessed using the NCRMP 2022 Benthic Community Assessment Survey Field Protocols for U.S. Atlantic (CRCP 2022a). The benthic community assessment survey collects point identification data at 15-cm intervals along a 15-m transect, categorizing the substratum type and identifying the biotic organism (if any) for that abiotic substrate type. The benthic community assessment survey also counts keystone macroinvertebrate species – Caribbean spiny lobster (*Panulirus argus*), queen conch (*Lobatus gigas*), and long-spined sea urchins (*Diadema antillarum*) within a 15-m x 2-m belt transect. Reef structure and complexity are also assessed along the transect. The topographic complexity survey records the minimum and maximum site depths and maximum relief in 1-m x 2-m cells along a 15-m x 2-m belt transect.

Reporting metrics:

- Coral cover will be reported as percent cover of corals by reef type for all species combined and for individual species and as percent cover of restored corals by reef type for all species combined and for individual species.
- Abundance and density (number per 1 m^2) of spiny lobster, queen conch, and long-spined sea urchins will be reported by reef type.
- Topographic complexity will be reported as range, mean, and standard deviation of relief measurements. Additionally, estimates of percent hard substrate in each relief category (<0.2 m, 0.2-0.5 m, 0.5-1.0 m, 1.0-1.5 m, >1.5 m) as collected in the Reef Visual Census (RVC) fish survey will be reported. (CRC Metric 2.3)

Fish Surveys

Reef fish community will be assessed using the NCRMP RVC Fish Survey Protocols for U.S. Atlantic (CRCP, 2022c). The RVC fish survey records fish present within a 7.5-m diameter cylinder in a 15-minute timespan and records abundance and mean, minimum, and maximum size by species.

Reporting metrics:

- Species richness, diversity, and evenness, as well as biomass by functional group, will be reported by reef type (CRC Metric 2.2).

Sampling Design

Restoration project monitoring will occur within a subset of randomly selected outplant plots. For each outplant zone and species group, subplot B of three randomly selected plots will be monitored.

Restoration monitoring will occur immediately prior to outplanting (within two weeks; Structure from Motion surveys only), three months post-outplanting, and one year post-outplanting. Monitoring will also occur three years post-outplanting for plots at which those timepoints fall within the project period.

Monitoring Methods

Landscape/Reef-Level Metrics: Restored Reef Areal Dimensions (Universal Metric 1)

Outplant Plots

The outplant plot is defined as a 10-m by 10-m area with a spacing of 2 m or less between outplanted corals, and the total outplant area will be calculated by summing the area of individual outplant plots.

Ecological Footprint

The ecological footprint will be measured using Structure from Motion (SfM) surveys. Each SfM survey will encompass a 10 m x 10 m monitoring subplot plus an additional 3-m buffer surrounding the plot. Photomosaics will be produced from the SfM surveys, and the ecological footprint will be measured as the area encompassing the outplanted corals and any observed spread (defined as new recruits or fragments of the outplanted coral species within 3 m of the outplant boundary). Thus, the ecological footprint is expected to expand beyond the original outplant plot area over time as outplanted colonies grow and asexual reproduction occurs via fragmentation. Additionally, any recruits of the same species that are within 3 m of an outplanted coral will be considered part of the ecological footprint.

Restored Reef Areal Dimension (RRAD)

The Restored Reef Areal Dimension (RRAD)[4] will be measured as the overall area in which corals are planted and the area that restored corals have spread over time to gauge overall impact and success of the restoration project (considered to be equivalent to the roughly 50-acre Restoration Focus Site over time). The RRAD will be measured using ArcGIS Pro and will be a summation of each ecological footprint over the Restoration Focus Site.

Reef Structure and Complexity

Changes to reef structure and complexity will be evaluated using the SfM surveys conducted within the monitoring plots. High spatial resolution digital terrain models will be produced from the SfM imagery and used to characterize surface roughness at each timepoint.

Reporting metrics:

- Outplant plot area (m^2)

[4] Restored Reef Areal Dimension (RRAD) is defined in the Coral Reef Restoration Monitoring Guide as “the area encompassed by outplants and the areas across which outplanted corals may spread.”

- Ecological footprint (m^2)
- Restored reef areal dimension (acres)
- Surface roughness per plot and percent increase or decrease since last monitoring timepoint

Population-level Metrics (Universal Metric 2) and Colony-level Metrics (Universal Metric 3)

To measure population- and colony-level metrics, individual outplanted coral colonies within the 10 m x 10 m monitoring subplots will be tagged for fate tracking. Photomosaics will be produced from the SfM imagery and used to digitally measure maximum diameter and planar surface area for each outplanted colony and to assess colony health.

Reporting metrics:

- Abundance of restored corals by species
- Density of restored corals (number corals per m^2)
- Mean restored coral size by species (cm^2)
- Percentage of number of corals by species in each size class, using size classes defined by the CRRMG (**Table 5**)
- Mean percent increase or decrease in planar area of tagged colonies since the last monitoring event
- Mean percent live tissue per tagged colony
- Percentage of corals in each live tissue bin as defined by the CRRMG (0% or dead, 1-25%, 26-50%, 51-75%, 76-99%, 100%)
- Prevalence of recent mortality, disease, bleaching, and predation

Table 5. Colony size class diameters (cm) and associated approximate surface areas (cm^2) based on circular shape as defined in the CRRMG.

Size Class Diameter (cm)	<5	5-10	11-20	21-30	31-40	41-50	51-75	76-100	>100
Size Class Area (cm^2)	7	44	189	511	990	1626	3117	6082	Variable

Genetic and Genotypic Diversity (Universal Metric 4)

Number of genets outplanted by species will be recorded for each outplant event. Unique genets will be presumed based on geographic distance of collection locations and distance between donor colonies. When possible, samples of each presumed genet will be exported for genetic analysis.

Reporting metric:

- Number of genets outplanted by species at each outplant plot

Water Temperature (Universal Environmental Metric 5)

A HOBO temperature logger will be deployed within one of the monitoring subplots for each species group and zone at the time of outplanting. Logger data will be collected at one-year monitoring event.

Reporting metric:

- Monthly mean, minimum, and maximum temperatures per site.

Reproductive Capacity or Maturity (Coral Population Enhancement Metric 1.2)

Due to the relatively short project term of four years, reproductive capacity will not be measured for this project. However, the program aims to measure this metric after the close of the project, pending availability of adequate personnel and financial resources. If possible, this metric will be measured five years after outplanting, and tagged colonies within the monitoring subplots will be observed on predicted spawning nights.

Reporting metrics:

- Reproductive capacity will be reported as proportion of monitored colonies that spawned by outplant subplot and species

Monitoring of Sexual Recruit Seeding

For each sexual recruit outplant plot, a sub-sample (minimum of 10) of seeding units will be scored and planted and tagged along a 10-m transect. One year after outplanting, presence or absence of each substrate will be recorded, and number of surviving recruits will be recorded for present substrates. Substrate retention, recruit survivorship, and yield will be reported.

Reported metrics:

- Number of substrates outplanted, average number of recruits per substrate
- Substrate retention, recruit survivorship, yield (CRC Coral Population Metric 1.5)

SUMMARY OF MONITORING METRICS AND EVALUATION CRITERIA

A summary of all monitoring and survey metrics is provided in Table 6.

Table 6. Summary of ecological goal-based and project performance-based monitoring metrics, methods, timepoints, and evaluation criteria.

Metric Type	Metric	Method	TimePoints	Target	Reference
Ecological: Coral population enhancement	Coral abundance and cover	NCRMP Coral Demographic Survey and NCRMP Benthic Community Assessment Survey	Pre-restoration (Oct 2022); summer 2024); end of project (summer 2025)	Workable Reef Crest – 10.4% coral cover; Forereef – 7.4% coral cover	Calculated for this project using Restoring Seven Iconic Reefs methodology
	Coral health	NCRMP Coral Demographic Survey		No target	N/A
	Species richness and diversity	NCRMP Coral Demographic Survey		Increased species richness and diversity	Achievement of restoration targets should result in increased richness and diversity
Ecological: Community and habitat enhancement	Invertebrate community diversity and abundance	NCRMP Benthic Community Assessment Survey	Pre-restoration (Oct 2022); summer 2024); end of project (summer 2025)	Increased net abundance from pre-restoration surveys	CRRMG
	Reef fish community	NCRMP Reef Visual Census Fish Survey		Increased net abundance from pre-restoration surveys	CRRMG
	Reef structure and complexity	NCRMP Benthic Community Assessment Surveys		Increased from pre-restoration measurements	CRRMG
Universal: Reef-level	Outplant plot area	Recorded for each outplanting event	Recorded at time of outplanting	22,800 m^2	Combined area of total number of planned outplant plots
	Ecological footprint	Structure from Motion (SfM) Survey	Immediately post-outplanting; 3 months post-outplanting; 1 year post-outplanting; 3 years post-outplanting (if within project period)	Net increase over time	CRRMG
	Restored reef areal dimension	GIS mapping	End of project	50 acres	Area of restoration focus site
	Restored reef complexity	Structure from Motion (SfM) Survey	Pre-outplanting; immediately post-outplanting; 3 months post-outplanting; 1 year post-outplanting	Increased from pre-outplant measurements	CRRMG

Universal: Population-level	Restored coral abundance by species	Structure from Motion (SfM) Survey	Immediately post-outplanting; 3 months post-outplanting; 1 year post-outplanting; 3 years post-outplanting (if within project period)	Abundance and density of restored corals retains ≥ 80% of immediate post-outplant values through one-year monitoring timepoint	CRRMG
	Restored coral density				
Universal: Colony-level	Mean coral size	Structure from Motion (SfM) Survey	Immediately post-outplanting; 3 months post-outplanting; 1 year post-outplanting	Initial size ≥ 20 cm TLE for staghorn, ≥ 20 cm^2 for elkhorn, and ≥ 300 cm^2 for brain, star, and other species	Target sizes based on coral size class survival probabilities in Edmunds 2015 and Foster & Foster 2018
	Percentage of number of corals by species in each size class			≥90% of outplants in size classes associated with above target sizes	Target sizes based on coral size class survival probabilities in Edmunds 2015 and Foster & Foster 2018
	Mean percent increase or decrease in planar area since last monitoring event			Net annual increase in area (cm^2): elkhorn – 1.5; staghorn – 3.1; star – 0.7; brain – 0.7; other – 0.7	Projected annual growth rates used in project target cover calculations
	Mean percent live tissue per coral			Mean live tissue per colony >80%	CRRMG
	Percentage of corals in each live tissue bin			>80% outplants survive during first year after outplanting >65% annual outplant survival through year 5	CRRMG
	Prevalence of recent mortality, disease, bleaching, predation			<5% of outplants exhibit tissue loss from bleaching <10% annual disease prevalence <5% annual predation prevalence	CRRMG

Universal: Genetic and genotypic diversity	Number of genets outplanted by species	Recorded for each outplant site	Recorded at time of outplanting	>5 putative genotypes per species outplanted at each restoration site	CRRMG
	Reproductive capacity	*In situ* spawning monitoring	5 years post-outplanting(after close of project if adequate personnel and financial resources available)	Any outplanted corals spawn (no specific target number since it is unlikely observers will be able to survey all possible nights and times that spawning might occur)	CRRMG
Indirect seeding of sexual recruits	Number of substrates outplanted, average number of recruits per substrate	Recruit scoring	Immediately prior to outplanting	1-6 settlers per outplanted substrate	TNC USVI 2021 recruit monitoring data
	Recruit survival and seeding unit retention	*In situ* recruit scoring and retention measurements	1 year post-outplanting	5% recruit survival; 75% seeding unit retention	TNC USVI 2021 recruit monitoring data
Universal: Water temperature	Monthly mean, minimum, and maximum	HOBO logger deployed at one subplot for each species group and outplant zone	Data offloaded 1 year post-outplanting	No target	N/A

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APPENDIX A: CORAL OUTPLANT PLOT LOCATIONS

Plot_ID	ReefType	Zone	Latitude	Longitude	Monitoring Plot	HOBO	Species
RC1	Reef Crest	3	17.76388801	-64.61069114	No	No	Elkhorn
RC2	Reef Crest	3	17.76397151	-64.61112961	No	No	Elkhorn
RC3	Reef Crest	3	17.76443736	-64.61355689	No	No	Elkhorn
RC4	Reef Crest	3	17.76424473	-64.61286184	No	No	Elkhorn
RC5	Reef Crest	3	17.76424012	-64.61165793	Yes	No	Elkhorn/Seeding Units
RC6	Reef Crest	3	17.76426023	-64.61326232	No	No	Elkhorn
RC7	Reef Crest	3	17.76402501	-64.61032547	Yes	No	Elkhorn
RC8	Reef Crest	3	17.76391468	-64.61176305	No	No	Elkhorn
RC9	Reef Crest	3	17.76386881	-64.6114659	Yes	Yes	Elkhorn/Brain
RC10	Reef Crest	4	17.76346378	-64.60733837	No	No	Elkhorn
RC11	Reef Crest	4	17.76352827	-64.60840313	No	No	Elkhorn
RC12	Reef Crest	4	17.76332216	-64.60622772	Yes	No	Elkhorn/Brain
RC13	Reef Crest	4	17.76346827	-64.6076667	No	No	Elkhorn
RC14	Reef Crest	4	17.763628	-64.60897116	Yes	No	Elkhorn
RC15	Reef Crest	4	17.76383894	-64.60954061	No	No	Elkhorn
RC16	Reef Crest	4	17.76324447	-64.60684913	No	No	Elkhorn
RC17	Reef Crest	4	17.76359956	-64.60807004	No	No	Elkhorn
RC18	Reef Crest	4	17.76324643	-64.60655608	Yes	Yes	Elkhorn/Seeding Units
RC19	Reef Crest	1	17.76545805	-64.62149192	Yes	No	Elkhorn
RC20	Reef Crest	1	17.76543332	-64.62282775	No	No	Elkhorn
RC21	Reef Crest	1	17.76538492	-64.61923593	No	No	Elkhorn
RC22	Reef Crest	1	17.76540993	-64.62083693	Yes	No	Elkhorn/Brain
RC23	Reef Crest	1	17.76529768	-64.62203645	No	No	Elkhorn
RC24	Reef Crest	1	17.76529157	-64.62117968	Yes	Yes	Elkhorn/Seeding Units
RC25	Reef Crest	1	17.76539924	-64.62046354	No	No	Elkhorn
RC26	Reef Crest	1	17.76542095	-64.62006569	No	No	Elkhorn
RC27	Reef Crest	1	17.76537253	-64.61881579	No	No	Elkhorn
RC28	Reef Crest	2	17.76483479	-64.61546614	Yes	No	Elkhorn
RC29	Reef Crest	2	17.76487175	-64.61575959	No	No	Elkhorn
RC30	Reef Crest	2	17.7652114	-64.6175513	No	No	Elkhorn
RC31	Reef Crest	2	17.76515425	-64.6171639	Yes	Yes	Elkhorn/Brain
RC32	Reef Crest	2	17.76534658	-64.61852512	No	No	Elkhorn
RC33	Reef Crest	2	17.76472732	-64.6151709	Yes	No	Elkhorn/Seeding Units
RC34	Reef Crest	2	17.76507366	-64.61637023	No	No	Elkhorn
RC35	Reef Crest	2	17.76532814	-64.61816553	No	No	Elkhorn
FR1	Forereef ACER	4	17.76414398	-64.60909876	Yes	No	Staghorn/Seeding Units
FR2	Forereef ACER	3	17.76482388	-64.61371558	Yes	No	Staghorn

FR3	Forereef ACER	3	17.76468618	-64.61316478	Yes	Yes	Staghorn/Star/Other
FR4	Forereef ACER	3	17.76464043	-64.61242599	Yes	No	Staghorn/Seeding Units
FR5	Forereef ACER	4	17.76378992	-64.60686445	Yes	Yes	Staghorn/Star/Other
FR6	Forereef ACER	2	17.76554916	-64.6165472	No	No	Staghorn
FR7	Forereef ACER	2	17.76568646	-64.61842703	Yes	No	Staghorn/Star/Other
FR8	Forereef ACER	1	17.76579341	-64.62110428	Yes	No	Staghorn
FR9	Forereef ACER	2	17.76532709	-64.61541296	No	No	Staghorn
FR10	Forereef ACER	2	17.76561076	-64.61723204	Yes	No	Staghorn/Seeding Units
FR11	Forereef ACER	2	17.76516375	-64.61498248	No	No	Staghorn
FR12	Forereef ACER	1	17.76569514	-64.61912925	No	No	Staghorn
FR13	Forereef ACER	2	17.76559718	-64.61693682	No	No	Staghorn
FR14	Forereef ACER	1	17.76568961	-64.62072139	Yes	Yes	Staghorn
FR15	Forereef ACER	1	17.76569885	-64.6196002	Yes	No	Staghorn/Star/Other
FR16	Forereef ACER	2	17.76563901	-64.61773007	Yes	Yes	Staghorn/Seeding Units
FR17	Forereef	3	17.76436501	-64.61050881	No	No	Brain/Star/Other
FR18	Forereef	3	17.76409673	-64.61116586	No	No	Brain/Star/Other
FR19	Forereef	3	17.76440997	-64.61172737	No	No	Brain/Star/Other
FR20	Forereef	3	17.76444563	-64.61309464	No	No	Brain/Star/Other
FR21	Forereef	3	17.7645427	-64.61356705	No	No	Brain/Star/Other
FR22	Forereef	3	17.76400957	-64.61000791	Yes	Yes	Brain/Star/Other/Seeding Units
FR23	Forereef	3	17.76454543	-64.6122507	No	No	Brain/Star/Other
FR24	Forereef	4	17.76378377	-64.60886077	No	No	Brain/Star/Other
FR25	Forereef	4	17.76346631	-64.60660528	No	No	Brain/Star/Other
FR26	Forereef	4	17.76373252	-64.60786286	No	No	Brain/Star/Other
FR27	Forereef	4	17.76410578	-64.60926815	No	No	Brain/Star/Other
FR28	Forereef	4	17.76416095	-64.6097703	Yes	Yes	Brain/Star/Other/Seeding Units
FR29	Forereef	4	17.76378849	-64.60712735	No	No	Brain/Star/Other
FR30	Forereef	1	17.7656408	-64.61995144	No	No	Brain/Star/Other
FR31	Forereef	1	17.76556541	-64.61887304	No	No	Brain/Star/Other
FR32	Forereef	1	17.76551043	-64.61943544	No	No	Brain/Star/Other
FR33	Forereef	1	17.76558724	-64.62123466	Yes	Yes	Brain/Star/Other
FR34	Forereef	1	17.76553938	-64.62225687	No	No	Brain/Star/Other
FR35	Forereef	2	17.76541674	-64.61757455	No	No	Brain/Star/Other
FR36	Forereef	2	17.76480821	-64.61478653	No	No	Brain/Star/Other
FR37	Forereef	2	17.76561216	-64.61801417	No	No	Brain/Star/Other
FR38	Forereef	2	17.76524486	-64.61603987	No	No	Brain/Star/Other
FR39	Forereef	2	17.76515506	-64.61555379	No	No	Brain/Star/Other
FR40	Forereef	2	17.7653382	-64.61707088	Yes	Yes	Brain/Star/Other
FR41	Forereef	2	17.76559958	-64.6186068	No	No	Brain/Star/Other