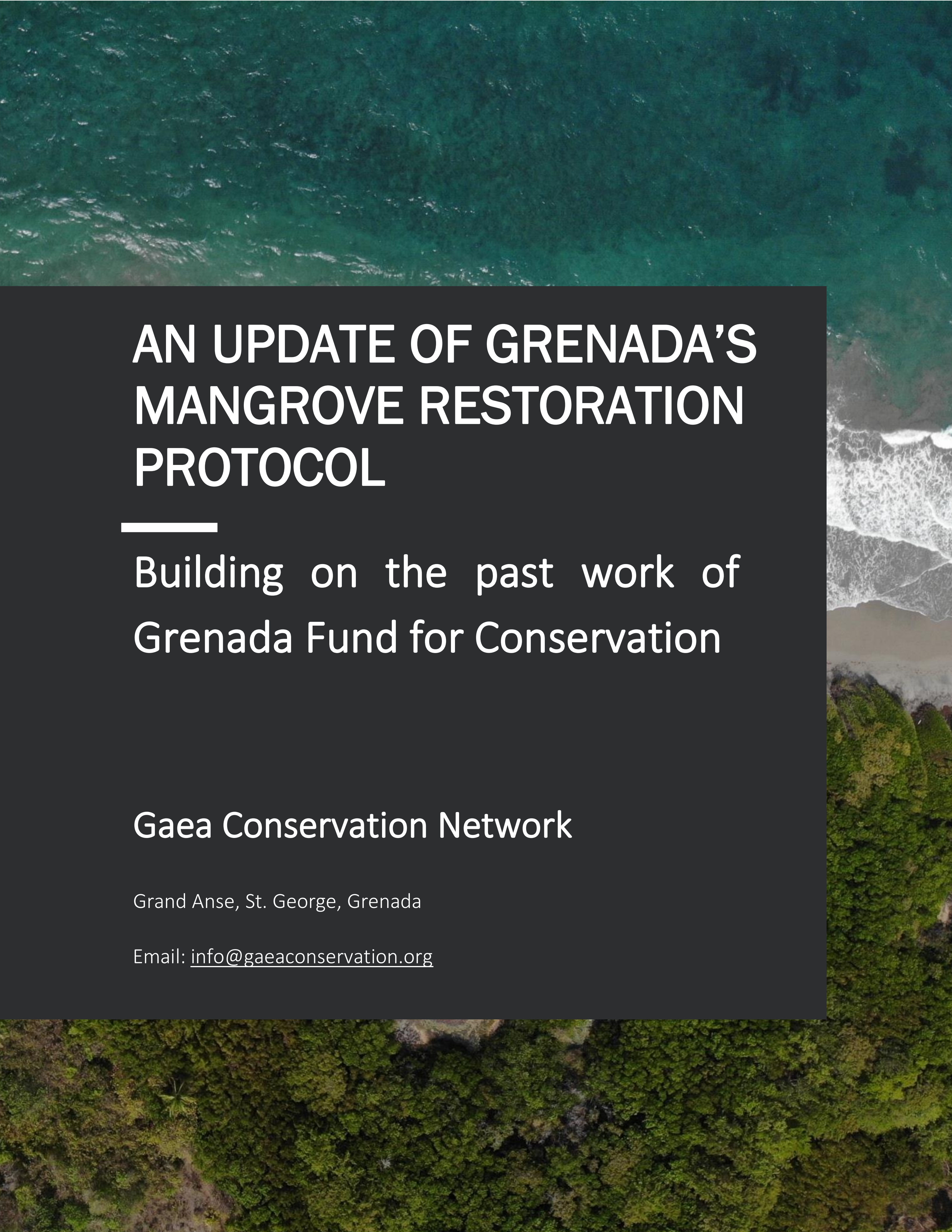

AN UPDATE OF GRENADA'S MANGROVE RESTORATION PROTOCOL

Building on the past work of Grenada Fund for Conservation

Gaea Conservation Network

Grand Anse, St. George, Grenada

Email: info@gaeaconservation.org

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Background:

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Introduction

The Need for Mangrove Restoration

Mangroves are tropical, flowering plants specially adapted to survive in saline and tidally influenced environments, with salt exclusion/excretion mechanisms, reproductive adaptations, and special root adaptations. These special adaptations not only help deal with the tidal changes, but the effects of climate change. Mangrove ecosystem services are extensive and well-documented, as mangroves can reduce coastal erosion, filter water from upland before it infiltrates the marine environment, protect coastal areas during hurricanes and storm surges, mitigate the impacts of sea-level rise, provide nurseries for fish and marine invertebrates, and are major carbon sinks.

Like many wetland ecosystems worldwide, mangroves and their associated ecosystem services are being lost at an alarming rate due to human activities. Human activities such as charcoal burning, shrimp farming, and unsustainable coastal development all play a major part in the drastic loss of mangrove coverage at our water's edge (FAO, 2007). These are also exacerbated by climate change impacts, such as surface temperature changes, sea level rise, and changes in weather patterns (Jennerjahn et al., 2017). The annual rate of mangrove deforestation around the world is estimated to be between 0.16–0.39% (Hamilton & Casey, 2016), and there has been as much as a 30–50% decline in mangroves in the last century (Feller et al., 2017). Because mangroves are the most carbon-rich ecosystem in tropics (Donato et al., 2011), sequestering four to five times that of tropical forests (Sanderman et al., 2018; Twilley et al., 2017), their annual loss to human activities can exacerbate greenhouse gas emissions (Adame et al., 2021). Naturally, mangrove ecosystems are biologically engineered to self-repair over time if environmental conditions are favourable. However, the rates of anthropogenic destruction and degradation often exceed that of natural recovery. Furthermore, in many cases, especially where they are removed for coastal development, the mangroves are replaced by hard structures (grey infrastructure), thereby eliminating any chance of natural recovery in those areas. To counteract our actions and mitigate climate change impacts, scientists often recommend mangrove restoration (Lewis 2009).

History of Grenada's Mangrove Restoration

Several mangrove restoration projects have been undertaken in Grenada over the last 2.5 decades, with varying success. The first site targeted for restoration was Petit Carenage/L'islet on Carriacou, which had sustained severe damage from Hurricane Janet and a suspected fire in the 1950s. The restoration was spearheaded by Dr. Gregg Moore with support from YWF-Kido Foundation; seedlings of both red (*Rhizophora mangle*) and black (*Avicennia germinans*) mangroves were planted in 1998 and monitored over the next 6 years (Moore, 2004). More than 20 years since its restoration, the damaged/denuded area is now revegetated (Figure 1). It is important to note, however, that the initial 1998 planting was not the only effort at this site, and Kido Foundation has continually planted mangroves over the years, with ongoing efforts as recently as late 2021.

Since the establishment of Grenada Fund for Conservation (GFC) in 2007, the organization has led multiple restoration projects on the island of Grenada, several under the guidance of Dr. Moore. Both Woburn and Calivigny, St. George, were severely damaged by Hurricanes Ivan and Emily in 2004 and 2005 respectively. Following a rapid assessment of mangrove sites throughout the tri-island state (Layman et al., 2006), several sites were identified that required intervention to facilitate recovery after the hurricanes, including Woburn and Calivigny. Recovery at both sites was hindered by anthropogenic stressors, including hurricane and household debris dumped in the mangal and effluent from the rum factory at Woburn. Work at Woburn began in 2009, and the last seedlings were planted at the site in 2013; it has since filled in substantially, with healthy stands of red and white mangrove (*Laguncularia racemosa*) in the interior and other coastal species along the perimeter (Figure 1). At Calivigny, planting efforts were less intensive with only one major planting in 2010; after all the non-natural debris was removed and the conditions for growth were restored, white mangroves recolonized the site naturally. It is now completely revegetated with a mix of red and white mangroves (Figure 1).

Figure 1. A few of the restoration sites across Grenada and Carriacou from left to right: Petit Carenage in 2001 (top) and 2019 (bottom); Woburn in 2011 (top) and 2020 (bottom); and Calivigny in 2009 (top) and 2020 (bottom).

More recent restoration efforts have been focused on the Greater Grenville Area in St. Andrew, which research has shown is particularly vulnerable to sea level rise. Grenville Bay is experiencing severe erosion due to the blasting of the coral reefs in Grenville Bay in the 1980s (local community knowledge). The first project was in Telescope (Little Bay) and ran from 2013 to 2019. GFC planted red mangroves in a hybrid planting approach both on-land and in-water using the Riley Encased Methodology (Riley & Kent, 1999), and most of the initial plantings failed. Only ~10% of in-water seedlings are still alive, and on land, one 25x50 ft enclosure remains with seedlings planted in 2017; these enclosed plants are now well over 15 ft tall and have produced their own propagules. The failures at the site are not only ecological (due to site incompatibility with red mangroves or overheating, etc.) but also social, as community dynamics and sabotage came into play.

Not far away, in Telescope (Big Bay), GFC also undertook restoration efforts at a large mangal that was decimated by clearing for charcoal production. The project ran from 2015 to 2018, and red mangroves were planted on both the landward and seaward edges of the mangal. Only the landward plots survived, and now have mature trees 10–15 ft tall with well-developed prop root systems; the seaward plots were likely buried by the high wave action and sand deposition along the shore. The threat of deforestation for charcoal production persists at this site (Figure 2).

Figure 2. Ongoing deforestation at Telescope (Big Bay), where there have been recent efforts to restore red mangroves by GFC. Taken in February 2021.

Further north within the same bay, at Pearls, is the most recent restoration project on island. Work in Pearls began in 2020 and ended in mid-2021, to slow the erosion and loss of beach area along the coastline. It is still too early to evaluate the success of this project, but most seedlings are growing well; however, high winds and waves, especially seasonal surges, are a continued threat.

Critique of Current Restoration Approach

Damaged or degraded mangroves are capable of self-repair or natural succession within a few decades (e.g., Calivigny), but two conditions are necessary. First, the tidal hydrology must be maintained, and second, propagules from nearby mature stands must be able to reach the degraded site and naturally establish (Lewis, 2001). Sites that have efficient hydrology and ample parent trees do not need mangrove seedlings in most cases. Lewis (2005) introduced the term "propagule limitation" to define a condition in which "natural recovery is slowed or stalled due to a lack of sufficient natural mangrove propagules being available to recruit at a degraded site". If the first condition is not met, then hydrologic restoration—defined by Lewis (2009 p. 790) as the "reestablishment of historical tidal connections"—is necessary. If the first condition is met but the second is not, then mangroves can be successfully restored by planting. However, due to the cost-and time-intensiveness of mangrove planting, it should be a last resort only if the two conditions (tidal flow and seedling availability) are restored and the system fails to naturally regenerate.

Unfortunately, many mangrove restoration projects experience high losses and low success rates because planting is done without proper site assessment or hydrologic restoration. In much of the literature, authors attribute failure in assisted mangrove restoration to inappropriate species selection (i.e., where the physiological needs of species differed from site conditions) and planting locations including low elevation and/or high exposure sites (e.g., Chan & Baba, 2010; Lewis & Brown, 2014; Trench & Webber, 2012). For these reasons, restoration success is very variable, with rates between 0 and 66% reported by Lewis, (2001). Restoration success rates in the Caribbean, and Grenada in particular, are higher on average, but there is still much room for improvement in our technique to increase the cost-effectiveness of restoration efforts. Furthermore, red mangroves have primarily been used in Grenada, with black also being planted for one project on Carriacou (Moore, 2004), but we believe it to be a gap that white mangroves, a known pioneer species, have not been incorporated into restoration efforts. Recent local research has found white mangroves to be especially plastic and tolerant of a wide range of environmental conditions, and Buckmire (2022) recommends it for use in restoration.

We must place greater emphasis on site assessment, hydrologic restoration, and appropriate species selection (if planting is deemed necessary) for successful mangrove restoration. The following five steps summarize the Ecological Mangrove Restoration (EMR) approach proposed by Lewis & Marshall (1997) (Lewis, 2001 p. 8):

1. "Understand the autecology (individual species ecology) of the mangrove species at the site, in particular the patterns of reproduction, propagule distribution, and successful seedling establishment.
2. Understand the normal hydrologic patterns that control the distribution and successful establishment and growth of targeted mangrove species.
3. Assess modifications of the original mangrove environment that currently prevent natural secondary succession.
4. Design the restoration program to restore appropriate hydrology and, if possible, utilize natural volunteer mangrove propagule recruitment for plant establishment.

5. Only utilize actual planting of propagules, collected seedlings, or cultivated seedlings after determining (through steps 1–4) that natural recruitment will not provide the quantity of successfully established seedlings, rate of stabilization, or rate of growth of saplings established as objectives for the restoration project."

Thus, we acknowledge that planting of mangroves will not always be necessary during mangrove restoration. This manual details the methods and procedures for mangrove restoration when planting is necessary—i.e., how to collect, care for, and transplant mangrove seedlings in the Grenadian setting. As recommended above, these should be preceded by appropriate site evaluation (detailed below) and hydrological interventions where possible (as described elsewhere).

Lewis' five EMR steps will be used to guide our mangrove restoration approach, adjusted to local conditions based on GFC's experience in the last decade and the results of a growth experiment conducted by GCN in summer 2021.

Growth Experiment

We conducted a growth experiment in early to mid-2021 to determine the optimal conditions for mangrove seedling growth in coastal areas in Grenada. We used a modified marsh organ design to create experimental units at 3 different tidal elevations (Figure 3; Peng et al., 2018). The sediment at the lowest level was always saturated (submerged), the middle level was saturated at low tide and exposed at high tide (semi-submerged), and the highest level was exposed and dry at all tides (on-land). We modified recycled drink cases by removing some of the internal dividers to create 6 cells; the individual cells provided better protection for seedling roots and minimized the spread of fouling between plants. Within each level, there were 5 crates with 6 cells each. 3 crates contained seedlings of one species (one each for red, black, and white mangroves) and 2 crates contained a mixture of species with 1 focal species and 2 seedlings of a different species (e.g., 1 white [focal] and 2 black [additional] seedlings). These 15 crates (3 levels of 5 crates each) comprised a single marsh organ, shown in the Figure 3.

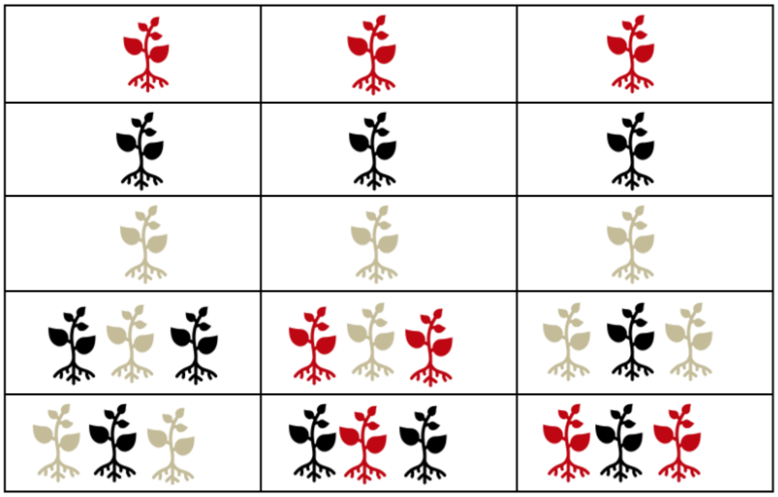


Figure 3. Experimental plots showing mono- versus multi-species cells.

We set up our marsh organs at Petit Bacaye, Westerhall, a sheltered bay with a natural mangrove forest and small river dividing the system (). There were 2 treatments, with 1 marsh organ located alongside the river in the shade and the other marsh organ located at the seaside exposed to direct sunlight. Because the river was influenced by the tides, the salinity at both sites varied; thus, it was only at low tide that salinity differed between the river and seaside treatments.

Figure 4. Drone images of the growth experiment site (Petite Bacaye, Westerhall), showing the sheltered bay, beach, and small river. Taken March 2021; photo credit: Reginald Joseph.

seedlings of the three mangrove species, rather than propagating them ourselves. We collected seedlings from Mt. Hartman and Woburn, which are both located near to the site of the experiment, from areas of high mangrove seedling density to avoid stressing the donor sites (Figure 5). Seedlings between 10–15 cm tall (10–15 cm of new growth for red mangroves) were selected as we believed they would have the greatest chance of survival in the acclimation process.

Figure 5. Team members collecting propagules for the marsh organs (left) and black mangroves propagules (right).

After collection, we sorted the seedlings by species and performed an initial culling to remove seedlings that showed a low chance of survival (such as those with broken stems or damaged roots from the extraction or initial handling process). Since mangrove restoration in Grenada has primarily been done with propagules and not harvested seedlings (wildlings), our experiment also served to inform best handling and acclimation procedures to maximize survival in future efforts.

The plants were placed in white 5-gallon buckets with a few inches of saltwater and covered with saran netting for shade. They were allowed to acclimatize for 1 week and the water was changed every 2 days. Finally, they were transplanted into the crates based on the layout described above, with each plant weighed and measured beforehand to facilitate monitoring and comparison. We monitored the plants for 10 weeks to record survival and growth rates, from March 19th to May 23rd, 2021.

Results of the Experiment

After 10 weeks in the field, we found that most of the plants did not survive. Adverse weather conditions around days 9 and 52, accompanied by storm surges, greatly increased mortality rates and there were mass die-offs of all three species (Figure 6). We observed that a few of the crates, which were located further inland along the river, remained protected from the storm surges, and sustained less damage overall. Many of the submerged and semi-submerged crates along the river were smothered by debris that washed downstream while several of the seaside crates were completely overturned with their contents spilled.

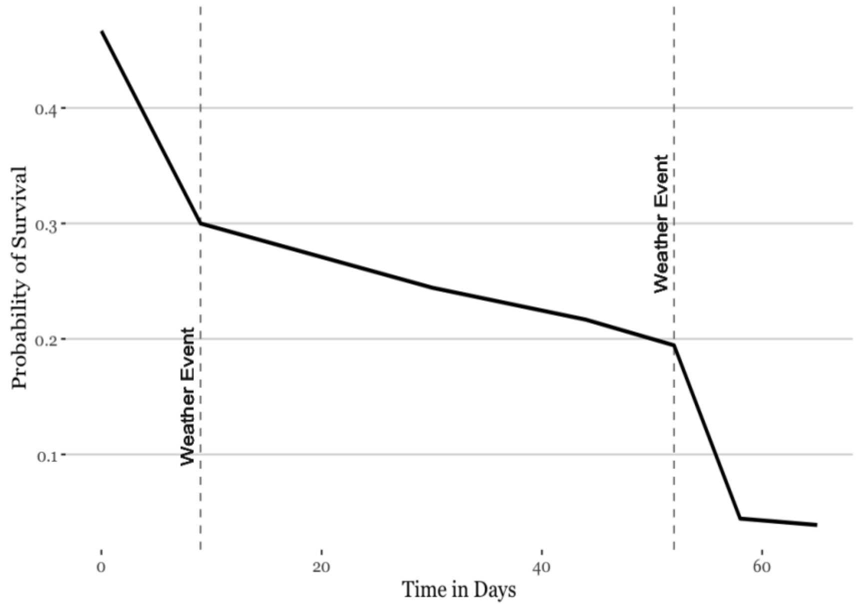


Figure 6. Overall probability of survival for growth experiment.

Species Comparison

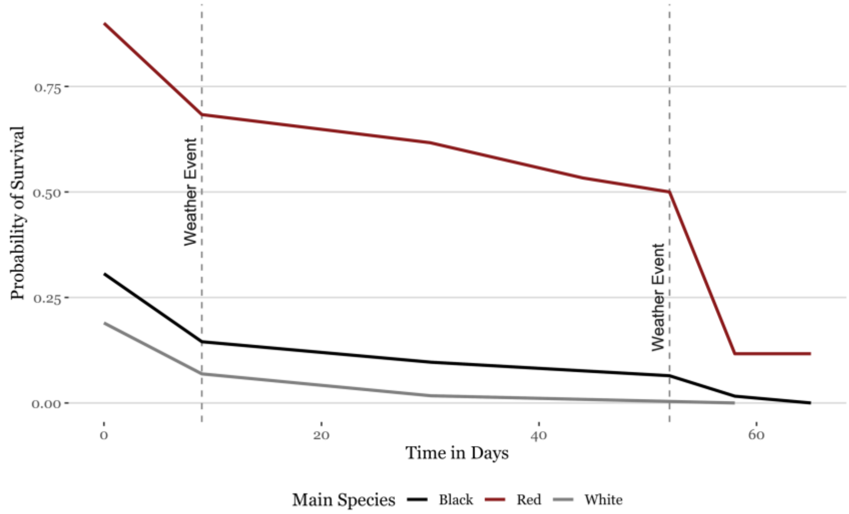


Figure 7. Probability of survival for three mangrove species during the growth experiment.

Red mangroves appeared to be the most resilient species overall (Figure 7), even when we control for where the marsh organ was located and the level of inundation. We used a cox proportional hazards model to explore if, when we control for other conditions, red still had a higher survival probability than the other two species. In this model, we considered the seedling survival percentage and how long the seedling survived. Thus, if a seedling survived for the length of the experiment, we assigned a non-zero death flag and a survival time of 63 days. We found that if the species was a red mangrove, it had an 80% higher chance of survival than black. Though not significant, if the species was white, the chance of survival was 38% lower than black. We suspect that red mangroves' larger seedlings (with greater nutrient reserves) and hardier stems likely explain why it had higher survival than black and white mangroves.

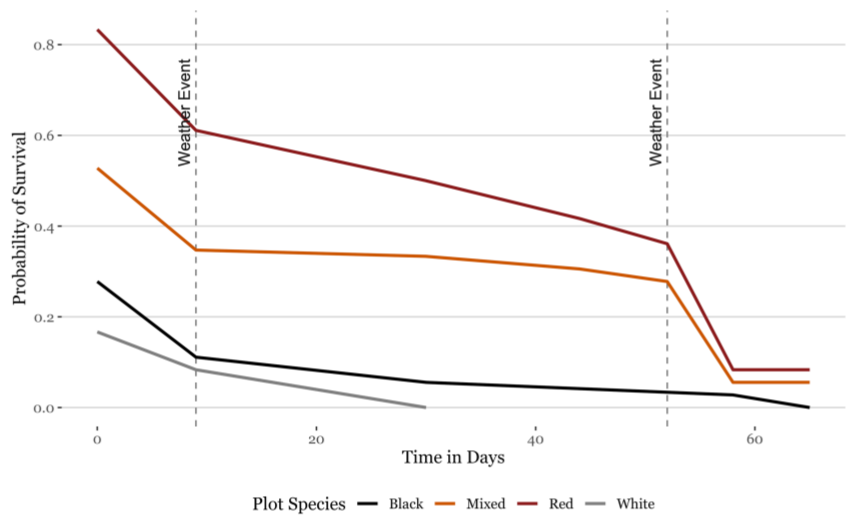


Figure 8. Probability of survival for various assemblages in the plots (crates). Here, we focus on the focal species of each assemblage; where red was the focal species, it was planted alongside white or black propagules, and vice versa.

In the cells with mixed-species assemblages, red was the dominant survivor (Figure 8), regardless of which other species was planted within the cell. We suspected that because red mangroves had taller seedlings, they may have shaded the other species, thus outcompeting them, or it may have simply survived due to its nutrient reserves while the other species burnt and/or starved more quickly.

Treatment (Shade vs Sunlight)

Plant units had marginal differences in survival based on whether they were along the river (shaded) or seaside (direct sunlight). Within the first few weeks of planting, most of the white and black mangroves in the on-land seaside crates appeared dehydrated and sunburnt, more so than the red seedlings, and many of these non-red seedlings died (Figure 9 and Figure 10). This die-off may be due to different sunlight tolerances of the species, or the less-resilient nature of white and mangrove seedlings after being transplanted. Although red mangroves may be better acclimated to the shaded understory than black and white (Hogarth 1999; BVIDDM 2020), they still showed the greatest survival because they were more resilient to being transplanted. This hypothesis was supported by our findings from a survival model that included both main species and condition. In this model, we included an interaction between condition and species; this model explores whether there is a difference in survival for each species

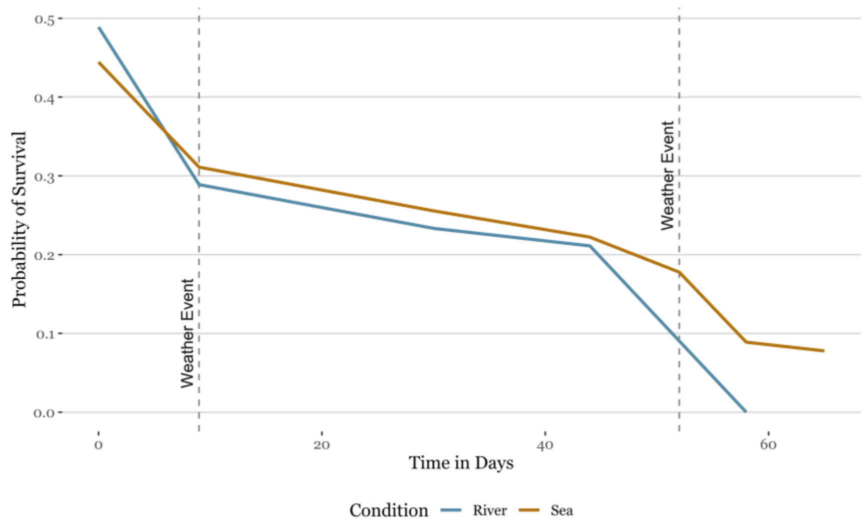


Figure 9. Probability of survival of plant units located in river (shaded) and seaside (direct sunlight).


Figure 10. Die-offs for non-red mangroves a few weeks into the experiment.

between the river versus sea. Our findings suggest that there is no difference in survival, regardless of species, whether the organ was near the sea (direct sunlight) versus the river (shade). Consequently, we recommend situating the seedlings in areas that mimic the conditions (including light intensity/exposure and salinity) where they will be transplanted. However, for black and white mangroves, we recommend greater care when transplanting wild-harvested seedlings – perhaps a longer period to acclimatize in buckets before transplanting.

Level (Submerged, Semi-submerged & On-Land)

Overall, plants in submerged and semi-submerged crates did not experience die-offs as readily as those on-land (dry) (Figure 11), suggesting that the ideal level of tidal inundation protects plants from both drowning and burning. As above, we used a survival model to explore whether there was a difference among species based on the tidal regime. Overall, plots that were semi-submerged had an 52% higher survival rate than those in dry conditions – plots that were fully-submerged had a 38% higher survival rate than those in dry conditions.

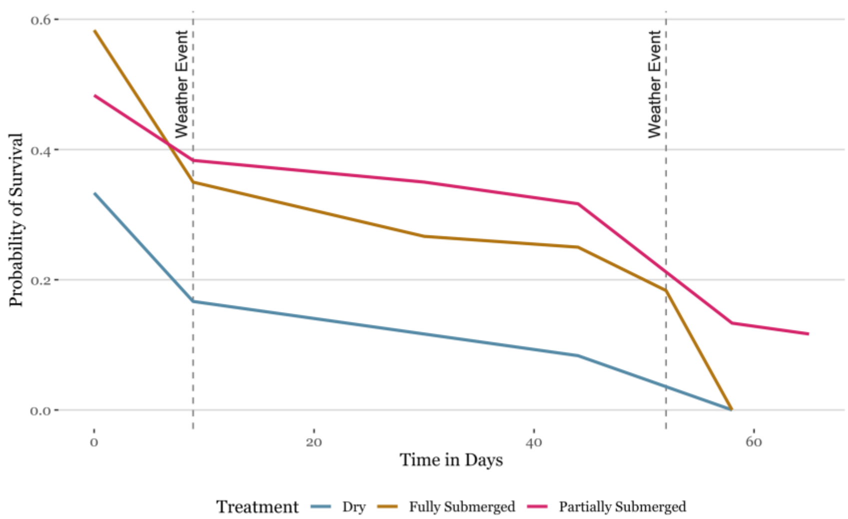


Figure 11. Survival plot of growth experiment by submersion level within the marsh organ.

While red and black mangroves were 77% and 74% more likely to survive in semi-submerged plots respectively (when compared to on land), red mangroves were also 36% more likely to survive in fully submerged plots than on land. Thus, both red and black mangroves had their highest chance of survival in partially inundated areas, though red, unlike black, could still see some gains in full-submerged crates. For the white mangroves, we saw no significant differences in survival based on the tidal levels.

Seedlings that grew 1 cm had a 1.2% higher chance of survival, regardless of species. We caution that the results for white and black might be unreliable, since they were continually buried, which obscured their true growth. Regardless, using a survival model, we explored growth rates among the species when we account for inundation levels. Both red and black mangroves had the highest growth in partially submerged plots (Figure 12), and growth in these plots increased the change of survival by 2%. For white mangroves, generally, increase in height from the start to end of the experiment were highest in the on-land plots (Figure 12).

All species lost leaves overall, but this loss was lowest for red mangroves in plots that were partially submerged, and for white and black mangroves in on-land plots.

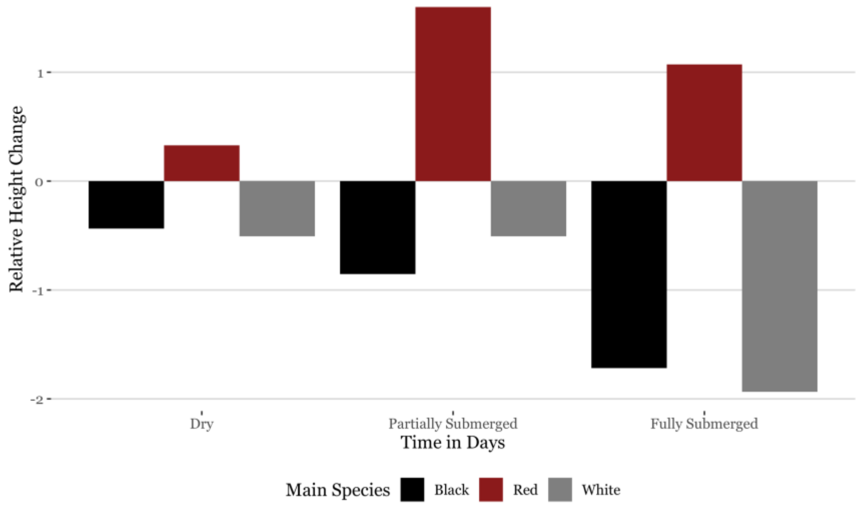


Figure 12. Mean change in height for each species from the begin to end of the experiment

This highest growth rate on land for white mangroves was corroborated by our observations after the experiment ended. In the on-land crates along the river, we observed natural white mangrove recruits from adult trees overhead, which suggests that this species germinates readily and perhaps should be planted from propagules rather than transplanted from wildlings.

Summary of Growth Experiment

These findings are in keeping with previous studies and descriptions of these species' characteristics. Trench, (2021) described that "the species with smaller propagules (*Avicennia* and *Laguncularia*) are less adapted to the edge of the coastline, being less resistant to water movement and physical injuries than red mangrove seedlings", which is the tidal sorting hypothesis (Rabinowitz, 1978). Red mangroves were seen to be the most resilient species with a few surviving units at the end of the experiment. These were subsequently transplanted nearby before we removed the crates from the study site. White and black mangroves, despite die-offs due to adverse weather conditions, showed some stability between the two storm surge episodes, suggesting that they likely can grow under the experimental conditions and can be planted in similar conditions for restoration. Their low survivability compared to red mangroves suggests that these are more vulnerable species that require greater care when replanting; we recommend collecting and germinating propagules for these two species instead. Red mangroves can be successfully transplanted, and thus propagation from seedlings or collection of wildings are both viable methods for this species. However, some previous studies have shown that mangrove saplings do not fare well in transplanted situations, especially larger saplings which have developed an extensive rooting network (C. Trench, personal communication); thus, well-established saplings should not be harvested for transplant.

Stable Isotope Analysis

To overcome or minimize the challenges of living in a saline environment, mangrove trees can use a variety of water sources, which can be discerned using stable isotope analysis (Sternberg & Swart, 1987). Understanding the water source choices of different species can inform restoration by revealing species' tolerances and preferences for rainwater, groundwater, or seawater, and thus allowing appropriate species selections when replanting different sites.

To determine whether the mangrove species differ in what water sources they use, we collected samples for stable isotope analyses at four sites in Grenada. In November 2019, we collected samples of each water source (i.e., runoff, stream, groundwater, ocean) and plant material (i.e., leaves, stems, and roots) from adult trees of each species.

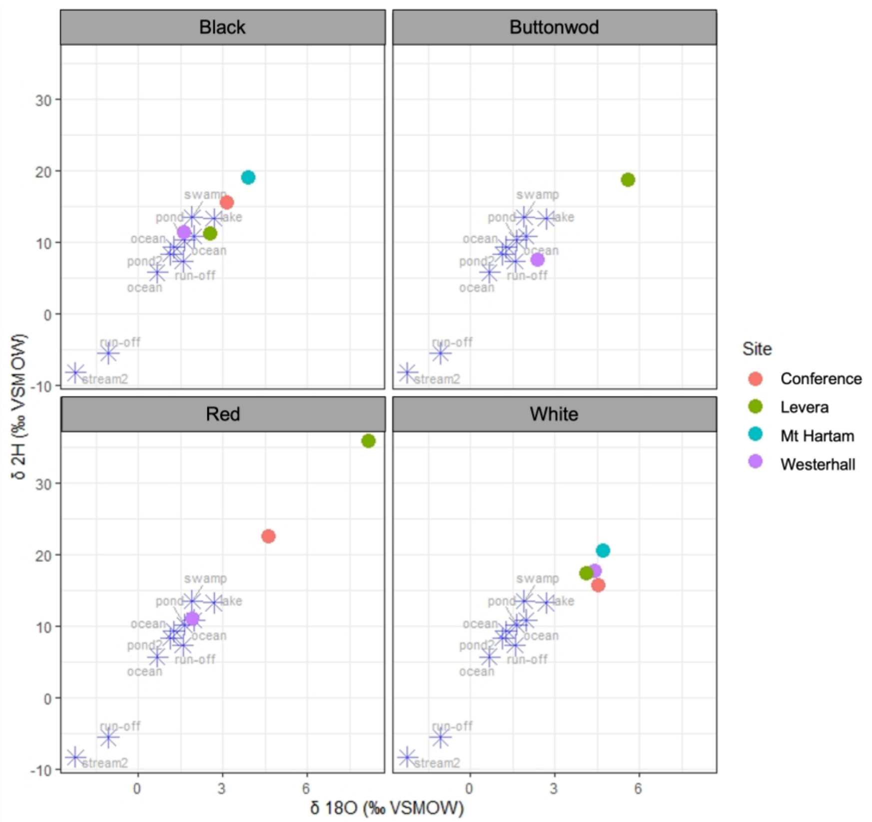


Figure 13. Results of stable isotopes analyses at four sites around Grenada

White mangroves displayed similar leaf water isotopic composition at all four sample sites, possibly indicating a strongly preferred source of water in this species (Figure 13). Consistent with habitat requirements, red mangroves displayed the most variability in leaf water isotopic composition among the sites, while black and buttonwood mangroves had moderate among site variability in isotopic composition. This does suggest that red mangroves will show higher survivability regardless of where they are positioned in a wetland as they are able to exploit more varied water sources, generally, while white will be more successful in specific conditions. This finding is consistent with our observations in the growth experiment; white showed the lowest survival overall but seemed to have higher growth rates in drier conditions, perhaps where their preferred water sources are more readily available. However, more research is required to identify exactly what that preferred water source is (whether run-off, stream, groundwater, or seawater).

Interestingly, recent research on white mangrove distribution and form in Grenada (Buckmire, 2022) found that although the species is capable of growing in shallow to intermediate water depths through various root adaptations, white mangroves do prefer drier or higher elevation habitat. The stable isotope and growth experiment findings support this preference for dry habitat and specific water sources, informing its placement during restoration efforts.

Proposed Mangrove Restoration Approach

In this manual, we propose the following five-step process for effective mangrove restoration: 1) site evaluation, 2) nursery set-up, 3) propagule collection and preparation, 4) in-situ acclimation, and 5) transplantation and monitoring. Local community members and/or private landowners (hereafter called stakeholders) will be involved throughout the process to ensure buy-in and increase the chances of restoration success.

1. Site Evaluation

If a site is shortlisted for mangrove restoration, there are a few things we must consider during site evaluation. First, in consultation with stakeholders, we should determine if mangroves were ever present at the site (if none are currently present). Preferably, we will restore mangroves mainly in areas where they naturally existed, but circumstances (such as severe coastal erosion or loss of offshore ecosystems like seagrass beds) may occasionally require the creation of a mangrove forest where one did not exist previously.

If mangroves were present in the recent past, we should next determine the cause of mangrove loss. These may include, but are not limited to:

- Removal for development: deforestation is the greatest cause of mangrove loss in the Caribbean (FAO, 2007). In many cases, developments involve modification of the hydrology of the site to accommodate the infrastructure. We should determine if and how the hydrology of the site was changed and discuss, with the stakeholders, how it could be restored before replanting.
- Changes in hydrology: certain types of construction may negatively affect the movement of water to or through a mangrove forest area. Roads across mangrove forest lands built without culverts or connecting waterways are well known to prevent water movement and cause a gradual die-off (Lewis, 2005).
- Disease: these cases are rarer but can severely affect the health and survival of mangrove plants (Osorio et al., 2016). We should survey any remaining plants to determine if they show signs of distress or if the disease remains in the population.

- Natural disaster: after hurricanes and storms, mangroves are typically able to regenerate naturally (Piou et al., 2006). Thus, if this has not occurred, we may be concerned that there has been a change in hydrology, or the conditions at the site (e.g., water or sediment chemistry) may be inhospitable to propagules. Testing of the water and/or sediment would be useful in identifying conditions that would make restoration unfeasible (e.g., poor water quality).

Next, we should determine both the current and historic species composition of the area we hope to restore. Current species composition can be determined from surveys, and historic information acquired from the relevant stakeholders. In brief, we should have a thorough understanding of the species turnover (what species were there, how the species composition may have changed, and the rate of this change) at the site, as this can influence which species we consider for replanting.

If a potential site has water and sediment chemistry within optimal ranges, and there is no culvert or blockage to the historic water flows, then it would be a strong candidate for restoration. In these cases, we may assume that poor propagule dispersal explains why the site has not naturally regenerated. If water and sediment chemistry are suboptimal, but there are adult plants present at the site, we may also consider assisted restoration (i.e., planting the species within a casing or on an uplifted bed).

2. Nursery Set-Up

Mangrove nurseries are established to tend seedlings to maturity before transplanting. All five countries in the Caribbean Basin that have published mangrove restoration manuals—Grenada, Jamaica, Guyana, the British Virgin Islands, and Mexico—recommend a nursery-based propagation approach for the preparation of seedlings (Bovell, 2011; BVIDDM, 2020; Moore, 2014; Trench & Webber, 2012; Tsuruda, 2013). Advantages of the nursery approach include development of roots before planting, greater stability once planted which will keep the seedlings from being washed away by tidal movements, protection from predators like crabs and caterpillars, development of leaves to allow for photosynthesis, and flexibility in the timing of restoration activities as seedlings can be available year-round, not just during periods of natural propagule production (Bovell, 2011; BVIDDM, 2020; Moore, 2014; Trench & Webber, 2012;

Tsuruda, 2013). All of these factors contribute to higher success rates than direct planting or “dibbling”. Already germinated seedlings, or “wildlings” can also be harvested from donor sites and transplanted in restoration sites, but this is discouraged by Moore (2014) and the BVIDDM, (2020) as it both disadvantages the donor sites by removing potential recruits and can damage the seedlings’ roots and result in poor survival once transplanted. However, using wildlings significantly reduces the required incubation time before restoration, and in our growth experiment, we successfully harvested and transplanted young wildlings; thus, wildling use is possible with great care and appropriate in certain circumstances.

For large-scale restoration projects, like those previously completed by Grenada Fund for Conservation, a large central nursery may be used from which plants are allocated and transported to various planting sites. However, for smaller scale projects on private land, it is more appropriate to decentralize the seedling stock and have the nursery closer to the relevant site. For this, we recommend on-site nurseries. The required size of the nursery will vary based on the size of the restoration area and the needs of the stakeholders and will be scaled to hold anywhere between 100 and 1000 seedlings.

As the nursery is a temporary structure, its construction should be simple (photo to be added). Four posts enclosed by fencing or slatted material and covered with saran netting or plastic will provide a structure that protects the seedlings from heat and interference by dogs and/or livestock. Treated material is recommended for the harsh conditions at the coast, but untreated lumber or even bamboo can be used to minimize initial costs. To further reduce costs, a natural covered area, between two trees for instance, would suffice, if there is some protection around the seedlings to deter animals. If in a public area, the nursery should be able to be locked in security, but on private land, this should not be a concern. Shelves can be built to increase the surface area for storing plants within the nursery, and pallets can be used as flooring material to even out sloped areas or to keep the plants off the ground in low-lying or frequently inundated areas.

At least part of the nursery should be covered to provide shade to seedlings. Shading helps protect the seedlings from desiccation and heat damage, but excessive shade can also make seedlings weak; a shade level between 30–80% is recommended (Bovell, 2011; Trench & Webber, 2012) This can be achieved using nursery shade cloth, greenhouse plastic, or natural coverings like coconut or palm branches; shade cloth has the added advantage of keeping insects and predators like caterpillars out of the nursery, while the plastic can help reduce the influx of freshwater into the nursery and thus prevent fluctuations in salinity (Bovell, 2011; Trench & Webber, 2012; Tsuruda, 2013).

For smaller-scale projects, we recommend on-site nurseries that mimic the structures used in the above-described growth experiment. Here, we plant the seedlings into recycled drink pallets, and each pallet is fastened to steel rods. Based on the outcomes from the growth experiment, we recommend placing the pallets in a low-elevation area that is semi-submerged and protected from the impacts of weather events (e.g., debris and silt when river overflows its banks) in the understory. This allows the plants to be watered naturally and reduces the time/energy required for nursery maintenance in these small-scale applications. For white seedlings, however, we recommend placing them in areas that are fed by ground water and precipitation (i.e., on-land).

3. Propagule Collection & Preparation

The species most used for mangrove restoration in the Caribbean is the red mangrove, for reasons including the large size and ease of collection of their propagules (Moore 2014), their tolerance for frequent flooding (Tsuruda, 2013), and their quick establishment and stabilization of the sediment for the other species (BVIDDM 2020). Only red has been historically planted on Grenada, with both red and black planted at Petit Carenage in Carriacou (Moore, 2004). While other countries in the region have planted varying combinations of species, only in Jamaica have all four species been prepared and planted with any success (Trench & Webber, 2012).

To maximize sapling survival and growth, Trench & Webber (2012, p. 38) recommend the following:

1. Using sufficiently aged saplings
2. Using sufficiently hardened saplings
3. Ensuring saplings are acclimated to correct salinity prior to transplantation
4. Suitable positioning of species in tidal range
5. Suitable species selection

6. Satisfying optimum physicochemical conditions
7. Designing and executing an appropriate management plan (including follow up, long-term monitoring and post-transplant mitigation).

Moore (2014 p. 4) also recommends the following “etiquette” rules for collection:

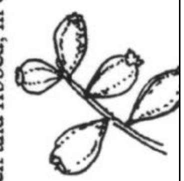
1. Only collect ripe propagules as collecting immature propagules results in planting failure and wastes precious resources.
2. Never collect more than 10% of the mature propagules in a given donor site to [ensure] we do not impact the reproductive success of these mature trees.
3. Collect from at least three donor sites to minimize impacts and increase the likelihood of genetic diversity in restoration areas.
4. Based on project needs, goals, and timeframe, we present two methods for seedling preparation using either propagules or wildlings.

From Propagules

The suggested best times for propagule collection varies by species: Mid-November to January for red mangroves (Moore, 2014). June to November for black mangroves, and July to September for white and buttonwood (Trench & Webber, 2012)

Propagules are best collected in the early morning and stored in the shade to keep them safe from desiccation and heat damage, and they should always be inspected for damage from insects or predators (Bovell, 2011; BVIDDM, 2020; Tsuruda, 2013). Propagules can be collected either directly from the tree or from the ground below the trees; the following table summarizes what to look for when collecting propagules (Table 1).

Table 1. Propagule characteristics and seedling collection guidelines for mangrove species

	Red	Black	White	Buttonwood
Propagule description (Sutton et al. 2004 p. 5)	Form torpedo-like plantlets on the tree 	About 1 inch long, flattened 	Green and ribbed, in clusters 	In clusters in rounded heads 
Signs of maturity	Yellow or reddish cotyledon, at least 20 cm long (Tsuruda, 2013) Brown, with darker, thicker propagule tips indicating greater maturity; avoid red or orange propagules (Trench & Webber, 2012)	Light yellow and cracked (Bovell, 2011) Colour of test changes from light green to purple and/or brown (Trench & Webber, 2012) At least 2 g (Tsuruda, 2013)	Colour changes from light green to golden or dark brown (Trench & Webber, 2012)	No data. May change from green to brown (personal observations)
Collection method	Can be collected from ground or from the water using a net (BVIDDM, 2020)	Can be collected from tree or ground; tree preferred as germination is very rapid once it reaches the ground (Trench & Webber, 2012)	Can be collected from ground as they appear less susceptible to predation than other species (Trench & Webber, 2012)	Best collected from tree as they disperse quickly once fallen (Trench & Webber, 2012)

Once collected, the propagules must be germinated. The longer propagules of red mangroves can be placed vertically in 5-gallon buckets with saltwater for rooting; this water should be changed every 2–3 days to prevent fouling and mosquito attraction, and white or yellow buckets are recommended to prevent overheating (Moore, 2014). For larger-scale projects, the red mangrove propagules can be placed in nursery troughs of running water, as in Jamaica. Propagules of any size can be allowed to soak (horizontally) in troughs or rectangular bins of fresh or brackish water for up to 5 days (Trench & Webber, 2012). The exception to this method is buttonwood, which should be kept from saltwater during germination, and in fact, is more commonly propagated from cuttings than seeds (Trench & Webber, 2012).

Once germinated, the rooted propagules (now seedlings) can be transferred to potting containers in a soil medium. Generally, a 50/50 mix of sand (for drainage and root development) and mud (for nutrients) is recommended, with the sediment ideally taken from the restoration site or one nearby (BVIDDM 2020); if erosion is a concern or there is little sediment available at the site, potting soil can be substituted for one or both sediment inputs. The potting containers can be 5×8 inches or 8×12 cm polythene or biodegradable cloth bags (with holes for drainage), plastic rootrainers (which have hinges to allow the seedling and its roots be removed without damage), or crates – as were used during our growth experiment. Seedlings should be planted in a clumped design within the containers, in monospecific clusters of 5–10 plants, as the proximity leads to positive interactions that may reduce mortality and increase growth (Renzi et al., 2019).

We recommend using the crates as they offer better mobility of the plants and allow several seedlings to be moved together as a unit for the acclimation stage; the crate system also increases ease of watering if there is a nearby water source where the crates can be placed to passively absorb water. Although we used segmented plastic crates for our growth experiment, we recommend undivided wooden crates for active restoration, preferably constructed with untreated material so they can be left to biodegrade in the environment if necessary.

From Wildlings

Alternatively, wildlings can be collected and transplanted in the nursery. From the results of our growth experiment, we recommend only harvesting red mangrove wildings, as they were more resilient to transplantation; choose seedlings with between 10–15 cm of new growth above the propagule as they have successfully germinated but are not yet fully established at the donor site. Care must be taken to avoid damaging the roots of seedlings when they are being dug up, and preferably, the root ball should be kept intact with the soil during harvest. Light-coloured 5-gallon buckets can be used to collect and store the seedlings, holding up to 50 seedlings per bucket. About three inches of soil should be left in the buckets lined with coconut husk to protect seedling roots. The buckets should be stored in a cool semi-shaded area, either in the nursery or under trees, or if neither is available, the buckets should be covered with saran netting.

Following collection, the seedlings can be kept for up to two weeks while being watered every two to three days. During this period the seedlings should be monitored for debilitating signs such as fouling or yellowing, which should be removed immediately to prevent spread to healthy plants. Once the plants are shown to be healthy and alive, they can then be moved directly into the crates in the nursery for growth and then acclimation.

4. In-situ Acclimation

In this section, we provide an overview on how one can prepare propagules/wildings for planting. While a nursery is most feasible for larger projects, the use of pallets on-site is a feasible alternative.

Nursery

In the nursery, the seedlings should be watered twice a day, in the mornings and evenings when it is cool to reduce evaporation, with a variable volume of water based on the shade level and wind conditions that day (Bovell, 2011). A solution of either fresh and saltwater, or of fertilizer and water, can be used for watering; mangrove growth is limited by nitrogen and phosphorous (Reef et al., 2010); thus, moderate nutrient enrichment will be beneficial for growth. Alternatively, seedlings can be irrigated naturally by the tides, if the nursery placement allows (Tsuruda, 2013) or placed in troughs of low salinity water (< 5 psu) to take in water as needed (Trench & Webber, 2012). The latter approach is used in Jamaica, where there is an extensive nursery at the laboratory with several troughs; however, space is a limitation of our on-site nurseries, and this method can only be used if there is a small enough plant stock and large enough space for the nursery. Thus, we recommend direct watering of the plants. The nurseries in Jamaica are in conjunction with an already existing supply of water (e.g., Marine Laboratories) as pumping water for nursery seedlings alone would be very expensive. At the Marine Laboratory nurseries, the water used is secondary water that had first flowed through the aquaria, and thus may have additional nutrients from fish waste, which is beneficial to the mangrove seedlings.

Once the plants are about 25 cm tall (25 cm new growth above the propagule for red mangroves), they should be graded and culled (where good/viable seedlings are selected and non-viable ones are removed; Bovell, 2011). They then must be acclimated to the site conditions where they will be planted, a process called “hardening-off”. The crates allow the plants to be moved and acclimated to various conditions at different locations/microhabitats within the site.

Saplings needed to be acclimated to both sunlight and salinity. Hardening-off for sunlight should take about a month, during which time the seedlings are gradually exposed to greater sunlight intensity. Each week, the saplings should be exposed to direct sunlight for a few hours each day, increasing until they are in full sunlight all day (Bovell, 2011; BVIDDM, 2020; Tsuruda, 2013). During this time, the volume and frequency of watering should also decrease, but ensure that the soil does not completely dry out (Bovell, 2011).

Hardening-off for salinity is also a gradual process. In Jamaica, seedlings are typically grown in low salinity (≤ 5 psu) as it facilitates faster growth. These seedlings are acclimated to higher salinities as needed for transplantation; this should be done at a rate of ~5 psu per day (Trench & Webber, 2012). The plants should be watered with a solution of increasing salinity, generally a mixture of fresh and saltwater. However, for an added boost of nutrients at this stage, the hardening-off can be done with a fertilizer solution, mixed with water to achieve the same gradual increase in salinity. Care must be taken when applying fertilizer solution or disposing of excess fertilizer treatment to minimize nutrient loading and eutrophication of nearby waterways (Trench & Webber, 2012).

Once the plants are acclimated to both the sunlight and salinity conditions at the restoration site, they are ready to be transplanted.

Another useful treatment, especially for red mangroves, is varying the water level for the nursery seedlings. Tidal inundation causes red mangroves to put out prop roots, which will make them hardier when transplanted to field conditions. This can only be done in nurseries with troughs of standing water, and water level could be varied from 1 cm above potting bag/crate surface to 15 cm above substrate level.

It is also strongly recommended to control the excessive growth of plant roots within the nursery, especially if plants will be in the nursery for more than 6 months. Plant roots may get tangled and will be difficult to entangle when it is time for transplant. Trench and Webber (2012) described methods of pruning the mangrove roots which extend from the seedling bags with garden shears, which had no negative effect on plant growth or performance.

Pallets

For smaller-scale projects, when the seedings are placed in pallets in the understory of mature trees, we recommend placing the pallets in an area with similar conditions to the final planting site. In these cases, we assume that the seedlings will be acclimatized to the high or low salinity conditions they will endure after transplanting. However, if the plants will be transplanted in a high sunlight area, we recommend that the pallets be exposed to these conditions gradually (as described above).

5. Transplantation & Monitoring

Transplanting Saplings

The day before the planned planting activity, the plants should be thoroughly watered. As the nursery is on-site, transportation should be relatively simple. Crates of plants can be loaded into a wheelbarrow and moved to the immediate planting area. As much as possible, seedlings should be covered from the sun and wind to avoid desiccation and damage before transplanting. The question of when to plant depends largely on the project needs and site conditions, but transplantation can occur as soon as 12 weeks (3 months) after propagation (Bovell, 2011; Moore, 2014) or after a year or two in the nursery (BVIDDM, 2020; Trench & Webber, 2012). Because of the flexibility of the crates, the acclimation stage can last as long as desired. Tsuruda, (2013) recommends planting within 6 months of collection and propagation and avoiding the dry season when evaporation rates and soil salinity are highest.

The saplings can be transplanted either with or without the crates. In high-energy sites or those at lower elevations, we recommend planting the crates as a unit. The structure of the crate will provide additional height and protection against wave energy and can help stabilize the sediment on eroding shorelines. Eventually, the saplings will grow through the crates (and over them in the case of red mangrove prop roots) and the crates themselves will biodegrade.

In sites at slightly higher elevations that are not completely inundated, saplings may be planted in the ground. In this case, they should be removed carefully from the crates so as not to damage the root systems and transplanted in a hole that comfortably fits the root ball. The clusters may be separated if the planting area is low-stress (regarding salinity or wave action) or planted together in high-stress areas. The latter ensures that the positive interactions are retained and speeds up growth and canopy closure (Renzi et al., 2019; Wang et al., 2019). The crates can then be reused in the nursery or at another site.

Monitoring

After planting is complete, the site should be monitored regularly in the short term (Figure 14). The first month is critical, as any major issues with the planting method or incompatibilities with the site may be revealed in this period. If these are detected, then corrections can be made early on to maximize the survival of the saplings and prevent complete failure. For the first month, the site should be visited at least once a week to check on the health of the plants.


Figure 14. Team monitoring transplanted propagules, checking growth rates and survival.

Thereafter, monitoring can be done at 1-month intervals to measure parameters such as survivorship, height, number of leaves (for the first 6 months), number of shoots (after the first 6 months)and presence or abundance of natural recruits (Lewis & Brown, 2014). This should be continued at least until the plants are fully established and begin producing aerial roots and/or propagules. Longer-term monitoring may be possible based on the needs of the project and continued access to the site, for a period up to 5 years (Lewis, 2009). As the system develops, additional parameters can be measured such as community-level data on the presence or density of associated fauna like crabs, birds, or fish (Lewis & Brown, 2014). Photographs are also useful as a low-tech, low-cost option for tracking the overall progress of a site (e.g., BVIDDM 2020).

Recommendations & Additional Notes

- White mangroves should be added to the seedling stock for restoration in Grenada, as their plasticity may make them suitable for a wide range of conditions and provide a buffer against coastal habitat modifications induced by climate change (Buckmire, 2022).

- Both white and black mangroves are pioneer species and should be used before or alongside red mangroves in a multi-species approach to harness the strengths of all three local species and overcome some of the challenges of reliance on red mangroves (Buckmire, 2022).
- White and black mangroves were shown to need extreme care when transplanted from wildlings. Preferably, white, and black mangroves should be collected as propagules and germinated in the nursery.
- Red mangroves are resilient enough to be transplanted from wildlings.
- When planting in a clustered design, use only the same species (or species of similar size, such as white and black) to avoid overshadowing by taller species (i.e., red mangroves).

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