Demonstration of a New Technology for Restoration of Red Mangrove (Rhizophora mangle) in High-Energy Environments

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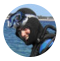

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PAPER

Demonstration of a New Technology for Restoration of Red Mangrove (*Rhizophora mangle*) in High-Energy Environments

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ABSTRACT

Restoration of red mangroves (*Rhizophora mangle*) in high-energy environments has proven difficult in the past, but it is a critical aspect of restoration science, since mangroves provide natural protection to shorelines and buffer sensitive nearshore tropical ecosystems. We present here the initial field results from a pilot test of a new technique for the restoration of *R. mangle* in high-energy environments, using anchored armored concrete cultivator pots to stabilize the juvenile mangrove until it can establish a network of buttress roots. Mangroves were reared in a nursery for 15 months before transplantation to fully and partially exposed field sites. Mangroves transplanted in this way on Grand Cayman Island were able to survive two direct hurricane hits shortly after transplantation during the hurricane season of 2008, with survival rates ranging from 42% to 73% depending on the exposure of the site. We discuss the implications of these results and a proposed revision to our technique, which we hope will eliminate the work-intensive and costly nursery phase while also facilitating higher survival rates by minimizing washout, which was a key source of mortality, accounting for 20%-50% of mortalities depending on site.

Introduction

Mangrove forests are some of the most productive ecosystems in the world (Tomlinson, 1986; Hemminga et al., 1994). In addition, the diverse and plentiful ecosystem services provided by mangal make this system one of the most critical tropical habitats for protection. Mangroves provide a natural solution to protect shorelines from storms and provide erosional stability (Hogarth, 2007; Scoffin, 1970; Woodroffe, 1992), without many of the ecological and aesthetic pitfalls of engineering projects such as groins and seawalls. Mangroves also help reduce the impact of anthropogenic nutrient pollution by assimilating inorganic nutrients from run-off and transforming it into rich organic material, which fuels the detrital food webs in areas that are otherwise often quite oligotrophic (Jagtap, 1998; Ogden et al., 1997). Furthermore, mangroves provide critical nursery habitat for fish, birds, and invertebrates (Hogarth, 2007; Laegdsgaard and Johnson, 1995; Nagelkerken et al., 2001, 2002) and increase local and regional diversity (Nagelkerken et al., 2002; Dorenbosch et al., 2007).

In particular, mangrove-lined systems, which remain submerged even at low tide, have been shown to provide an even higher level of valuable nursery habitat than fringing mangrove systems (which drain completely at low tide) (Lugendo et al., 2007). It should be noted, however, that both lined and fringing mangrove habitats will also increase water residence time, decrease current speed and reduce wave action, thus providing sessile animals a safe place to settle, and juveniles and other small animals with a calm environment to find shelter and food (De Vos, 2004; Wolanski and Ridd, 1986; Wolanski et al., 2001).

The benefits of mangrove systems to fisheries have also been well documented. Many studies have commented on the effectiveness of seagrasses and mangroves as nursery habitats and food sources for commercially important finfish species (Dahlgren et al., 2006; Nagelkerken et al., 2000, 2001, 2002) and have stressed the importance to preserve the "recruitment corridors" formed by the succession of mangrove, seagrass, and coral reef communities, as many invertebrates and fishes species undertake ontogenic migrations between habitats (Hiddink, 2003; Mumby and Hastings, 2008). Recent studies have found that the biomass of several commercially important fish species are more than double when adult habitat is connected to mangroves (Mumby et al., 2004, 2006). Reducing mangrove habitat complexity would decrease the biodiversity and abundance of the associated fauna and potentially have cascading consequences at higher trophic levels with potential penalties for fisheries (Manson et al., 2005).

In spite of the established body of literature documenting the ecological importance of these environments, natural and anthropogenic disturbances are increasingly impacting mangrove ecosystems, and the unquenchable desire for beachfront real estate places the mangrove-lined and fringing mangrove systems at particular risk. They are one of the world's more threatened tropical ecosystems (Valiela et al., 2001), and today's mangrove deforestation rates can exceed that of tropical forest, with 2,251 $km^2 y^{-1}$ lost in the Americas alone (Richmond, 1993; Mumby et al., 2004).

Despite this disturbing trend, only a very small portion of the attention paid to the development of habitat restoration techniques has been directed towards mangrove restoration for fisheries and ecosystem purposes. Many previous restoration efforts are designed around harvesting of mangroves for wood or using the mangal to trap sediment for agriculture (e.g., Lewis, 2005). These efforts are done using technologies that are several decades old and have met with mixed results (Ellison, 2000; Lewis and Gilmore, 2007), typically some modification of a PVC encasement methodology (e.g., Riley and Selgado-Kent, 1999) or by direct planting of juvenile mangroves or mangrove propagules (seeds). While traditional methods are typically suitable for the restoration of mangal in low-energy shallow areas, they are not well suited to restoration of many coastal mangrove-lined ecosystems, which may be subject to stresses such as deeper water, wave action, and soil erosion, since these techniques provide minimal protection from waves and other physical forces. However, it is these fringing systems that provide the most fisheries and ecosystem benefits (Aburto-Oropeza et al., 2008; Turner and Lewis, 1997; Lewis and Gilmore, 2007).

Ironically, it is often these systems that are in the greatest need of intensive restoration efforts, since mangroves are often needed to protect the shoreline from the same forces that typically prevent the areas in question from repopulating naturally or with traditional restoration techniques. Ever since the tsunami in Indonesia in 2004, public awareness about the importance of mangroves for natural shoreline protection and restoration of ecosystem function is increasing (e.g., Lewis, 2000; Aburto-Oropeza et al., 2008), but a great deal of additional effort is still necessary to determine how best to protect—and where necessary, to restore—this ecosystem.

We present here the results from initial field testing of a new technology: an armored concrete cultivator pot for the restoration of red mangrove (*Rhizophora mangle*) in high-energy environments on Grand Cayman, British West Indies (BWI). The armored cultivator technique is designed specifically to re-introduce *R. mangle* to areas where it was eradicated due to storm damage or development and is not able to re-colonize sustainably because of waves, surge, or storms. While this technique is also suitable for restoring calmer areas that cannot re-grow naturally due to shoreline fragmentation or lack of available propagules, it is not recommended for these scenarios, since traditional restoration techniques, which tend to be less expensive and time consuming, have been demonstrated to be effective in these environments (e.g., Ellison, 2000; Lewis, 2005).

We also discuss lessons learned in the implementation of this project, which can be applied to future high-energy restoration projects. Over the course of this project (over 3 years), we have constantly refined our techniques and technology. Presently, we are in the initial phases of pilot tests using a revised version of the armored cultivator technique.

Study Site

We decided to use Grand Cayman, BWI, as our study site for a number of reasons. Grand Cayman's mangrove ecosystems have endured important stress during the last years with the passage of several major hurricanes (e.g., Ivan in 2004 and Wilma in 2005, which both reached Category 5 on the Saffir-Simpson Hurricane Scale), and today, a large percentage of the island's near-shore mangal has not yet recovered. The hydrology of Grand Cayman's coasts has been disrupted over the last decade, generating high-energy conditions in most of the coastal area of the island's South Sound (Figure 1), preventing natural resettlement of mangroves, which typically settle in sheltered areas. Although propagules are able to endure wave and tidal action, settlement and seedling growth require a low-energy environment. In an effort to rehabilitate near-shore ecosystems and restore the mangrove forest around the island, several restoration projects have been attempted using traditional techniques (direct planting, split PVC) and have failed (T. Austin, personal communication). Given the documented failure of traditional techniques to restore *R. mangle* to these high-energy environments, this environment pro-

FIGURE 1

Map showing relative position of field sites on Grand Cayman, BWI. The Nursery and Sailing club (protected) site are located in the island's relatively sheltered North Sound, while the South Sound sites (monitored in red, unmonitored in white) are fully exposed. Budget and logistical restraints prevented thorough monitoring of many of the South Sound mangroves located on private property.

vides an ideal testing ground for new technology.

Working together with the Cayman Islands Department of Environment and local user groups and stakeholders, we chose exposed sites along the island's South Sound that had recently lost all mangrove cover (but with documented evidence of mangrove presence within the last few years) as targets for rehabilitation. We also chose a lower-energy comparison site in the island's North Sound (similarly recently stripped of its mangrove cover) and a sheltered nursery site that was used to give the propagules time to establish a strong root system inside the cultivator before transplantation to the exposed sites (Figure 1).

Materials and Methods

The centerpiece of this restoration technique is the armored cultivator unit itself. The cultivator is a specially designed concrete miniature Reef Ball™ artificial reef unit with a large opening at the top, one small opening on each side (for water circulation), and a large hole at the bottom to allow an optimal anchoring of the root system into the substrate (Figure 2). Each cultivator unit is approximately 25 cm tall, 40-45 cm in diameter, with an interior volume of approximately 0.05 m^3, and weighs about 16 kg when empty. A solution of sugar water is used as the de-molding agent, which gives the concrete its textured appearance. The anticipated lifetime of the armored cultivator in seawater is approximately 10 years (although this can be adjusted up or down during the production phase by using concrete admixtures). While we did not test any technical modifications to the system, the armored cultivator can be modified in a number of ways, including reducing the size of the openings to further reduce washout and adjusting the strength of the concrete or the weight of the unit to deal with more severe conditions.

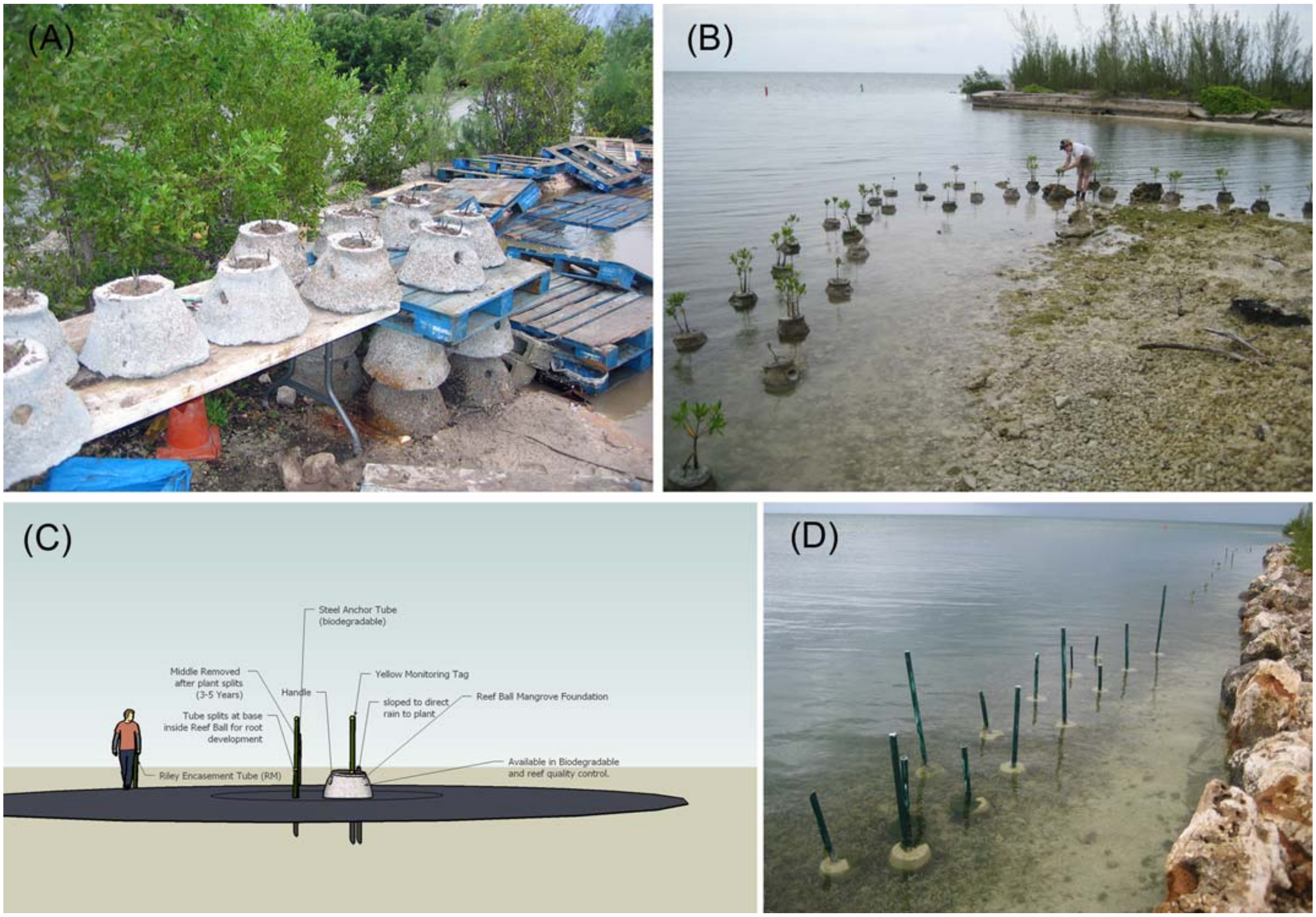
The bottom hole on each unit is filled with a paint can lid, which is placed into the mold before pouring the concrete. This creates a stable bottom for the cultivator, which prevents the roots from escaping the cultivator during the nursery stage and can be removed when the plant is transplanted or allowed to erode naturally. A paint can lid is used for this step because it is easily available and degrades over a period of about a year, which is about the period of time necessary for the young mangrove's roots to fill the cultivator pot, at which point, it can penetrate the degraded bottom and reach the substrate below. In addition, the degradation of the lid may provide a small amount of iron to the environment. Iron, a trace nutrient element, could have a major control in the nitrogen fixation in the tropics, and thus, excess iron might provide more nitrogen to mangroves (Mills et al., 2004).

In November, 2006, the implementation of an 850-unit pilot test of the system began. Each of the cultivators was lined with burlap (to reduce initial soil washout) and filled 3/4 full with soil. Four to six *R. mangle* propagules (depending on propagule size) were placed in each cultivator along with 15 g of Osmocote™ 12-month slow-release fertilizer, and then the unit was filled to the top with soil. The cultivators were then placed in a specially constructed nursery adjacent to a canal, in approximately 30 (±10) cm of water at mean tide (with a tidal fluctuation of only a few centimeters). This depth was chosen to ensure that all cultivators were submerged at least to the drain holes at high tide (to facilitate water exchange) and that no propagule was completely submerged at low tide (to prevent "drowning"). The nursery depth was designed to be similar to the anticipated planting depths, which were governed by local hydrology and shoreline topography, as well as literature values, which suggest that while submerged, mangroves provide the most fisheries value, but that survival rates are drastically impacted when plants are inundated more than 30% of the time (Aburto-Oropeza et al., 2008; Lewis, 2005). The nursery was connected to the main canal via a small breachway which facilitated some water exchange while buffering the mangroves from any strong currents or waves.

The cultivators remained in the nursery for approximately 15 months. Previous laboratory research has shown that the lifespan of this fertilizer in seawater is reduced to approximately 90-120 days (Krumholz et al., 2007); therefore, an additional 15 g of fertilizer was added during a subsequent monitoring visit approximately 120 days after planting. At this time, a

FIGURE 2

Composite image showing (A) armored cultivators filled with soil and mangrove propagules awaiting deployment into the nursery (in background) and (B) armored cultivators being anchored into final position at the North Sound transplant site. (C) Conceptual sketch of revised armored cultivator system, which eliminates nursery sketch (Google Sketch-up™). (D) Pilot test of new armored cultivator system 5 months after deployment—note leaves from juvenile mangroves extending from the top of several units.



random sampling was completed in order to monitor the total number of seedling per planter, the number of stilt roots present of the tallest plant in each planter survey, the height and the thickness (both to the nearest mm) of the seedling in the pot, and correlate against environmental variables in the nursery.

After 15 months, the cultivators and mangroves were removed from the nursery, and the side and top holes were patched using a weak biodegradable concrete mixture designed to protect the cultivator from washout during transport and re-stabilization (and then to break up within a few months). Mangroves were transported to four transplant locations. Three of the locations were high-energy sites along the exposed South Sound (two private waterfront properties and a public beach), and the fourth location was immediately adjacent to the nursery at the Cayman Islands Sailing Club, in the relatively protected North Sound (Figure 1). This location serves as the low-energy site although it is still subject to waves in excess of 0.5 m on a regular basis. Immediately prior to planting, the bottoms of the cultivators (the paint can lids) were removed to allow the roots access to soil. Where necessary (in areas of particularly high exposure or hard bottom), cultivators were anchored by driving a 0.75-m rebar stake through a fitted opening in the cement top of the cultivator and into the soil below to provide lateral stability until the roots could establish a strong foothold. The mangroves were then monitored before and after the 2008 hurricane season for growth and survival at the different locations; however, budget and logistical constraints restricted the availability of accurate monitoring data from two of the South Sound sites (Figure 1), leaving only one well-monitored high-energy site, as well as the low-energy North Sound site.

Because logistical constraints prevented implementation of the project during a time when fresh propagules were available, propagules were collected from nearby beaches. The healthiest propagules available were picked up, and in order to control for potentially reduced viability of propagules, a number of "direct plant" controls were set along the side of the nursery to estimate the natural (unmanipulated) mortality of the seeds collected. These juvenile mangroves were not transplanted and were isolated from storm, wind and wave action; thus, these controls provide a reasonable estimate of "baseline" natural mortality rates.

Results

The propagules were monitored four months after planting (February 2007), again in January 2008 to determine the effectiveness of the nursery grow out technique, and finally in June 2008 and December 2008 to determine the effectiveness of the deployments.

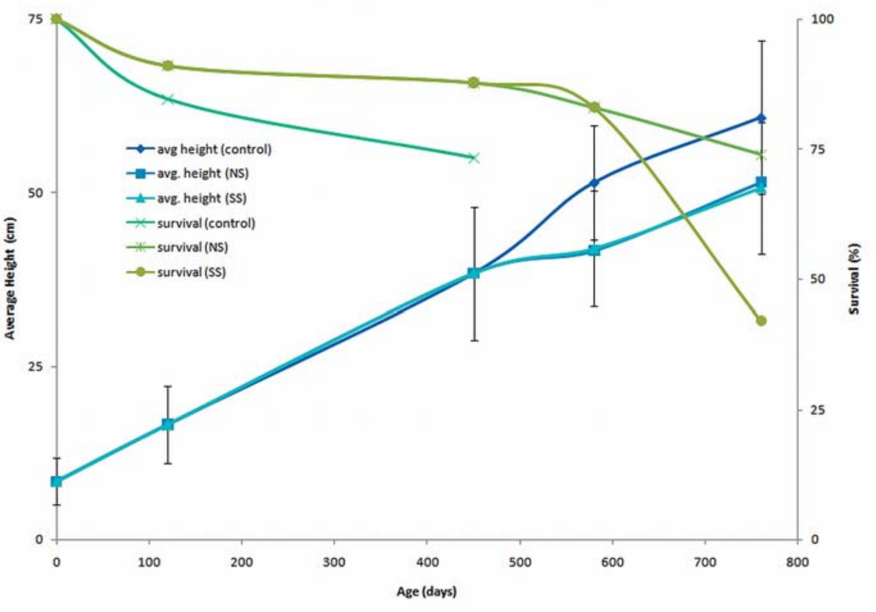
Approximately 91% of the cultivators had a successful germination rate (after four months), and the total survival rate to the end of the nursery stage was just over 87% (an annualized mortality rate of only about 4%, excluding the initial germination failures), indicating that once initial germination failures are overcome, survival is very high. This compares favorably with the annualized survival rate for our direct plant controls of 74% (Figure 3). At the time of transplantation, cultivators had an average of 2.5 (±1) propagules, and the mean number of prop roots on the healthiest propagule of each planter was 1.1 (±1.3). The mean height of the trees at this point was 38.5 (±9) cm, and the mean thickness was 13.3 (±3.0) cm. We attempted to correlate any of these factors to the planting depth of each cultivator in the nursery to determine the optimal nursery depth, but all correlations (Barvais-Pearson with 95% confidence interval) were not statistically significant. Growth rate was also not significantly different between controls and cultivators while in the nursery (Figure 3).

After transplantation, the mangroves were monitored again in June, before the onset of hurricane season. Mortality during the five months after the January monitoring, and before the onset of hurricane season, was 6%-7% (annualized mortality of about 15%-17% for this five-month period)—a small increase over the baseline nursery rate which was possibly related to transplantation stress. This impact could also be seen in growth rate, as the height of cultivator mangroves averaged 41.8 (±8.2) cm at this point, while direct planted control mangroves averaged 51.4 (±11.6) cm (P < 0.01, n = 51, 15) (Figure 3).

At the conclusion of the hurricane season, results varied dramatically by site. The South Sound (highly impacted) site took severe direct hits from two hurricanes and suffered mortality rates of 57%. Approximately 20% of these mortalities could be attributed to washout of all soil from the cultivator, and a further 25% was due to complete burial of the cultivator. The cause of the remaining mortalities could not be determined; however, only about 2% of the cultivators came un-anchored and shifted position. The more protected

FIGURE 3

Survival (green) and growth (blue) of juvenile mangroves in North Sound (NS), South Sound (SS), and the control group of direct planted mangroves (no armored cultivator) in the nursery. Growth values are the average height of the tallest tree in each cultivator, measured from the top of the cultivator (or from the sediment for controls). Error bars are 1σ. Survival rates are cumulative total percent survival.



North Sound site still suffered higher mortality than the fully protected controls (26% vs. 19%, $P < 0.05$, $n = 119, 13$), but mortality was significantly less than that at the South Sound site ($P < 0.001$, $n = 119, 49$) (Figure 3). Of the North Sound mortalities, 51% were due to washout of all soil from the cultivator, and less than 1% of the cultivators came un-anchored. The cause of the remaining mortalities is unknown. Growth rates in the exposed sites also suffered compared to direct plant controls. Although the average height of surviving trees between the two experimental sites was similar (51.5 cm in North Sound vs. 50.4 cm in South Sound), both of these treatments were significantly shorter than the controls (60.8 cm) ($P < 0.01$, $n = 119, 49, 11$) (Figure 3).

Discussion

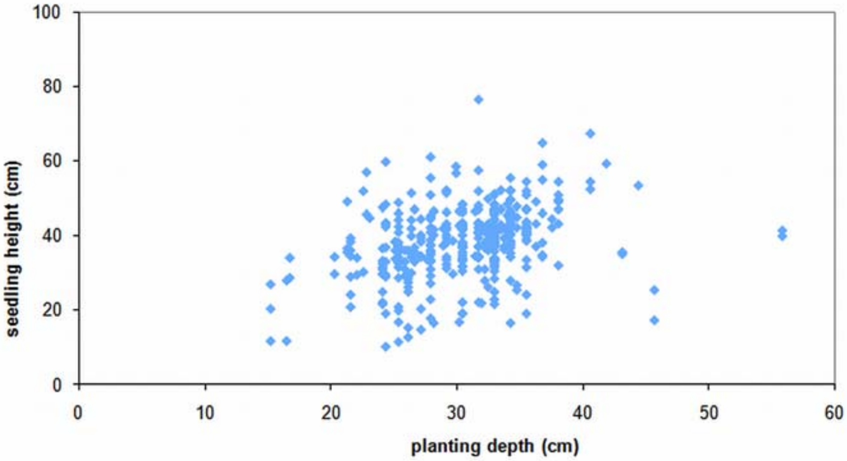
The relatively low mortality of cultivators in the nursery is not particularly surprising. Given that mortality rates in cultivators were lower than that of direct planted controls, and that both controls and cultivators had almost no mortality from 4 months until 15 months, it seems safe to assume that most of this initial mortality is due to failed germination, which could be reduced by timing the planting phase to the availability of fresh propagules. However, it is easy enough to re-plant cultivators that fail to germinate, so long as the cultivators are monitored early enough for replants to establish themselves before transplantation.

We expected to observe an optimal planting depth, with reductions in growth and increased mortality for cultivators positioned either deeper or shallower than this depth. However, no such trend was observed (Figure 4). This may be because there were insufficient replicates at the deepest and shallowest areas of the nursery to detect the trend, or it may be because the depth range in the nursery is insufficient to elicit a reduction in growth or survival. This is an unfortunate consequence of attempting to extract scientific data from a restoration, in that budget restrictions tend to dictate that cultivators should not be planted at depths where anticipated survival would be low. Although some of our post-transplant data (discussed later) indicate that deeper planting depths have higher survival rates, the propagules do not appear to be particularly sensitive to changes in nursery depth (within reason, of course). The range of suitable nursery depths might be a topic for future research.

The hurricane season of 2008 was a relatively busy one for the Cayman Islands, which sustained nearly direct hits (eyewall less than 50 miles away) from hurricanes Gustav and Paloma (categories 2 and 3, respectively), both of which battered the South Sound area particularly hard. The ability of transplanted mangroves, even in the most exposed location, to survive this level of storm energy so soon after transplantation is encouraging, although mortality rates above 50% at the most exposed site are higher than desirable. However, the cultivator itself performed admirably, with less than 2% of the units dislodging, even at the more exposed site. At the South Sound site, the cultivators were deployed in clusters across the range of desired planting depths. In the cluster nearest to shore, which was placed in only about 3 cm of water at low tide (10 cm at high tide), many of the cultivators were covered with sand during the storms, which may have contributed to the 100% mortality experienced by this cluster of 11 cultivators, which, perhaps, needed to be planted further from shore (cultivators in deeper clusters at this site had 57%

FIGURE 4

Seedling height (after 15 months in nursery) as a function of nursery depth. No statistically significant relationship exists in the data as shown, which may be because of the relative paucity of data points at the depth extremes, or it may be because the range of planting depths is insufficient to detect a trend.



survival). No clearly observable trend between depth and survival was evident in North Sound, but the range of planting depths at that site was deeper (10-20 cm at low tide).

As the mangroves grow and continue to establish their root mass, one would expect their ability to resist storm energy to increase further (although their resistance would probably never significantly exceed that of a fully developed natural community, and thus, they would still be at risk from a direct hit from a category 4 or 5 storm). It was hoped that the transplanted mangroves would have had more time to establish a root network before being hit by hurricane force winds, which presumably would have reduced or eliminated washout-related mortality (50% of fatalities in North Sound, 20% in South Sound). This could perhaps be facilitated by transplanting in October or November, right after hurricane season, to allow the maximum time for stabilization.

Furthermore, as the mangroves continue to grow, it is expected that the cultivators will eventually break down under the combined stresses of the outward pressure of the mangrove root ball and the slow degradation of the concrete by the seawater. A biodegradable concrete (rather than the reef strength concrete typically used to make Reef Balls™, which has a lifespan in seawater of 500+ years) was used here because of the ultimate goal of this specific restoration project (no trace of human impact); however, in areas with environments even more severe than those tested here or where slower growth rates are anticipated, a stronger and/or heavier cultivator could be used to give the cultivators additional resistance.

One of the most difficult phases of this project was the vast amount of manpower and logistics required to carry the fully loaded cultivators into and out of the nursery phase. Even with the assistance of the Cayman Islands Department of Environment and numerous "volunteers," the 15-month-old mangroves proved quite a challenge to move around (they weighed about 30-35 kg at that point), and the additional logistical and financial expense associated with the nursery step is not always feasible. On account of these restraints, we are now pilot testing a new armored cultivator technique, which was designed to bypass the nursery step (Figure 2).

Several modifications to the cultivator were made, including reducing the size of the side holes, closing the top, and facilitating the incorporation of a biodegradable (if available) or removable PVC wrack protection device similar to that described by Riley and Selgado-Kent (1999), with a lengthwise slit to facilitate removal after 3-5 years. A biodegradable plaster of Paris fertilizer disc was also incorporated and was tested to have a lifespan of approximately 12 months (Krumholz et al., 2007, Krumholz, unpublished data) in lieu of the paint can bottom. This disc is more environmentally friendly and can deliver a customized blend and concentration of fertilizer directly to the roots of the plant, minimizing washout and, thus, the potential risk of nutrient advection onto sensitive nearby environments such as coral reefs (e.g., Koop et al., 2001; Richmond, 1993). The assembly is held in place either by hammering a hollow 1.5-inch-diameter angle cut iron pipe into the substrate and then placing the fertilizer disc, cultivator, and wrack tube on top of the protruding anchor (the fit is accomplished by casting a 1.5-inch hole into the center of the fertilizer disc). The angle cut anchor forces a wide opening in the slit at the bottom of the PVC, securing the unit and allowing the roots access to the competition-free soil inside the cultivator (Figure 2). A propagule is then dropped into the top opening, and the system is theoretically self-sufficient, requiring no intervention except to remove the wrack protector after 3-5 years if a biodegradable alternative is not available (or too expensive). This system has the additional benefit of being highly customizable. In addition to the modifications discussed above, this new system allows the user to adjust the height of wrack protection and the concentration of fertilizer based on the needs of the specific restoration.

A pilot test of this new system is in progress, and it is expected that the washout will be eliminated and the mortality from flotsam reduced, thus providing higher survival rates. Results are still preliminary, but at this point, survival appears to be quite high, with growth and survival rates slightly higher but statistically comparable to direct planted controls in a sheltered area (mean survival 86% vs. 82%, mean height 59 cm vs. 51 cm, $n = 15$). The main liability of this revision to the technique is that it is much more sensitive to the initial viability of the propagules, since only one propagule goes in each cultivator.

The evolution of high-energy mangrove restoration techniques is certainly still a work in progress, but it is a topic of critical management significance, given the manifold anthropogenic stressors on tropical systems such as mangroves and coral reefs (which are supported and protected by the mangroves). By working together with local stakeholders and interest groups to develop a wide range of pilot studies in different systems throughout Florida and the Caribbean, we hope that the techniques associated with high-energy restoration will continue to be refined, with the ultimate goal of producing a cost-effective turnkey restoration technique which can be used in high-energy areas where traditional techniques have shown limited success.

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