RESPONSE OF A STORM-DAMAGED MANGROVE SYSTEM TO RESTORATION PLANTING, CARRIACOU (GRENADA), WEST INDIES

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ON THE COVER: HEALTHY RED MANGROVE (*RHIZOPHORA MANGLE*) GROWN FROM SEED.
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1.0 Introduction

Mangroves are the principal vegetation of low-energy intertidal zones of tropical coastlines (Lugo and Snedaker 1974). The term ‘mangrove’ may refer to either a plant of tropical inter-tidal forest communities, or a group of these plants assembled into a continuous community (Tomlinson 1986), also known as mangal. For the purposes of this discussion, I will refer to individual mangrove species as mangrove(s), while mangrove communities will be referred to as mangal. The true mangroves are characterized as having a 1) range limited to mangal and not extending into terrestrial communities, 2) the ability to form monotypic stands, 3) demonstrate morphological adaptation(s) to life in a saline, coastal environment, such as formation of aerial roots and vivipary, 4) have physiological mechanisms for salt tolerance and salt exclusion, and 5) show taxonomic isolation from terrestrial relatives, as adapted from (Tomlinson 1986, Lugo 1990). True mangroves comprise five families, containing 9 genera and 34 species of woody, salt-tolerant trees, which are pantropically distributed. However, the following text will focus on the two most dominant species within the neotropics, the red mangrove (*Rhizophora mangle*) and the black mangrove (*Avicennia germinans*).

A variety of factors has been suggested which contribute to and/or limit the successful establishment and distribution of mangrove species. Among these factors are salinity (Lopez-Portillo and Ezcurra 1989, Lin and Sternberg 1993), tidal sorting of propagules (Rabinowitz 1987), seed predation (Smith et al. 1989), availability of light (Smith 1987), water intake and photosynthetic gas exchange (Lin and Sternberg 1992b), and soil hydrogen sulfide (H_2S) toxicity (Nickerson and Thibodeau 1985, Thibodeau and Nickerson 1986, McKee et al. 1988). While considerable research has focused upon the individual and combined factors governing mangrove establishment and growth, relatively little long-term studies exist which apply this knowledge to restoration and ecosystem rehabilitation initiatives.

While natural short-term impacts such as hurricanes may cause temporary destruction of mangroves, the forests are readily re-established by seedling recruitment and/or epicormic sprouting by local mangrove species (Baldwin *et al.* 1995). Anthropogenic wetland impacts, however, such as oil spills and eutrophication, harvest of tree and wood products, and alteration of hydrology and clear-cutting for development (Lugo 1990, Ellison and Farnsworth 1996) threaten the long-term integrity and functional values of these coastal wetlands. It is essential to understand the biology and ecology of mangrove establishment so that restoration of these systems may be undertaken with any expectation of success.

Like much of the Caribbean and the Lesser Antilles, mangroves are no longer a dominant coastal feature in Carriacou or its parent island of Grenada. While scattered individuals exist along undisturbed portions of the coastline, only three significant regions of mangrove forest remain on the island; a fringe and scrub forest dominated by *Rhizophora* in Tyrrel Bay, a robust stand of inundated *Laguncularia racemosa* (white mangrove) flanking Lauristan Airport, and a mixed *Rhizophora-Avicennia* forest at Petit Carenage/LAppelle. Each of these systems plays a significant ecological role, harboring a variety of economically significant and unique animal species, while providing important storm damage protection. Despite their immediate and long-term value, the integrity of each of these systems is being degraded by natural and anthropogenic disturbances. The significant die-back of a major portion of the Petit Carenage mangrove is the focus of this investigation, which documents the preliminary results of planting locally-derived propagules of two common neotropical mangrove species, red mangrove (*R. mangle*) and black mangrove (*A. germinans*), into this presumably storm-damaged mangrove forest. Pre- and post-planting edaphic conditions have been monitored (including soil H_2S, E_h, salinity, and pH) together with estimates planting survivorship. The objective of the following Technical Report is to characterize the restoration planting site and to provide an interim survivorship assessment. This assessment includes 1) a description of the methods used for pore water biogeochemistry and determination of planting survivorship, 2) a schematic map of past and future restoration planting areas and associated mangrove habitat zones, 3) an evaluation of previous restoration efforts, and 4) associated findings and conclusions to date.

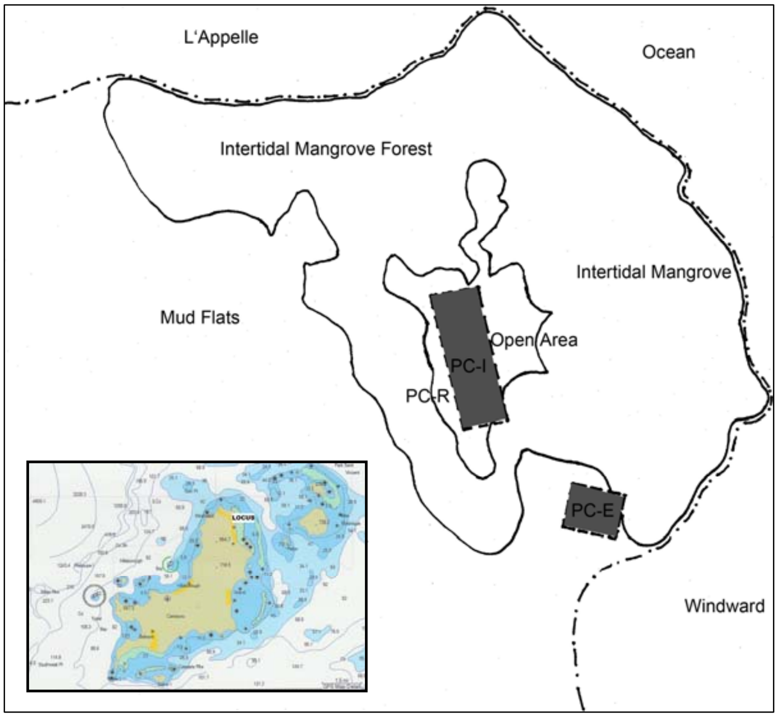
Figures 1 and 2: (*Left)* View of the Petit Carenage/L'Appelle mangroves with the sand/mud flats in the foreground. The island of Petit Martinique to the northwest is seen in the background. (*Right*) Overview of the barren interior of the mangrove forest prior to restoration planting (circa 1997). Deadwood is primarily *R. mangle*.

2.0 Site Description

The Petit Carenage/L'Appelle mangrove occurs on the northeastern tip of Carriacou, a semi-peninsular area encompassing approximately 8 acres, included within the High North National Park and Protected Seascape (Huber et al. 1988, Moore et al 2000). Despite its relatively small size, the mangal is notably productive (Moore 2004), with the seaward individuals reaching over 6 meters in height bearing multitudes of viable propagules. The mangal is dominated by *R. mangle, A. germinans* mangrove, and saltwort (*Batis maritima*), while scattered white mangrove, manchineel (*Hippomane manchinella*), and buttonwood (*Conocarpus erectus*) fringe the landward edge of the system. The dominant *R. mangle* and *A. germinans* are arranged in a predictable zonation pattern, with *R. mangle* occupying the coastal portion of the mangal, while *A. germinans* are well-established within the landward portion of the system. Diurnal tides affect the seaward portion of the system with regularity; however, this tidal flushing is less regular within the mangrove interior and landward edges of the system resulting in extended, alternating periods inundation and exposure to air, respectively. An approximately 1.4-acre portion of the interior of the mangal was virtually void of live plants resulting from a hurricane and subsequent fire reported in the 1950s. This area, representing a transition zone between *R. mangle* and *A.*

germinans, was planted in an attempt to restore the original plant community in 1998. The relative location of the site and the restoration planting areas are shown in Figure 3. Following six years of observation and data collection, the performance of this grassroots restoration has formed the strategic basis for additional restoration planting, hands-on education, and community involvement initiatives for the continued protection of mangroves on the island of Carriacou.

Figure 3: Schematic map of past and present restoration areas within Petit Carenage and L'Appelle. PC-I = forest interior plot (discussed in this report). PC-E = forest edge plot, and PC-R = random arrangement planting areas to be discussed under separate cover.



3.0

3.0 Methdology

3.1 *Plot Establishment*

In 1998, three (3) experimental treatment groups were established along linear transect lines within the forest interior plot (PC-I). Within each of these three groups were four (4) treatment types including 1) monospecific red, 2) monospecific black, 3) mixed (red and black) species plots, and 4) experimental control (no planting). Each planting plot comprised of 50 individuals, planted in 5 rows of 10 within a 1m^2 plot, set approximately 10 meters apart from plots within the same transect and from adjacent transects as described in Ellison and Farnsworth (1993) and Moore (1997). The plots were planted with propagules collected within or directly adjacent to the study area, within areas with minimal canopy cover from mature mangroves. A total of 1,800 propagules were planted (900 of each species). To minimize potential effects of tidal elevation on seedling survival, study plots were established within a uniform elevation determined to vary no greater than +/-2.5cm across the planting area footprint. The relative location of the transect lines and planting plots was determined using the mean of three repeated GPS readings and associated mapping software (Garmin BlueCharts v1.0).

3.2 *Site Preparation*

As described above, the site of investigation is within the interior of an existing mangrove system. The specific areas were originally unvegetated. Scattered dead trunks of *R. mangle* exist within some areas and this deadwood was left in place throughout the restoration planting and monitoring. Plot boundaries were demarcated by numbered wooden stakes placed at each corner. No other alteration of the site occurred during plot establishment.

3.3 *Pore Water Chemistry*

Prior to planting, preliminary edaphic conditions were recorded to facilitate monitoring of potential changes in soil environmental conditions during establishment. These parameters included pore water salinity, redox potential, pH and sulfide concentration. Additionally, sediment texture and grain size analyses were conducted to characterize the substrate to be replanted.

Salinity, redox and sulfide concentration were be obtained from pore water samples extracted from the root zone (at a depth of approx. 20 cm) using a stainless steel ‘sipper’ and plastic syringe (Portnoy 1997). Salinity of pore water was measured in the field using a hand-held refractometer calibrated with a standard saline solution. Pore water redox potential was also measured in the field using a Thermo-Orion model 290A combination redox/pH meter outfitted with a platinum redox electrode (model # 9001). Subsamples of pore water were fixed in the field using a 20% ZnAc solution and analyzed colorimetrically in the field laboratory at Kido Ecological Research Station (KERS) using Cline’s reagent and a LaMotte SmartSpec Spectrophotometer.

At six locations throughout the restoration planting area, a 2 cm diameter core of peat/sediment was obtained to a minimum depth of one meter using an Eijkelkamp soil core auger. Core samples were wrapped in aluminum foil, sealed in plastic, and chilled until analysis. Sediment texture and grain size analyses were conducted for a subsample of this core corresponding to the average live root depth (estimated at 15-20 cm). Additionally, percent organic matter, sand, silt and clay fractions were determined from this subsample.

3.4 *Survivorship and Growth Estimates*

Initially, individual propagule mortality was accounted during annual observations. However, due to infrequency of monitoring beyond our control, surviving individuals became difficult to accurately differentiate. After approximately 3 years of observation, the dense branching and growth obscured the boundary between individuals, at which point we began to estimate survivorship based upon percent cover of live plants within the boundary of each $1m^2$ transect plot. Although not as quantitative as originally designed, the estimation of percent cover demonstrates the significant increase in plant coverage within this formerly unvegetated area. In this way, this estimate best represents the degree of restoration planting success.

3.5 *Statistical Analyses*

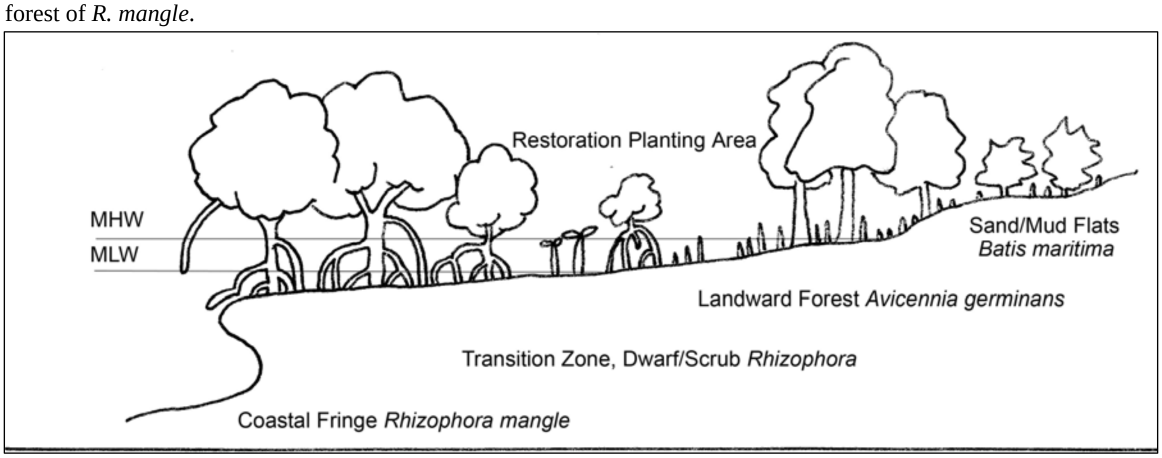
Following collection of additional data, one-way multivariate analyses of covariates were utilized to compare changes in pore water chemistry and sediment textures to describe potentially significant differences in these variables within the transplant area and across environmental gradients present on the site. These data were then considered in light of additional restoration plantings and existing sediment conditions within these sites. Dependent treatment types were considered with respect to soil parameters examined to assess and evaluate both directly measured and derived values of outcome parameters. Analyses were performed using JMP v.4.0 (SAS Institute Inc.) software package for inferential statistics.

4.0 Results

4.1 *Comparative Biogeochemistry Habitat Gradients*

Biogeochemical data were collected along a topographic gradient from land to sea in 2003 and 2004 to characterize the overall site conditions and to provide reference for the observations made within the restoration planting site located in the mangrove interior. Consistent with literature examples, a distinct gradient was observed for many of the parameters examined across sand/mud flat, *A. germinans* mangrove, forest interior, and fringing *R. mangle* habitats (depicted in Figure 4, below).

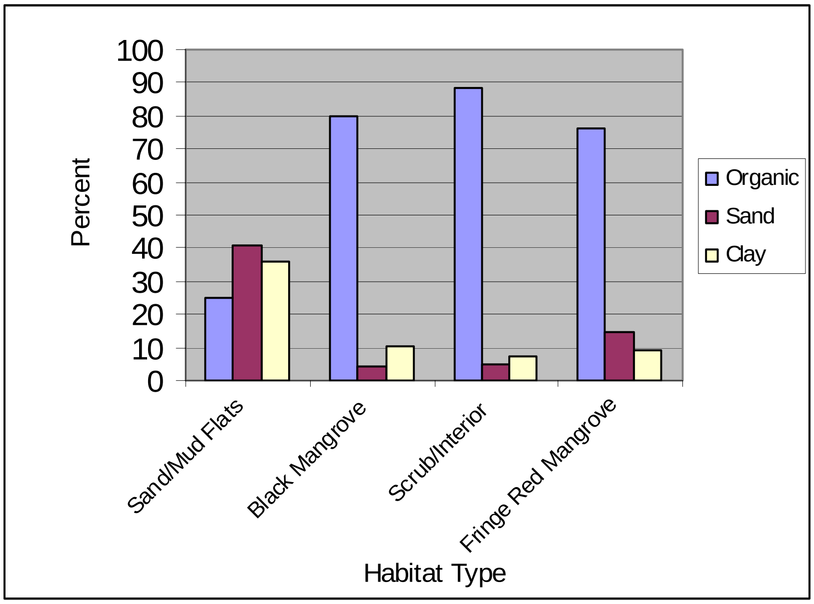
Figure 4: Schematic depiction of habitat zones occurring at Petit Carenage/L'Appelle from land (*right*) to sea (*left*), including sand/mud flats, landward forest of *A. germinans*, a transitions zone with planted *R. mangle*, and coastal fringe forest of *R. mangle*.



Perhaps the most dramatic gradient was observed for pore water salinity, which was highest within the mangrove interior (67.5+/-0.8ppt), often double the salinity of typical well-mixed ocean water (est. 35ppt). These values were significantly higher than the sand/mud flats (51.9+/-3.1ppt), *A. germinans* mangrove (53.9+/-3.6), or fringing *R. mangle* forest (34.9+/-2.7) habitats. Comparable gradients were observed for pore water sulfides, which were highest within the interior (4.0+/-0.1mM), followed by the *A. germinans* mangrove (3.6+/-0.4mM) and fringing *R. mangle* forest (3.0+/-0.3mM) habitats. However, these differences were not significant. Sulfide concentrations were lowest within the landward sand/mud flats (0.8+/-0.3mM), and this value was consistently different from all other habitats. In like manner for pore water redox potential, only the sand/mud flat mean

(-182.4+/-18.9mV) was significantly different from the other habitats which ranged from -279.9+/-4.6mV to -328.9+/-18.3mV.

Figure 5: Comparison of percent organic and inorganic fractions within surface sediments along a linear gradient from land to sea.

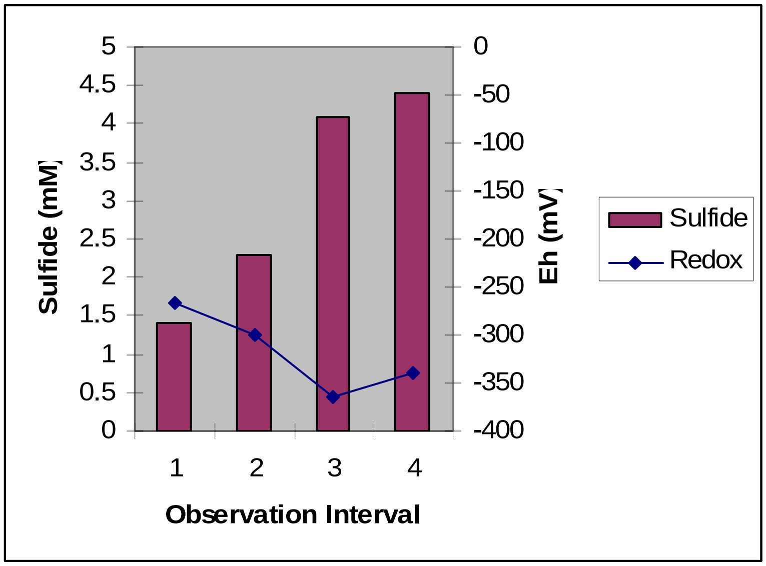


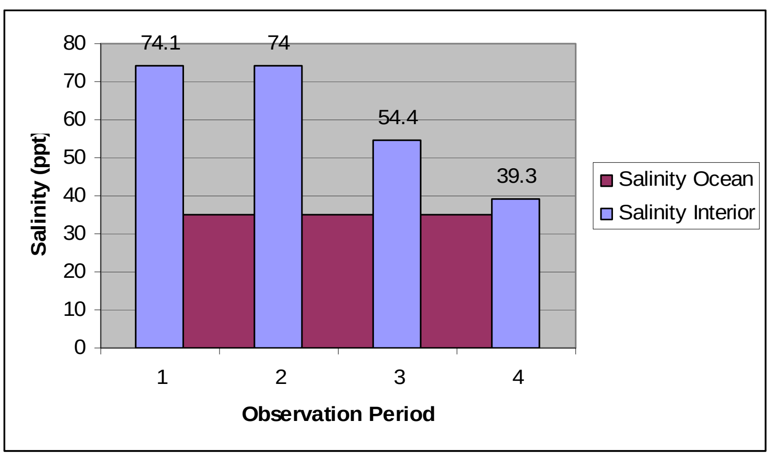
Sediment texture demonstrated moderate variation from land to sea, with the only significant differences occurring between the sand/mud flats edge and the remaining vegetated habitats. Organic fractions were highest within the scrub *R. mangle* interior (88.5%), with *A. germinans* mangrove (80%) and fringing *R. mangle* forest habitats (76.5%) ranking slightly lower (Figure 5). Terrigenous inputs of inorganic materials such as sand, silt and clays were greatest in the landward sand/mud flat habitat, while littoral inputs from the sea were apparent within the fringing *R. mangle* forest habitat. The scrub *R. mangle* interior had the lowest percentage of inorganic materials, likely due to the lack of tidal exchange and subsequent transport of inorganic materials into the system.

4.2 *Biogeochemistry of the Restoration Planting Area*

Generally, the scrub *R. mangle* interior exhibited a gradual degree of biogeochemical change over the six year observation period. While minor in absolute value, these differences are significant for all variables examined with the exception of pH. Redox potential reflected the highly reduced soil conditions, decreasing steadily over time. From 1998 to 1999 and 2003 to 2004 values did not differ between consecutive years, although the mean pre-restoration value in 1998 (-252.3+/-5.6 mV) differed significantly from the final observation period in 2004 (-344.2+/-15.9mV, $p < 0.001$). The redox values were negatively correlated with mean sulfide concentrations (3.6+/-0.1mM and 4.1+/-0.3mM) measured over the same period, which increased over the period from 1998 to 2004 (r^2=-0.56, $t<0.001$) (Figure 6). The most dramatic temporal change was observed for salinity (Figure 7), mirroring a similar decrease noted across the habitat gradients discussed above. From the pre-restoration conditions, salinity declined sharply after 1999. A mean decrease of 32ppt was observed with relatively low sample variability from 1998 (74.1+/-0.6ppt) to 2004 (41.0+/-1.5ppt).

Figures 6 and 7: Linear decrease in pore water sulfide and redox potential (*top*) and changes in pore water salinity (*bottom*) observed over the four observation periods from 1998 through 2004 as compared to the measured salinity of ocean surface water adjacent to the site. Observation Periods 1 through 4 correspond to 1998, 1999, 2003 and 2004.





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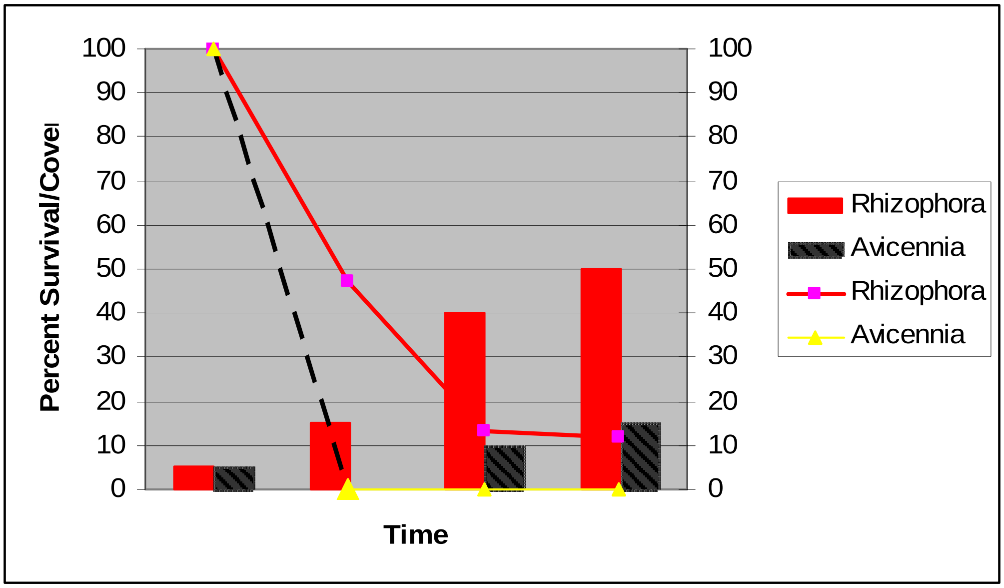
4.3 <u>*Restoration Planting Survivorship*</u>

Mortality of planted mangrove propagules was much higher for *A. germinans* than *R. mangle* at this site. *A. germinans* propagules were completely absent by the beginning of year 2, presumably having been eaten by herbivorous crabs which may have damaged many *R. mangle* propagules. No evidence of the planted individuals remained. *R. mangle* propagules demonstrated initially high mortality (53% reduction from year 1 to year 2), followed by a gradual decline over the observation period (Figure 7). While estimating individual survival by the end of year 6 was difficult, we estimate that approximately 14% of the original *R. mangle* propagules survived into mature seedlings or shrubs. More importantly, however, is that the relatively few that survived accounted for a significant increase in plant coverage within the formerly unvegetated mangrove interior. Mean percent cover increased from less than 5%in 1998, to 52% and 16% (for *R. mangle* and *A. germinans*, respectively) in 2004. Non-planted *A. germinans* invaded the plantation area, primarily from the landward edge of the interior where a substantial *A. germinans* forest had remained. The majority of *A. germinans* growth appeared to be from vegetative sprouting or as dense patches of pneumatophores. However, in 2004 sprouting propagules and first year seedlings were also observed within the northern and northwestern portions of the plantation area.

Figure 7: The decline in surviving propagules shown (line chart) in contrast to the increase in percent cover of each species (bar chart) over time. The *x-axis* label "Time" refers to 4 observation periods (1998, 1999, 2003 and 2004). Percent cover was estimated visually as a percent of the original dimensions of the restoration planting plot area ($1m^2$). Additional growth outside of these areas is not accounted for in this estimation.



5.0 Discussion

5.1 *Restoration Planting Performance*

Clearly, *R. mangle* propagules outperformed *A. germinans* at this site over the observation period based solely on survivorship estimates of individuals planting in 1998. Because *A. germinans* propagules were likely eaten and/or removed from the site by crabs, their actual ability to establish and sustain in the site was not measured. Alternative planting strategies, such as seedling encasement have been shown to be effective to protect nutrient-rich seeds from being consumed (Kent and Lin 1999, Kitaya et al. 2002), or by staking seeds in place to potentially prevent tidal migration prior to rooting (Nickerson and Moore, *unpublished data*). Despite this presumed failure, our 2004 assessment noted that *A. germinans* occupied a significant portion of the total vegetated area within the restoration planting footprint following the success of *R. mangle* propagules within this same area. This result could not have been predicted based on the initial site conditions prior to restoration planting in 1998, at which point no live *A. germinans*, propagules, or pneumatophores were observed within the planting footprint. These results suggest that invading *A. germinans*, which previously had been limited to the landward portion of the mangal, may have derived a benefit from establishment of *R. mangle*, or perhaps more likely, that environmental conditions at the site had changed such that *A. germinans* and *R. mangle* could exploit the area.

The ability of each species to modify the soil environment during establishment has been a much-debated topic by mangrove ecologists (Thibodeau and Nickerson, 1986, McKee 1993). However, the typical scenario described is one in which as root growth increases, more oxygen is translocated to the rhizosphere and the sediments become less reduced, and thus less physiologically stressful for plants. In the present example in Carriacou, the opposite appears to have occurred. Redox potential declined as sulfide concentrations increased, suggesting a more inhospitable soil environment. Moreover, these changes occurred simultaneous with a pronounced decrease in pore water salinity.

Figures 8 and 9 : Images of pre and post restoration planting (facing northwest) taken from within the mangrove forest interior in 1997 and 2004 respectively. The white PVC pipe in the image on the left represents the identical location represented by the wooden stake/sign in the image on the left, where presently *A. germinans* and *R. mangle* seedlings abound. Local participants and researchers from the University of New Hampshire are shown here collecting pore water for analysis of sediment chemistry.

The observed salinity decrease could have been the result of seasonality and precipitation, as the majority of sampling took place during the seasonal high precipitation period (rainy season). However, the hypersaline conditions first observed in 1998 and 1999 were also recorded during this same, rainy season. Despite their tolerance of salinity (Lin and Sternberg 1992, Lin and Sternberg 1993, Lopez-Portillo and Ezcurra 1989), mangroves must pay a high physiological cost to exclude or excrete damaging salts from their tissues (Tomlinson 1986). Thus, reductions in salinity within the rhizosphere of these mangroves would represent a net benefit. Regardless of the cause, we suggest that the dramatic reduction in water salinity within the restoration planting area is the most significant factor contributing to the establishment and success of planted and invading *R. mangle* and *A. germinans* at the site.

5.2 *Summary and Future Management Considerations*

As represented in Figures 8 and 9 (above), the performance of planted *R. mangle* propagules within the forest interior habitat of Petit Carenage/L'Appelle has been encouraging for the continued preservation and expansion of this threatened habitat in Carriacou. The majority of the original damaged area within this system has been planted, and native *R. mangle* and *A. germinans* are proliferating. A goal of this work was to establish a reproducible, cost-effective method to continue to systematically plant and restore mangroves within Petit Carenage, L'Appelle, and other areas within Carriacou and the Grenadines.

From this work, we have determined that coastal sites with highly reduced, organic sediments *can* be effectively re-vegetated using the propagule planting techniques described herein. Planting *A. germinans* propagules appeared to be effective in the specific site conditions, however, modification to the planting strategy could result in success. Regardless, planting monospecific *R. mangle* propagules *can* result in successful establishment of mature *R. mangle* seedling, shrubs and small trees, followed by natural recruitment of *A. germinans*. Future restoration planting should explore alternative planting arrangements, further active protection of vulnerable propagules during the rooting stage, as well as examination of costs and benefits of planting propagules versus carefully uprooted seedlings which may be less susceptible to predation by crabs.

From the results reported here, we are confident that the remaining unvegetated areas within the Petit Carenage/L'Appelle mangal can be effectively re-planted with *R. mangle* propagules, resulting in rapid establishment of mature plants over the short term (3-5 years). The areas denoted in Figure 3 above (PC-E and PC-R), represent some of these areas, however more are planned within this system and others in Carriacou. Presently, with the help of local volunteers we are planting some of these additional areas to further the restoration effort and to transfer the technology onto local people who will ultimately maintain the protection of these habitats for future generations. The results of these plantings and the strategies employed to involve local participants will be reported under separate cover.

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