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Recovery And Restoration Of The Seagrass Halodule Wrightii After Boat Propeller Scar Damage In A Pole-troll Zone In Mosquito Lag

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RECOVERY AND RESTORATION OF THE SEAGRASS *HALODULE WRIGHTII* AFTER BOAT PROPELLER SCAR DAMAGE IN A POLE-TROLL ZONE IN MOSQUITO LAGOON, FLORIDA

by

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ABSTRACT

This study combined documentation of four boat propeller scar types in *Halodule wrightii* seagrass beds in Mosquito Lagoon, Florida with manipulative field experiments to document scar recovery times with and without restoration. Scar types ranged from the most severe scar type (Type 1) with trench formation which had no roots or shoots in the trench, to the least severe (Type 4) scars that had no depth, intact roots and shoots shorter than the surrounding canopy. For 110 measured existing scars, the frequency of each scar type was 56% for Type 1, 10% for Type 2, 7% for Type 3, and 27% for Type 4. In the first manipulative experiment, experimental scars were created to document the natural recovery time of *H. wrightii* for each scar severity within one year. Type 4 scars recovered to the control shoot density at 2 months, while Types 1, 2, and 3 scars did not fully recover in one year. Mean estimated recovery for *H. wrightii* is expected in 25 months for Type 1, and 19 months for Types 2 and 3. For the second manipulative experiment, three restoration methods were tested on Type 1 scars over a 1 year period. Restoration methods included: (1) planting *H. wrightii* in the scar trench, (2) filling the trench with sand, and (3) filling with sand plus planting *H. wrightii*. There was complete mortality of all transplants at 2 months and only 25% of scars retained fill sand after 1 year. With dense adjacent seagrass beds, natural recovery was more successful than any of my restoration attempts. Thus, I suggest that managers should concentrate on preventing seagrass destruction rather than restoration.

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CHAPTER 1: GENERAL INTRODUCTION

Seagrass ecosystems are one of the most productive areas on earth, although they cover only 0.1 - 0.2% of the ocean globally (Duarte 2002, Duffy 2006, Erftemeijer and Lewis 2006). Seagrass ecosystems are unique because they provide structure to barren sediment bottoms, enhance community diversity through increased primary productivity, provide substrate for epiphytes that fuel intricate food webs, serve as critical nursery habitat, and stabilize coastal sediments (Beck et al. 2001, Burfeind and Stunz 2006, Duffy 2006). Seagrasses act as important energetic links between terrestrial and marine ecosystems by exporting about a quarter of their net production to adjacent ecosystems (Duarte and Cebrián 1996, Duarte 2002).

Unfortunately many valuable seagrass ecosystems are decreasing at an alarming rate worldwide from direct and indirect human impacts (Costanza et al. 1997, Durate 2002, Bostrom et al. 2006). Direct impacts, such as mechanical damage from dredging, coastal construction, siltation, trawling, boat scarring and anchoring, bomb blasts, eutrophication, fish farming, and food web alterations, are all visible causes for seagrass declines (Duarte 2002, Bostrom et al. 2006, Erftemeijer and Lewis 2006). Indirect causes, such as global climate change, and natural disasters, such as hurricanes, are also contributing to seagrass declines (Duarte 2002, Bostrom et al. 2006, Erftemeijer and Lewis 2006).

In Florida, impacts from propeller scarring are increasing and are threatening the existence of seagrass ecosystems (Handley et al. 2007). The only statewide assessment of seagrass scarring documented at least 70,000 ha of seagrass were moderate to severely-scarred (Sargent et al. 1995). There are many high traffic boating areas around the state of Florida that have been studied, including Tampa Bay and the Florida Keys (Handley et al. 2007). A propeller scar is created when a boat propeller tears through the rhizomal mat of a seagrass bed, allowing for erosion that may lead to the creation of barren sand trenches, and thus seagrass bed fragmentation (Durako et al. 1992, Burfeind and Stunz 2006). Seagrass recovery from propeller scar damage is both site specific and depth dependant. Full recovery of shoal grass, *Halodule wrightii*, takes 0.3 - 4.6 years (Table 1). For turtle grass, *Thalassia testudinum*, complete recovery from a propeller scar can take 0.3 - 60 years (Table 1). Differences in recovery between sites may be due to strength of currents, sediment type, and water depth (Durako et al. 1992, Dawes et al. 1997, Hammerstrom et al. 2007). Both Tampa Bay (Dawes et al. 1997) and the FL Keys (Kirsh et al. 2005) have tidal currents that increase erosion after propeller scar injuries. Tidal currents can cause the scars to become deeper trenches where seagrass recolonization is less likely (Kirsch et al. 2005). Seagrasses typically cannot grow down into trenches, making scar recovery very difficult or impossible without outside intervention (restoration) (Kirsch et al. 2005).

Though propeller scar damage has been studied on Florida's west coast and Keys, propeller scarring has never been studied on the east coast. The Indian River Lagoon system (IRL) along the east coast of central Florida was designated as an Estuary of National Significance by the Environmental Protection Agency and has been listed as the most productive and species-rich estuary in North America (IRL NEP 2008) (Figure 1). Biological diversity in the IRL is very high in part because it is located in a transition zone that encompasses temperate and subtropical climate zones (Steward et al. 2006). This diverse assemblage provides a critical habitat for over 2000 species of macrophytes, invertebrates, fishes, birds and mammals (Smithsonian Institution 2007). It also contains the most diverse assemblage of seagrass species of any estuary in the United States, consisting of seven species: *Halodule wrightii, Syringodium filiforme, Thalassia testudinum, Halophila johnsonii, Halophila decipiens, Halophila engelmannii*, and *Ruppia maritima* (Steward et al. 2006). The value of IRL seagrass beds are estimated at $329 million per year, or $14,000 per hectare for the commercial and recreational fishing industry alone (IRL NEP 2008). The value for seagrasses is even higher if other types of recreation, aesthetics, and water quality functions are considered; however, there are currently no monetary estimates for these benefits (IRL NEP 2008).

Over the last 50 years, the abundance of seagrass the IRL has decreased 13% on average, and up to 90% in some areas (Virnstein et al. 2007). Between 1992 and 1993, it was documented that 2,400 hectares of seagrass in the IRL were scarred by boats when surveyed (Sargent et al. 1995). Over the past decade, an increase in boating activity led to increased seagrass scarring in the IRL (MINWR CCP 2008). Aerial surveys documented an increase in the number boaters in the northern IRL from 2002 to 2006, which accompanied the trend of increasing human population in surrounding areas that have negatively impacted the lagoon (Scheidt and Garreau 2007). About 46,000 boaters were documented in the northern IRL between 2006 and 2007, of which 76% were fishing boats (Scheidt and Garreau 2007). Boaters used the northern IRL year round, and there was no difference in the mean number of boats per month (Scheidt and Garreau 2007). Over half of the boaters using the IRL traveled 51-100 miles to fish, showing that the IRL is a very popular place to go boating for all people in central Florida and not just coastal residents (Scheidt and Garreau 2007).

In addition to the increase in boating activity, there have been advances in boating technology that allow recreational boaters to travel with outboard motors in shallower waters. Newly designed, shallow boat hulls accompanied by outboard motors mounted on hydraulic lifts are now able to maneuver in very shallow areas. For example, Flats Cats^{TM} states their shallow water boats can travel and maneuver in as little as 9 cm of water on plane at speeds up to 32 km/h (flatscats.com/performance.htm).

Moderate to severely-scarred areas have increased in the northernmost portion of the IRL, also known as Mosquito Lagoon (MINWR CCP 2008). In response to this increase, Merritt Island National Wildlife Refuge (MINWR) enacted a pole-troll zone to protect 1,272 hectares of Mosquito Lagoon seagrass in the spring of 2006 (MINWR CCP 2008). The Pole-Troll Zone prohibits boaters from using their main combustion engines, with the exception of marked channels. Boaters are allowed to troll with a shallow electric motorized propeller, pole, or paddle to maneuver in places outside the channels. Fines for the destruction of seagrasses range from $50-1000 (FWC 2008). Between 2002 and 2006, aerial surveys documented an increase in boaters from 483 to 603 in the Pole-Troll Zone, of which 86% were recreational fishing boats (Scheidt and Garreau 2007). In 2006, Scheidt and Garreau documented that the Pole-Troll Zone changed boater behavior to increased use of poles and trolling motors, however 80% of the boaters in transit did not use the channels (2007). MINWR immediately initialized a large-scale analysis of aerial photography (taken in the summer of 2007) to assess the total amount of seagrass area currently damaged, the effectiveness of the Pole-Troll Zone, and to monitor the scar recovery from repeated aerial photos. This project is nearing completion by Dynamac Corporation (D. Scheidt personal communication). My study complements this research as a ground-truthing, fine-scale combination of observations and manipulative experiments to document: (1) the existence of multiple scar types in Mosquito Lagoon, (2) recovery time of each type of scar, and (3) restoration methods for the most severe scar type. My results are important to help develop a seagrass management plan Mosquito Lagoon.

My study is novel because it is the first to describe and document the severity of individual propeller scars in very shallow waters of Mosquito Lagoon. Initial measurements of existing propeller scars were used to design a manipulative field experiment to document the natural recovery time of the dominant seagrass, *H. wrightii* in different scar severities. A second manipulative field experiment was conducted to test if three restoration methods could speed up the recovery time of *H. wrightii* when applied to the most severe scar type.

CHAPTER 2: BASELINE SCAR MEASUREMENTS

Methods

Propeller scars had never been measured in Mosquito Lagoon, so I gathered baseline measurements on existing boat propeller scars in Mosquito Lagoon. My objectives were to document differences in severity within individual scars, and find the mean dimensions for each scar severity. In addition, the observations and measurements detailed below were necessary information to design manipulative experiments to examine *H. wrightii* seagrass recovery with and without restoration described in Chapter 3.

Study organism

Halodule wrightii, is the dominant seagrass in Mosquito Lagoon (Hall et al. 2001). Also known as shoal grass, *H. wrightii* (Figure 2), is considered a pioneer species of seagrass because it can tolerate greater variations in salinity, water depth, and clarity than other seagrass species (Sargent et al. 1995, Dunton 1996). Compared to *Thalassia testudinum*, and *Ruppia maritima*, *H. wrightii*, is the most salt tolerant and able to survive up to 70 ppt (Koch et al. 2007). In Mosquito Lagoon, *H. wrightii* occur at a mean depth range of 0.5-1.9 m (Hall et al. 2001). *Halodule wrightii* requires approximately 20% direct light to grow (Steward et al. 2005). *Halodule wrightii* can be found on substrate ranging from sand to mud, usually containing less than 6% organic composition (Terrados and Duarte 1999, Hemminga and Duarte 2000).

Halodule wrightii and all seagrasses are submerged angiosperms, underwater plants that spread using a horizontal underground growing stem structure called a rhizome (Marbá and Duarte 1998, Hemminga and Duarte 2000, Marbá et al. 2006). From the rhizome, both roots and leaves are produced (Duarte 2002). Roots are shallow and create an oxidized micro-layer in which nitrogen-fixing bacterial communities reside (Welsh 2000). Leaves, also called blades, are bundled together in various numbers depending upon the season, and are bound together at the shoot. These vertical stems, or shoots, are the most commonly counted structure for seagrass density measurements.

Halodule wrightii is a perennial monocot that produces seeds that can last up to 46 months (McMillian 1991, Orth et al. 2000). However, seeds or seedlings of *H. wrightii* have never been documented in the IRL, and therefore sexual reproduction is considered absent or a rare event (Hall et al. 2006a). The primary dispersal method for *H. wrightii* in the IRL is rhizome fragmentation (Hall et al. 2006a). Fragments of *H. wrightii* containing 3 short shoots were most commonly found floating above seagrass beds, and were discovered to be viable for up to 4 weeks of floating in the IRL (Hall et al. 2006a).

In the Caribbean and Florida, *H. wrightii* is one of the first species to colonize, followed by *Syringodium filiforme*, and eventually leading to the climax species *Thalassia testudinum* (Marbá and Duarte 1998). These three species can coexist in the same seagrass bed due to root partitioning (Duffy 2006). *Halodule wrightii* has the shortest roots and occupies the surface sediment, *S. filiforme* occupies the area below *H. wrightii* roots and *T. testudinum* has the deepest roots that reside below the other two species (Duffy 2006).

Study area

Mosquito Lagoon is the northern portion of the IRL along the east coast of central Florida (Dybas 2002) (Figure 1). It stretches from Ponce de Leon Inlet south to Cape Canaveral, Florida and 16,000 ha are protected by MINWR and Canaveral National Seashore (CANA) (Scheidt and Garreau 2007). Mosquito Lagoon is home to 41 federally listed species, which is more than any other refuge or park in the continental United States (MINWR CCP 2008). Mosquito Lagoon's

4,500 hectares of seagrass beds are world renown for sport-fishing, and provide habitat for commercially important fish species including snook, tarpon, red and black drum, spotted sea trout, and striped mullet (MINWR CCP 2008).

Mosquito Lagoon is unique to previously studied propeller scarred areas because of the shallow water depth, slow water motion and fine sediments (Steward et al. 2006). Mosquito Lagoon is very shallow, 1.7 m depth on average (Steward et al. 2006). Southern Mosquito Lagoon has semi-diurnal tides that are microtidal, with the maximum water level change of 10 cm and less than 2 cm in some areas (Smith 1993, Hall et al. 2001). Water motion in the lagoon is predominately wind-driven, with winds ranging from 0-30 mph on average that create water variations of only ±10-30 cm (Smith 1993, Hall et al. 2001). Water levels in the lagoon are seasonal, occurring with annual rise and fall of ocean water levels, with high water levels peaking in October-November, and lowest water levels in April-May (Hall et al. 2001). Average rainfall for the lagoon is 1 cm (Hall et al. 2001). During the year, mean water salinity ranged from 20-35 ppt, mean water temperature ranged from 15-31 ^{o}C, and light attenuation ranged from 0.3-1.69 m^{-1} with 0.92 m^{-1} on average (Hall et al 2001). Sediments in Mosquito Lagoon primarily consist of fine slit-clay loam (Steward et al. 2006).

Measurements of existing propeller scars

To understand the diversity of propeller scars currently in Mosquito Lagoon, I flew in a helicopter with MINWR to document areas that were severely scarred. Then I measured all scars (110 total) that could be found by boat in each severely scarred area along the length of Mosquito Lagoon between September 2006 and February 2007 (Figure 3). Measurements for each scar included: depth, width, *H. wrightii* canopy height in the scar, and *H. wrightii* canopy height surrounding the scar. Other descriptive measurements collected included: GPS location, scar orientation (compass direction), salinity, temperature, water clarity depth (measured before entering water using a turbidity tube in cm), and sediment from one core (3 cm diameter x by 5 cm deep) per scar. The percent cover of the following was also recorded: *H. wrightii* cover in each scar, *H. wrightii* cover surrounding each scar, rhizome cover in each scar, drift algae cover in each scar, and leaf litter cover in each scar. Percent cover was measured using a 1 x 0.25 m strip quadrat divided into four sections, only one 0.25 x 0.25 m section in the quadrat was counted for density measurements, and the quadrat was haphazardly chosen per scar (Dawes et al. 1997).

Intra-scar measurements

Intra-scar variation is the change in scar severity type within a single scar. The distance between and length of each scar type (severity) was measured for 15 m in one direction for all 110 scars. For every severity scar type encountered within one scar, the following measurements were collected: scar depth, width, and canopy height in and surrounding the scar, and percent cover of *H. wrightii* in scar, *H. wrightii* surrounding scar, rhizome in scar, and the number *H. wrightii* shoots in and surrounding the scar.

Sediment analyses

Sediment cores collected from each scar were analyzed for grain size fractions and organic content. All 110 sediment samples were dried for 48 hours at 80^{o} C and then ground with a mortar and pestle. Samples were then sieved into 5 fractions: > 5 mm, 5 mm, 2 mm, 1 mm, and < 1 mm. Each fraction was weighed and percents of each fraction were calculated.

Next, sediment grain size fractions were recombined, and the complete sediment samples were dried at 80^{o} C for 24 hours prior to being placed in a muffle furnace for organic content analysis (Parker 1983, Fabiano et al. 1995). Samples were weighed before and after being placed in a muffle furnace for 2 hours at 450^{o} C (Parker 1983, Fabiano et al. 1995). The organic content was calculated from the change in weights and expressed as percent organic matter.

Statistical analyses

All measurement data were initially tested for normality using Shapiro-Wilks test, and homogeneity of variance using Levene's test in SPSS Statistical Software (Version 11.5). All measurements were transformed using $\log_{10}$, except for percent fractions which were transformed using arc sin to normalize the data. Only transformed measurement data were used in analyses.

To document if there were different types of scars, I entered all measured variables in Canonical Discriminant Analysis to determine the number of unique scar types and which variables were most important in classifying each scar type. The Wilk's Lambda test was used to test which measurements were significant in defining scar groups. The frequency of each scar type was calculated from the 110 measured scars. The overall mean and mean per scar type for each general measurement were calculated.

Correlations of all measured variables were tested with Pearson two-tailed tests. To further test the significant correlation of scar depth versus scar width, a linear regression was calculated for scar Type 1, since it was the only scar type having depth.

All scars were mapped in GIS, and GPS coordinates were used to compute distances in meters from each scar to the nearest channel (Figures 1, 3). Channels included the Atlantic Intracoastal Waterway, the edge of the Pole-Troll Zone and the inner channels of the Pole-Troll Zone. Distances were used to see if there was a pattern in scar sediment type using Canonical Discriminant Analysis. Sediment fractions were also tested to see if there was a pattern among scar types and if sediment type could predict scar types using Canonical Discriminant Analysis.

Sediment fractions for each scar type were tested with a one way analysis of variance (ANOVA) to test if the mean of each fraction was significantly different in each scar type.

Results

Scar severity categories

Canonical Discriminant Analysis was used to test for categories of scar severity based on measured scar dimensions, and four groups were clearly distinguished (Figure 4). Types 1 and 4 scars (most extreme) were more accurately classified and intermediate scar Types 2 and 3 were less clear. (Table 2). I concluded that four types of propeller scars accurately represented propeller scarring in Mosquito Lagoon because 91.8% of all scars were correctly classified (Table 2). Significant variables used to classify scar types were: (1) shoot density in scar, (2) percent root cover, (3) scar depth, and (4) scar canopy height (Wilk's Lambda $p < 0.001$).

Type 1 was the most severe scar type, exhibiting a trench formation, having the bottom of the scar deeper than the surrounding sediment surface and an absence of seagrass shoots and visible rhizomes within the scar (Figure 5). Type 2 was a scar type having the bottom level with the surrounding sediment surface, and with an absence of seagrass shoots and visible rhizomes (Figure 5). Type 3 was a scar type having the bottom level with the surrounding sediment surface, and containing rhizomes but no shoots (Figure 5). Type 4 was a scar having a bottom level with the surrounding sediment surface, and containing rhizomes with shoots that were cut shorter than the surrounding canopy height (Figure 5). All four scar types exhibited a linear path through the seagrass and could not be distinguished from a boat. However, aerial photos were underestimating the amount of scarring because Type 4 scars could not be seen, since there was not enough contrast between the seagrass and the sediment (D. Scheidt personal communication). Out of the 110 scars measured, the most severe scar type (Type 1) was the most common at 56.4%, followed by the least severe scar type (Type 4) at 27.3%, Type 2 at 10.0%, and Type 3 at 6.4% (Figure 6).

General scar measurements

The mean width (± S.E.) of all measured scar was 32 (± 2) cm, and the mean depth of scars ranged from 9 (± 1) cm in Type 1 to 1 (± 1) cm in Type 4 (Table 3). Scar depth was significantly correlated with scar width in Type 1 scar (ANOVA: $p < 0.001$, $r^2 = 0.476$; Figure 7). Scar direction was not significantly correlated with any measured variable (Pearson correlation: $p > 0.088$).

Two species of seagrass, *Halodule wrightii* and *Syringodium filiforme,* were found in and surrounding the scars. The mean shoot density of *S. filiforme* was 1%, while *H. wrightii* comprised 99% of all measured seagrass. Since *H. wrightii* was the dominant species of seagrass in Mosquito Lagoon, from here on I report only seagrass measurements for *H. wrightii*. The mean *H. wrightii* shoot count in scars ranged from 0 (± 0) in Type 1 to 44 (± 6) in Type 4 scars. Scar Type 4 mean *H. wrightii* shoot density inside the scar was less than half of the mean surrounding *H. wrightii* shoot density (Table 4). The mean *H. wrightii* canopy height in scars ranged from 0 (± 0) in Type 1 scars to 12 (± 1) in Type 4 scars. The surrounding seagrass canopy height mean was similar in each scar type, ranging from 27-32 cm (Table 3). The percent cover (± S.E.) of *H. wrightii* in Type 4 scars was 25 (± 4)% and was less than half of the mean percent coverage of *H. wrightii* surrounding the scar, 62 (± 5)% (Table 4).

Mean percent root cover ranged from 56-73% in scar Types 3 and 4, while scar Types 1 and 2 did not have roots. Mean percent leaf litter cover was quite variable, ranging from 10 (± 4)% in scar Type 4 to 55 (± 5)% in scar Type 1 (Table 4). Mean percent cover of drift algae was also highly variable among scar types (Table 4).

Intra-scar measurements

Of the 110 scars measured, only 2 scars contained multiple scar types. Both scars alternated between Type 1 and Type 4 scar severities, repeatedly alternating along the 15 m sections measured. Scar Type 1 was more frequent comprising 65% of both scars, while Type 4 severity comprised 35%. Severities switched 5 times in the first scar and 6 times in the second scar. The mean length (± S.E.) of a severity section was 1.6 (± 0.4) m. The mean length ranged from 1.9 (± 0.6) m in Type 1 scar sections to 1.3 (± 0.6) m in Type 4 sections. Only Type 1 scars sections had depth, and the mean depth (± S.E.) was 13.9 (± 1.7) cm. The remaining 108 scars had a constant severity for at least 15 m along the length of each scar.

Scar sediment analysis

Sediment composition varied among scar types. Scar Types 1 and 4 were significantly different in all fractions (ANOVA: $p < 0.01$; Figure 8). Type 4 scars were dominated more by fine (< 1 mm) sediments than Type 1 scars, with intermediate levels in scar Types 2 and 3. Overall, 60% of all sediment samples were predominately composed of the most fine sediment (< 1 mm) fraction (Figure 8). Mean organic content was 2.3 (± 0.1)% for all samples and did not significantly differ among scar types.

Canonical Discriminant Analysis was used to test if scar categories could be classified with sediment type and location, using the following measurements: sediment fractions, nearest channel distance, scar GPS location, scar depth, and water depth. There was no pattern in the location of sediment types (Figure 9). Sediment fractions classified scars into two groups rather than four groups, as predicted by the scar and seagrass measurements (Table 5, Figure 9). Thus, sediment fractions were not good predictors of the scar types.

Discussion

My study was the first to discover that different severities within individual propeller scars exist, and the first to document the dimensions of propeller scars in the IRL. Of the scar types I identified, only Types 1 and 2 were documented in previous studies (Table 1). The scarring observed in Mosquito Lagoon is less severe than other areas, such as Tampa Bay and the Florida Keys. Seagrass recovery from propeller scar damage is both site specific and depth dependant (Table 1). Sites that have more tidal or current motion are likely to erode scars deeper and wider, making seagrass recovery difficult (Kirsh et al. 2005). Sediment composition may influence how well the seagrass can grow and remain rooted when exposed to currents (Durako et al. 1992, Dawes et al. 1997, Hammerstrom et al. 2007). For example, Tampa Bay's substrate is composed of siliceous sand that is firmer than the Florida Keys, which has a different mineral composition in the substrate of carbonate sand (Fonseca et al. 2004). Scars in the Florida Keys have more coarse sediments with a lower pH than the sediments from surrounding seagrass beds; this however was not found in Tampa Bay scars (Sargent et al. 1995). Sites that are in more shallow water may take longer to recover (Table 1).

Mosquito Lagoon is microtidal with very slow, wind-driven currents. I predict scars created in Mosquito Lagoon to be less severe than previously studied areas. However, Mosquito Lagoon is also very shallow with fine, unstable sediments, which may make the recovery more difficult. Table 1 shows propeller scars can range 0.3 – 7.0 m in width, and 10 – 40 cm in depth. Previously documented scars can be far more severe than the most severe scars (Type 1) I have documented in Mosquito Lagoon, with mean size of 32 cm wide x 9 cm deep.

The measurements of existing scars were analyzed to not only understand the severity of propeller scarring in Mosquito Lagoon, but to design experiments to test the recovery of

H. wrightii from all propeller scar types. The first objective in planning the experiments was to document if different scar types exist, and the frequency of each type in Mosquito Lagoon. Four different scar severities were documented (Figure 5). Out of the 110 scars measured in the field, the most severe scar type was the most common (Figure 6).

My second objective was to identify mean measurements for each scar type, and use them to make experimental scars. Only the mean dimensions from the four scar types were used in testing the recovery time of *H. wrightii*. Multi-severity scars were not included in the experiments because they were very rare in the landscape, only 2 scars out of 110 were found to have multiple severities. Since 99% of all seagrass measured was *H. wrightii*, it was the only seagrass measured for recovery time in the experiments.

My third objective was to determine if sediment composition was an important factor in identifying scar types, and if sediment types were distributed in a pattern or gradient in the landscape. The distribution of sediment types was used to decide if the experiment should be planned in more than one location. Canonical Discriminant Analysis results showed that sediment type was not a good predictor of scar type, and no clear sediment patterns were found in the landscape. Sediments were heterogeneously distributed, and were predominantly composed of fine sediments (< 1 mm), with 2% mean organic matter (Figure 7). Since sediment types were not found in a specific pattern or at specific locations, only one location was used for the manipulative experiments.

In summary, my study documented propeller scar dimensions and individual scar severities for the first time in Mosquito Lagoon. I found that there were four main areas with intense scarring, three of which were within the Pole-Troll Zone boundaries (Figure 3). All scars in these areas were measured, and the most common scars found were the most severe scars (Type 1). If regulations were strictly enforced, then the majority of the scars in the seagrass would be made by trolling motors. Trolling motors have adjustable mounts for changing propeller depth in shallow water to avoid hitting the sediment. Trolling motors are battery powered, and are not powerful enough to plow through the sediment creating less severe scars (Type 4). According to Engeman et al. (2008), seagrass restorations are far more expensive than prevention methods that involve adding signage and law enforcement officers. I would recommend that the Pole-Troll Zone should have more than 2 signs (a sign at each channel entrance), especially since Scheidt and Garreau found that 80% of boaters in transit do not use the marked channels (2007). New signs would only cost an average of $192 each (Engeman et al. 2008). I also recommend that there be more than one officer to patrol the 1200 ha Pole-Troll Zone. More patrol officers would each cost an average of $59,400 per year (Engeman et al. 2008). To put costs into perspective, a single patrol officer's annual salary was equivalent to the value of 0.42 ha of seagrass in the Florida Keys (Engeman et al. 2008). For every seagrass hectare in the IRL protected to allow recovery, or protected to prevention boat scarring, an additional $14,000 is gained in fisheries resources (IRL NEP 2008). More than 119 species of fishes have been documented in the IRL, and seagrass percent cover is an important factor in determining fish assemblages (Kupschus and Tremain 2001). Many fish species in the lagoon reproduce in the ocean, but rely on estuarine juvenile phase to complete the reproductive cycle (Kupschus and Tremain 2001). Seagrass ecosystems should be protected because they are critical in creating habitat in areas of barren sediment, enhancing community diversity, establishing intricate food webs, and stabilizing coastal sediments (Beck et al. 2001, Burfeind and Stunz 2006, Duffy 2006). Seagrass beds in the Indian River Lagoon provide a critical habitat for over 2000 species of invertebrates, fishes, birds and mammals, and are a key reason why the IRL is the most productive and species-rich estuaries in North America (IRL NEP 2008, Smithsonian Institution 2007).

CHAPTER 3: MANIPULATIVE EXPERIMENTS

Methods

Using the mean measurements for each scar type from Chapter 2, two complimentary manipulative experiments were conducted to examine and potentially maximize *Halodule wrightii* recovery from propeller scars in shallow Mosquito Lagoon waters. The first experiment evaluated the natural recovery rate of *H. wrightii* in the four scar types. I hypothesized that different severity in individual propeller scars would cause different recovery times for *H. wrightii*. The second experiment assessed the success of known restoration methods for the most severe scar type (Type 1). I hypothesized that the addition of different restoration methods would cause Type 1 scars to recover faster than natural recovery.

Study area

The location for my manipulative experiments was in an area with minimal boat traffic. In order to reduce the likelihood of boats running over the experiments, experiments were placed in the Pole-Troll Zone where boaters were not allowed to use their main combustion engines (Figure 1). Experiments were placed in a dense seagrass bed between the barrier island of Canaveral National Seashore and an island west of the barrier island within the Pole-Troll Zone, which effectively blocked boat traffic in two directions (Figure 1). The seagrass bed's mean depth (± S.E.) was 56 ± 4 cm. The seagrass bed was dominated by *H. wrightii*, with occasional small patches of *Ruppia maritima* in spring (personal observation). The GPS coordinates for this seagrass bed location were N28.48.702 and W80.45.705.

Layout and monitoring of experiments

The experimental treatments described below were placed in a randomized block design to control for natural landscape variation (Figure 10). For the randomized block design, one replicate of each treatment was placed in a block, with a total of eight treatments per block (Figures 10, 11). There were 10 replicates for each treatment, and thus 10 blocks total. Each block was 18 x 18 m and was divided into nine equal 6 x 6 m sections. Eight of the nine sections contained a single scar treatment (Figure 10). In the center of each section, each experimental scar was placed a minimum of 2 m away from all other scars. All experimental scars were 200 cm long x 32 cm wide. Treatment location and scar direction within each block were randomized using Excel. Each experimental scar was marked with an aluminum tag on a PVC pole one meter away from each end. All PVC poles were pushed down into the sediment leaving 15 cm remaining above the sediment surface (Figure 12).

All experimental scars were measured in the center for new seagrass recruitment and growth. Measurements included scar width, depth, scar slope angle, *H. wrightii* canopy height inside scar, *H. wrightii* canopy 1 m away from scar side, *H. wrightii* shoot density per 25 x 25 cm inside scar, and *H. wrightii* shoot density per 25 x 25 cm at 1 m away from scar side. Also, the percent cover of *H. wrightii* inside the scar, the percent cover of *H. wrightii* 1 m away from the scar, percent leaf litter cover, and drift algae cover were measured. Water measurements were collected on each sampling date and included: salinity, temperature, and water clarity depth (measured before entering water with a turbidity tube in cm). Also, any erosion that occurred in the scars was documented. All measurements were taken immediately prior to digging the experimental scars, then after 2 weeks, 1 month, 2 months, 3 months, 6 months, 9 months, and 12 months. The initial measurements were taken on 17 July 2007, and final measurements were taken on 3 August 2008.

Natural recovery of seagrass in experimental propeller scars

To document the natural recovery time of *H. wrightii* in each scar type, 10 replicates of each type of scar were created and measured for recolonization at set intervals over one year. Treatments included: (1) Type 1 scars with a depth of 9 cm, no roots and no shoots inside the scar, (2) Type 2 scars with no depth, no roots, and no shoots, (3) Type 3 scars with no depth and no shoots, but with intact roots, and (4) Type 4 with roots, shoots, and blades cut from mean canopy height of 44 cm to 12 cm high. The controls for this experiment were areas of dense seagrass of the same dimensions (200 cm long x 32 cm wide) as the experimental scars within larger seagrass beds. Type 1 scars were created using a 32 cm PVC plow, so that the depth (9 cm), width (32 cm), and scar angle (45^o) in all experimental Type 1 scars remained constant (Table 6). The plow consisted of a diagonally cut and sharpened piece of 32 cm diameter PVC with aluminum mesh attached at the end with rivets, and fitted with an aluminum rod through the center for handles (Figure 13). The PVC plow created uniform scar depth and slope angle for all Type 1 scars, which could not be done using a hand shovel or boat propeller (Table 6). Type 2 scars were created by severing the seagrass roots with a garden spade and raking out the seagrass inside scars with a 32 cm long rake. Type 3 scars were created by trimming all above-ground biomass to the benthos within 200 cm x 32 cm areas using grass shears. Type 4 scars were created by trimming all seagrass blades to 12 cm above the benthos within 200 cm x 32 cm areas using grass shears (Table 6).

All measurement data were initially tested for normality using Shapiro-Wilks test, and homogeneity of variance using Levene's test. Due to non-normality, experiments were analyzed using separate Kruskal-Wallis tests (the non-parametric equivalent of a one-way ANOVA) to test for significant differences among treatment means for each growth measurement and scar dimension variable separately for each time period. Since Kruskal-Wallis tests were repeated eight times for each measured variable, the Bonferroni method was used to correct the significance level from p= 0.05 to p = 0.00625.

Restoration of experimental propeller scars

To test restoration methods to potentially reduce the recovery time of *H. wrightii*, I tested three known protocols with the most severe scar type and measured recolonization at set intervals over one year.

Halodule wrightii is considered the ideal transplant species since it is more tolerant to a wide range of conditions than other seagrass species (Buckholder et al. 1994; Dunton 1996). *Halodule wrightii* can recover faster than other species of seagrass because it has a greater density of shoot and rhizome nodes, providing the ability to branch more often and produce more shoots with blades (Durako et al. 1992; Sargent et al. 1995). *Halodule wrightii* is often used to stabilize the sediment for climax seagrass species such as *T. testutinum*; this technique is called "compressed succession" (Hall et al. 2006b). *Halodule wrightii* has been successfully replanted using staples (Hall et al. 2006b), peat pots (Sheridan et al. 1998), planted in sand tubes (Hall et al. 2006b) and large sod squares (Thorhaug 1986). I decided to use restoration methods shown to be successful transplanting *H. wrightii* in other areas of Florida. Hall et al. was successful in using the staple method to transplant *H. wrightii* and sand tubes to fill in scars in both Tampa Bay and the Florida Keys (2006b). The scars in both places recovered in one year to control *H. wrightii* densities (Hall et al. 2006b). Since this was successful, I decided to use the staple method to transplant *H. wrightii*, and use fine sand to fill scars. I did not use sand tubes because commercially available tubes were larger than the experimental scars were deep, and the current flow was minimal in Mosquito Lagoon.

All treatments and the control started by creating a Type 1 scar trench (200 x 32 x 9 cm). Restoration methods tested were: (1) planting *H. wrightii* in the scar trench, (2) filling the scar trench with commercially available sand, and (3) filling the scar trench with commercially available sand followed by planting *H. wrightii*. The control was a Type 1 scar with no added restoration. All treatments and the control were replicated 10 times. For the fill only and the fill and plant treatments, scars were filled with 0.57 m^3 of Kolorscape^{TM} extra fine play sand (1 mm grain size). Each bag was opened underwater and poured directly into the scars. After all bags were poured, the scar surfaces were smoothed flat by hand. All planting of *H .wrightii* used the staple method described in *NOAA's Guidelines for the Conservation and Restoration of Seagrasses in the United States and Adjacent Waters* (Fonseca et al. 1998). Each transplant unit of *H. wrightii* was composed of a three-shoot fragment with a growing tip. The rhizome of each transplant was attached to a metal garden staple with a paper twist tie (Figure 14). Fragments with three shoots were used because it is the most common fragment size produced from natural *H. wrightii* fragmentation in the IRL (Hall et al. 2006a). Three-shoot fragments can attach to substrate and root within 2 weeks (Hall et al. 2006a). Each planted scar contained 16 transplant units, in a 4 x 4 array. Each row was spaced approximately 25 cm apart within the scar. All seagrass was collected and transplanted within 4 hours.

All measurement data were initially tested for normality using Shapiro-Wilks tests, and homogeneity of variance using Levene's tests. Due to non-normality, experiments were analyzed using separate Kruskal-Wallis tests to test for significant differences among treatment means for each growth measurement and scar dimension variable separately for each time period. Since

Kruskal-Wallis tests were repeated eight times for each measured variable, the Bonferroni method was used to correct the significance level from 0.05 to 0.00625.

Sediment core analysis

One sediment sample per experimental scar was collected before the creation of the scar and at the end of the experiments to test if composition changed over time. Each sediment core was analyzed for grain size fractions and organic content. All sediment samples were dried for 48 hours at 80^{o} C and then ground with mortar and pestle. Samples were sieved into five fractions: > 5 mm, 5 mm, 2 mm, 1 mm, and < 1 mm. Each fraction was weighed and percentages were calculated. After sieving, complete sediment samples were dried at 80^{o} C for 24 hours prior to being placed in a muffle furnace for organic content analysis (Parker 1983, Fabiano et al. 1995). Samples were weighed before and after being placed in a muffle furnace for 2 hours at 450^{o} C (Parker 1983, Fabiano et al. 1995). The organic content was calculated from the change in weights and expressed as percent organic matter. Kruskal-Wallis tests were used to document if there were significant differences among initial and final sediment fractions, and organic content in samples.

Results

Site consistency

Water temperature ranged from $18\text{-}30^{o}$, salinity ranged from 33-44 ppt, and water clarity depth ranged from 36-60 cm among blocks (Figures 15-17). The mean water depth (± S.E.) was 56 (± 4) cm for all blocks (Figure 18). Water clarity may have been greater if measured with a different device because my turbidity tube was 60 cm long; the maximum measurement possible was 60 cm (Figure 17).

Halodule wrightii density, percent cover and canopy height of the seagrass surrounding scars were not significantly different from the between blocks over one year (Figures 19-21). Mean density (± S.E.) of *H. wrightii* surrounding scars and in control plots ranged from 77 (± 4) to 235 (± 10), however some areas had densities as high as 469 shoots per 25 x 25 cm in the spring (Tables 6, 8). Mean canopy height (± S.E.) of *H. wrightii* surrounding scars and in control plots ranged from 21 (± 1) to 47 (± 1) cm over one year (Tables 6, 8). Mean percent cover (± S.E.) of *H. wrightii* surrounding scars and in control plots ranged from 28 (± 2) to 87 (± 2)%, including half of the scars in the spring and summer having 100% cover (Tables 6, 8).

Natural recovery experiment

Type 4 scars recovered to the *H. wrightii* density, percent cover, and canopy height of the control treatment in 3 months, and was the only scar type to completely recover within one year (Figures 22-24, Table 6). First colonization by a single rhizome across the width of the most severe (Type 1) scars was observed at nine months. After 12 months, mean *H. wrightii* shoot density (± S.E.) increased from zero to 116 (± 21) in Type 1, 115 (± 20) in Type 2, and 154 (± 31) in Type 3 scars (Figure 22, Table 6). Types 1, 2, and 3 were significantly different from the control at 12 months (Kruskal-Wallis: $p < 0.001$; Table 7). If scars continue to increase in shoot density at the same rate, then I would expect to see recovery to control density in 28 months for Type 1 and 2 scars, and 21 months in Type 3 scars.

Percent cover of *H. wrightii* (± S.E.) increased from zero initial cover to 46 (± 9)% in Type 1, 47 (± 9)% in Type 2, and 58 (±12)% in Type 3 scars at 12 months (Figure 23). Scar Types 1, 2, and 3 were significantly different from the control at 12 months (Kruskal-Wallis: $p < 0.001$; Table 7). If scars continue to increase in percent cover at the same rate, then I would expect to see recovery to control levels in 25 months for Type 1 and 2 scars, and 20 months in Type 3 scars.

Scar canopy height for Types 1, 2, and 3 was not significantly different from the mean control height (± S.E.) of 38 (± 2) cm (Kruskal-Wallis: $p = 0.001$; Table 7). However, all increased in mean canopy height (± S.E.) from initial values of zero to 25 (± 2) cm in Type 1, 26 (± 3) cm in Type 2, and 30 (± 2) cm in Type 3 (Figure 24). If scars continue to increase in canopy height at the same rate, then I would expect to see recovery to control values in 18 months for Type 1 and 2 scars, and 15 months in Type 3 scars.

There was a significant difference between scar root density for scar Types 1-3 and control and Type 4 at one year (Table 7). Mean percent root cover (± S.E.) in Type 4 scars recovered to 96 (± 3)%, Type 2 to 57 (± 12)%, Type 3 to 53 (± 10)%, and Type 4 to 54 (± 11)% (Figure 25).

In the recolonization of scars that had depth, leaf litter acted as a natural fill for rhizomes. Rhizomes from the surrounding *H. wrightii* extended toward the center of the scar and attached on top of the leaf litter. Leaf litter percent cover was higher in the scar Types 1-3 than control and Type 4 (Figure 26). Type 1 scars initially had a significantly greater proportion of leaf litter after the second month than all other treatments (Kruskal-Wallis: $p < 0.001$; Table 7). At 12 months, percent leaf litter cover was low and there was no significant difference in leaf litter cover among all treatments.

Scar dimension measurements were compared with control values of zero depth, zero width, and zero scar angle. Only Type 4 scars were not significantly different from the control in all measurements after one year (Table 7). Although significantly different from the control after one year, the mean scar depth was reduced from 9 cm initially to 4 (± 1) cm in Type 1 scars, and increased to 2 (± 1) cm in Type 2 and 3 scars (Kruskal-Wallis: $p = 0.001$; Figure 27, Table 7). If scars continue to decrease in scar depth at the same rate, then I would expect to see recovery in 22 months for Type 1 scars, and 15 months for Type 2 and 3 scars. Scar width also decreased from 32 cm to 22 (± 3) cm in Type 1, 18 (± 3) cm in Type 2, and 20 (± 7) cm in Type 3. All were significantly different from the control at the end of one year (Kruskal-Wallis: $p < 0.001$; Figure 28, Table 7). If scars continue to decrease in scar width at the same rate, then I would expect to see recovery in 38 months for Type 1 scars, 27 months for Type 2 scars, and 32 months for Type 3 scars. Scar slopes in Type 2-4 scars were not significantly different from the control after one year. Type 1 scars were significantly different from the control, however the slope was reduced from 45^{o} to $13 (\pm 3)^{o}$ over 1 year (Kruskal-Wallis: $p < 0.001$; Figure 29, Table 7). If scars continue to decrease in scar angle at the same rate, then I would expect to see recovery in 17 months for Type 1 scars.

Sediment fractions among scar Types 1-4 and control were not significantly different at 1 year. There was a significant difference between initial and final sediment in fraction sizes: > 5 mm, 5 mm, 1 mm, and < 1 mm (Kruskal-Wallis: $p < 0.007$; Figure 30). Sediment fractions sizes 1 mm, and < 1 mm were the largest in all samples, with all other sizes composing less than 10% of the sample. Initial fine sediments ranged from 11-65 % in size < 1 mm, and 23-87% in size 1 mm. Initial sediment samples mean percent fraction sizes (± S.E.) were 0.8 (± 0.1)% for > 5 mm, 5.7 (± 0.4)% for 5 mm , 10.3 (± 0.4)% for 2 mm, 31.7 (± 1.3)% for 1 mm, and 51.4 (± 1.3)% for < 1 mm. Final fine sediments ranged from 30-63% in size < 1 mm, and 26-50% in size 1 mm. Final sediment samples mean percent fraction sizes (± S.E.) were 2.0 (± 0.2)% for > 5 mm, 8.3 (± 0.5)% for 5 mm , 10.5 (± 0.3)% for 2 mm, 35.3 (± 0.8)% for 1 mm, and 43.9 (± 1.1)% for < 1 mm. There was no significant difference in organic among all final sediment samples, and between initial and final sediment samples (Figure 31). Mean percent organic matter (± S.E.) in initial samples was 4.9 (± 0.4)%, and 3.8 (± 0.1)% in final samples.

Seasonal variations in natural recovery

Seasonal variations were observed in *H. wrightii* density. Initially, shoot density slightly increased in controls and all scar treatments until fall November 2007, then dropped to a significantly lower shoot density in winter (February 2008) (Kruskal-Wallis: $p < 0.001$; Figure 22). The large die-back during winter reduced densities to 6 (± 2) shoots per 25 x 25 cm in Type 1 scars, 13 (± 5) in Type 2 scars, 28 (± 9) in Type 3 scars, 73 (± 12) in Type 4 scars, and 80 (± 28) in the control (Figure 22, Table 6). However, *H. wrightii* increased exponentially in all scar types during spring and summer (February through August 2008), ending with mean densities (± S.E.) of 116 (± 21) shoots per 25 x 25 cm in Type 1 scars, 115 (± 20) in Type 2 scars, 154 (± 31) in Type 3 scars, 244 (± 21) in Type 4 scars, and 271 (± 16) in the control seagrass plots (Figure 22, Table 6). Mean shoot density among treatments in winter was significantly lower in all treatments than in summer 2008 (Kruskal-Wallis: $p < 0.001$; Figure 22, Table 6). A similar seasonal pattern of significantly lower mean *H. wrightii* percent cover (Kruskal-Wallis: $p < 0.001$) and canopy height (Kruskal-Wallis: $p < 0.001$) was observed among all treatments.

Seasonal variations in scar dimensions were also observed. Scars increased in depth during the fall and maintained a significantly deeper depth of 12 (± 1) cm in Type 1, 7 (± 1) cm in Type 2, and 5 (± 2) cm in Type 3 during the winter (Kruskal-Wallis: $p < 0.001$; Figure 27, Table 6). Scar width erosion was worst in winter, scars significantly increased in width to 41 (± 4) cm in Type 1 scars, to 51 (± 12) cm in Type 2 scars, 32 (± 9) cm in Type 3 scars (Kruskal-Wallis: $p \leq 0.001$; Figure 28, Table 6). Type 4 scars were not eroded. The slope angle eroded creating a significant increase scar angle slope of 29 (± 9)^{o} in Type 2, and 12 (± 7)^{o} in Type 3 over 12 months (Kruskal-Wallis: $p \leq 0.02$; Figure 29, Table 65).

Restoration experiment

There was 100% mortality of the 320 transplants after 60 days (4 observation periods) (Table 9). The two treatments having *H. wrightii* planting units lost almost half of the planting units after 2 weeks, and all after 2 months. Transplants on staples were lost from either sediment burial or from sediment erosion under staples. Many of the planting units were buried in the scars, possibly due to the staple sinking through the fine sediment, or fine sediments settling out of the water column. After 2 weeks, about half of the planting units in each plant-only treatment were buried to a mean depth (± S.E.) of 6 (±2) cm.

Many transplants lived for a short period (up to 2 months) while attached to an eroded or elevated staple, however all transplants died after 2 months. Many of the garden staples with transplants in both the plant-only and fill and plant treatments had the sediment eroded out from under the staple exposing the transplants between 2 and 12 cm above the benthos. Despite none of the transplants contributing to scar colonization, the fill and plant, and plant-only treatments were colonized naturally from the adjacent seagrass bed (Figure 32). The plant-only treatment showed initial seagrass recolonization after 2 months despite the mean scar depth of 10.5 cm (Table 8). The fill and plant treatment did not show any sign of recolonization after 3 months (Table 8).

The sand fill treatment survived the longest, with 5 of 20 scars retaining sand throughout the entire year (Table 9). The sand fill treatment did provide stable sediment for surrounding *H. wrightii* to colonize from the adjacent seagrass bed.

None of the restoration treatments significantly differed from the natural recovery of Type 1 scars for all *H. wrightii* measurements, including *H. wrightii* shoot density, percent *H. wrightii* cover, canopy height, percent root cover, and percent leaf litter cover (Figures 32-36, Tables 8, 10). Scar depth, width, and angle were reduced over time in all restoration treatments, and none of the treatments significantly differed from Type 1 scars (Figures 37-39, Tables 8, 10). Only the seagrass control was significantly different from all restoration treatments and Type 1 scars in all measured variables (Table 10).

Sediment fractions among restoration treatments, Type 1 scars and control were significantly different in fraction size 5 mm after 1 year (Kruskal-Wallis: $p = 0.031$; Figure 40). There was a significant difference between initial and final sediment in fraction sizes: > 5 mm, 5 mm, 1 mm, and < 1 mm (Kruskal-Wallis: $p < 0.002$; Figure 40). Sediment fractions sizes 1 mm, and < 1 mm were the largest in all samples, with all other sizes composing less than 10% of the sample. Initial fine sediments ranged from 11-65 % in size < 1 mm, and 23-87% in size 1 mm. Initial sediment samples mean percent fraction sizes (± S.E.) were 0.8 (± 0.1)% for > 5 mm, 5.7 (± 0.4)% for 5 mm , 10.3 (± 0.4)% for 2 mm, 31.7 (± 1.3)% for 1 mm, and 51.4 (± 1.3)% for < 1 mm. Final fine sediments ranged from 13-55% in size < 1 mm, and 25-81% in size 1 mm. Final sediment samples mean percent fraction sizes (± S.E.) were 2.5 (± 0.3)% for > 5 mm, 8.1 (± 0.7)% for 5 mm , 9.7 (± 0.5)% for 2 mm, 40.5 (± 2.1)% for 1 mm, and 39.4 (± 1.5)% for < 1 mm. There was a significant difference in organic among restoration treatments, Type 1 scars and control sediment samples (Kruskal-Wallis: $p = 0.041$; Figure 41). Also there was a significant difference in organic content between initial and final sediment samples (Kruskal-Wallis: $p = 0.028$; Figure 41). Mean percent organic matter (± S.E.) in initial samples was 4.9 (± 0.4)%, and 3.5 (± 0.2)% in final samples.

Erosion observations

Many of the scars in both experiments suffered from erosion at the scar edges, away from the scar center where measurements were taken. Erosion at scar edges was separated into three categories: (1) holes, (2) wash-outs, and (3) sand patches (Figure 42). A hole was defined as any circular erosion that occurred within, and did not extend beyond the initial dimensions of the width or length of scar edge (Figure 42). A wash-out was a type of erosion that extended beyond the width or length of the scar and removed *H. wrightii* on 1 to 3 sides surrounding the scar (Figure 42). A sand patch was the result of losing the top fine-sediment layer that created depths ranging 15-30 cm deep, along with losing all four sides of *H. wrightii* surrounding the scar to erosional forces (Figure 42). Overall, mean scars that had holes was 11, mean scars that were washed out was 8, and mean scars that were turned into sand patches was 2 for each measurement period (Table 11). Out of both experiments, the control and Type 4 scars had significantly fewer holes and washouts (Kruskal-Wallis: $p < 0.001$). The fill-only and fill and plant treatments had the highest, having three times more holes and washouts than all other scar treatments (Table 11). The fill only and fill and plant treatments also had significantly more scars that turned into sand patches (Kruskal-Wallis: $p = 0.007$). Some scars likely started with one or more holes, possibly caused by stingrays, which expanded into a wash out and over time turned into a sand patch (Figure 43). Bioturbation from stingrays was not the only erosional force; it is likely that additional boat scarring and boat traffic wakes also contributed to scar erosion (Figure 44).

Every time I measured the experiments, I witnessed 2 to 3 boats that disregarded the channel signs and illegally used their combustion engines to transverse regulated seagrass flats, potentially creating new scars. Some of these scars were in the area of my experiments. Of the 70 experimental scars and the 10 controls in my experiment, 14 were bisected by a new propeller scar over the course of the year (Figure 44). Some boaters severed pvc marker poles with their main engine motor propeller (Figure 45). Six of 160 poles were damaged due to boat traffic over one year. Boat activity and bioturbation of scars from rays were the most common disturbances to scars and were likely the key erosional forces during the experiment.

Discussion

Natural recovery

By far the most successful way to restore all types of scars is to protect seagrass from boat traffic and let it naturally recover. I predicted that different severities in individual propeller scars would cause different recovery times for *H. wrightii,* and different recovery times were observed. In the natural recovery experiment, the scars that had the highest recovery within a year were those that started with intact *H. wrightii* rhizomes and cut blades (Type 4 scars) (Figure 9). The Type 4 scars grew to the control *H. wrightii* density within 2 months and were equal to the control in all seagrass and scar measurements after 3 months. Types 1, 2, and 3 did not recover by the end of 1 year to control densities of percent cover, percent root cover, canopy height, scar width, slope angle, and depth. Since there was depth and width remaining in scar Types 1-3, *H. wrightii* colonization was reduced. Recovery of Type 1 scars which had depth was not significantly different in seagrass measurements from that of Type 2 and 3, which did not have depth, showing that depth of 9 cm does not slow seagrass recolonization in scars in Mosquito Lagoon. The lack of difference between seagrass recolonization of Type 1 scars, and Types 2 and 3 maybe due to leaf litter acting as a natural fill in scars having depth. If the current rate of recovery continues in each measured variable, the mean estimated recovery time for *H. wrightii* is 25 months for Type 1, and 19 months in Types 2 and 3.

Seagrass restoration

Seagrass restoration is a challenging endeavor, and few studies have had success in establishing new seagrass growth from transplants (Fonseca et al. 1998). Low survival and failure of seagrass transplants is all too common (Fonseca et al. 1998). Fonseca et al. (1998) documented that the mean transplant survival was 47% out of 53 published restoration studies. Campbell

(2002) documented that less than 22% of published transplantation efforts in Australia were successful in achieving 50% transplant survival. However, Hall et al. (2006b) showed that the staple method was successful in transplanting *H. wrightii* into scars in Tampa Bay and the Florida Keys, where transplants established 100% *H. wrightii* cover after 1 year in both locations. In my experiment, I tested a combination of two previously successful and cost-effective restoration methods used by Hall et al. (2006): filling the scar with sand, and placing transplants of *H. wrightii* in the scar using garden staples. I predicted that the addition of different restoration methods would cause Type 1 scars to recover faster than natural recovery, however none of the restoration methods enhanced the recovery time. Many of my scars filled with sand were eroded over time. After 2 months, 25% lost all fill sand and after one year 75% of scars lost all fill sand completely (Table 9). I had hoped to have high transplant success, since (1) *H. wrightii* removed from the experiment was replanted in the same area, (2) transplants were replanted within 1 to 4 hours the same day, and (3) all transplant units of *H. wrightii* included a growing tip at one end of the rhizome. However, all transplant units were lost within 2 months. Knowing that stress to the transplants was minimized and the control treatments showed no signs of die-off from water quality or sediment conditions, I hypothesize the main cause of mortality was erosion, as evidenced by the mean (± S.E.) sediment erosion depth of 7 (±3) cm under staples. Boat activity and bioturbation of scars from rays were the most common disturbances to scars and were likely the key erosional forces during the experiment.

Despite erosion forces, the majority of the 70 experimental scars exhibited *H. wrightii* recolonization during the year. Eight scars (10%), recovered to 100% *H. wrightii* seagrass cover within 1 year. Nineteen scars (20%) recovered to greater than 75% cover. Twenty-nine scars (40%) recovered to greater than 50% cover. Only four scars (5%) did not show any recolonization or recovery inside the scar within 1 year (Figures 26, 34). Of those four scars, three were fill and plant treatments and one was a Type 2 scar.

My experiment has provided helpful information for resource managers. First, the staple method was not a productive transplant method for *H. wrightii* in Mosquito Lagoon. Only one transplant out of 320 deployed in the experiment survived at 2 months. Second, although the sand-filled scars provided a solid substrate on which seagrass could colonize, there were no significant differences in any growth measurements between filled treatments and the natural recovery of Type 1 scars. Thus, using sand to fill trenches did not enhance recovery and was not an effective restoration method for *H. wrightii* in Mosquito Lagoon. Third, despite the slow currents of Mosquito Lagoon and the protection of the seagrass bed by Pole-Troll Zone regulations, erosion may have played a key role in why the restoration failed.

Management recommendations

My results suggest that if the Pole-Troll Zone regulations were strictly enforced, new scars would not be created and all current scars would recover in 3 years or less. If Pole-Troll Zone regulations were effective, then the majority of the scars in the seagrass would be made by trolling motors. Trolling motors have adjustable mounts for changing propeller depth in shallow water and have less power than combustion engines which create less severe scars. Most trolling motors stop rotating if they reach the bottom, and are not powerful enough to plow through the sediment and impact seagrass root structure as combustion engines can. These less severe scars (Type 4) could completely recover in 3 months or less.

For areas of seagrass that are more intensely scarred, creating temporary, no-motor zones that park management could rotate every 3 years would allow enough time for the impacted seagrass beds to recover. Along with the recovery of seagrass in a no-motor zone, various species that depend upon seagrass would likely increase, such as commercially important fish stock (Duffy 2006). More than 119 species of fishes have been documented in the IRL, and seagrass percent cover is an important factor in determining fish assemblages (Kupschus and Tremain 2001). Many fish species in the lagoon reproduce in the ocean, but rely on estuarine juvenile phase to complete the reproductive cycle (Kupschus and Tremain 2001). For every seagrass hectare in the IRL protected to allow recovery, or protected to prevention boat scarring, an additional $14,000 is gained in fisheries resources (IRL NEP 2008).

Restoration versus prevention

According to Engeman et al. (2008), seagrass restorations are far more expensive than prevention methods that involve adding signage and law enforcement officers. The damage to seagrass beds between 1994 and 2005 in the Florida Keys was valued at $28 million dollars, and estimated to increase $1 million in value each consecutive year (Engeman et al. 2008). However, this huge loss could have been prevented with additional signs that cost an average of $192 each, and patrol officers costing an average of $59,400 per year (Engeman et al. 2008). To put costs into perspective, a single patrol officer's annual salary was equivalent to the value of 0.42 ha of seagrass (Engeman et al. 2008). Previous seagrass restorations in the Florida Keys have been very costly at $940,000 per ha to restore (Fonseca et al. 2002, Lewis et al. 2006). Besides the hefty price tag, seagrass restorations can take over 10 years to complete, and there is no guarantee that they will be successful (Engeman et al. 2008). For example, a seagrass mitigation project for renovation of Port Manatee in Tampa Bay compared many seagrass restoration techniques, few of which were successful (Lewis et al. 2006). The cost to transplant 2.94 ha of seagrass and restore 1.86 ha of seagrass was $3.3 million per ha of seagrass restored (Lewis et al. 2006). The 2.94 ha of seagrass was mitigated as transplants to enhance areas of degraded seagrass from boat traffic (Lewis et al. 2006). The restoration methods of hand-transplanting individual shoots, hand-planting shoot bundles, hand-planting bundles in peat pots, mechanized transplanting, modified manual shovel planting, and prevention methods of creating a no motor zone combined were successful in establishing and preserving 1.86 ha of seagrass (Lewis et al. 2006). The least costly and most successful method used to restore seagrass beds was to create a no motor zone in which 0.77 ha of seagrass recolonized propeller scarred areas in 18 months (Lewis et al. 2006).

Future of seagrass in Mosquito Lagoon

Seagrass ecosystems are critical in creating habitat in areas of barren sediment, enhancing community diversity, establishing intricate food webs, and stabilizing coastal sediments (Beck et al. 2001, Burfeind and Stunz 2006, Duffy 2006). Seagrass beds in the Indian River Lagoon provide a critical habitat for over 2000 species of invertebrates, fishes, birds and mammals, and are a key reason why the IRL is the most productive and species-rich estuaries in North America (IRL NEP 2008, Smithsonian Institution 2007). In my study, I looked at a major threat to seagrass ecosystems, boat propeller scarring. I documented for the first time the severity of boat propeller scarring in the IRL. In my manipulative experiments, I found that natural recovery was faster than any restoration attempted method. Natural recovery of propeller scars can be as quick as 3 months if some of the root structure and blades remain intact. Though my restoration methods were not effective for scars in Mosquito Lagoon, the scars were naturally recolonized. Erosion was a problem in both experiments, but despite bioturbation from rays and additional boat scarring, 40% of all experimental scars returned to greater than 50% *H. wrightii* cover after 1 year. I agree with Engeman et al. (2008) that more resources should focus on the prevention of scarring seagrass beds than which restoration methods would work best, especially for Mosquito Lagoon where there are thousands of hectares of healthy seagrass beds to recolonize scarred areas. Enhanced vigilance is required from users, managers, and enforcers to protect the seagrass beds that are critical to the biodiversity of Mosquito Lagoon and the IRL. Surely, prevention is the best way to preserve our seagrass beds and the associated biodiversity for the future.

APPENDIX A:

LIST OF FIGURES

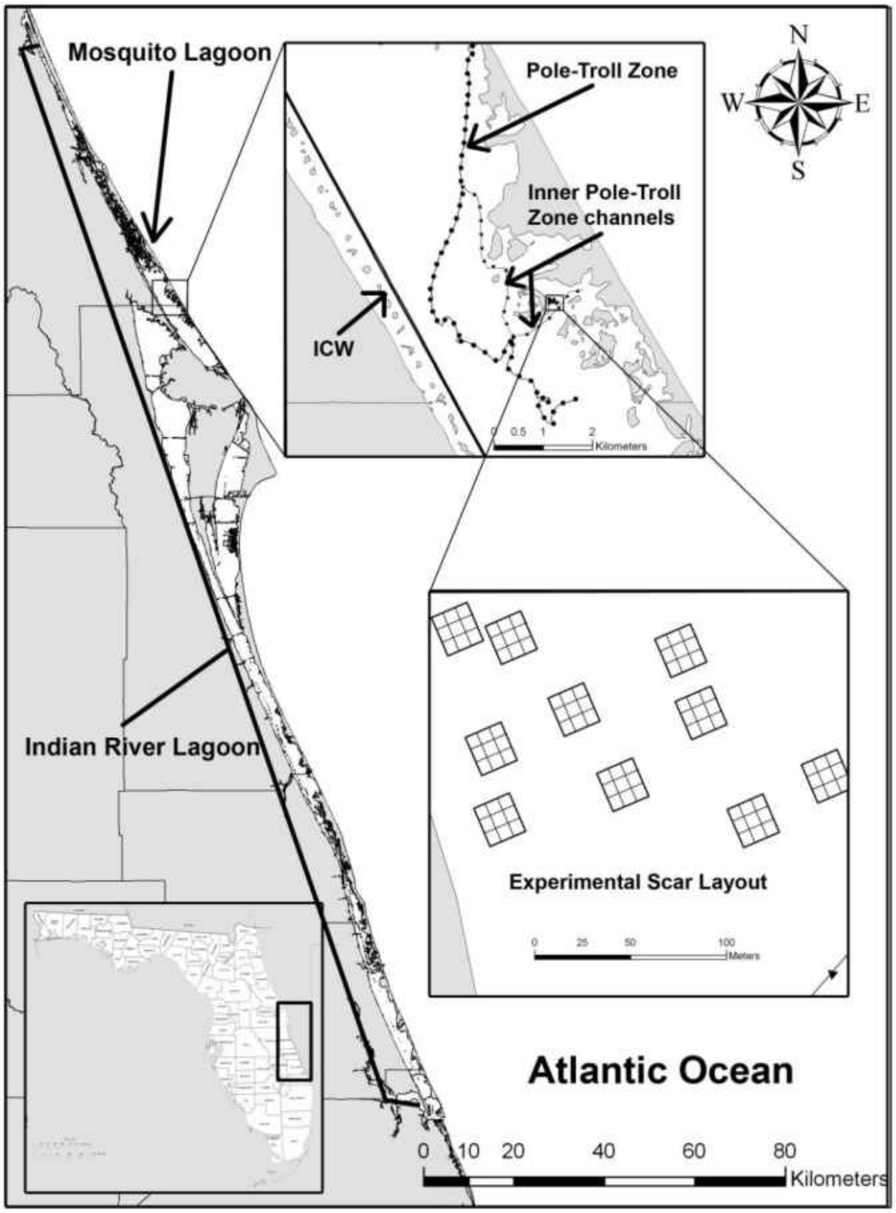

Figure 1: Map of experimental scar locations in the Pole-Troll Zone of Mosquito Lagoon, Florida. Boundary of the Pole-Troll Zone is marked by a dotted line with black circles. Channels include: the Atlantic Intercoastal Waterway (ICW) as a solid black line, and the inner Pole-Troll Zone channels are dotted lines within the Pole-Troll Zone boundaries.

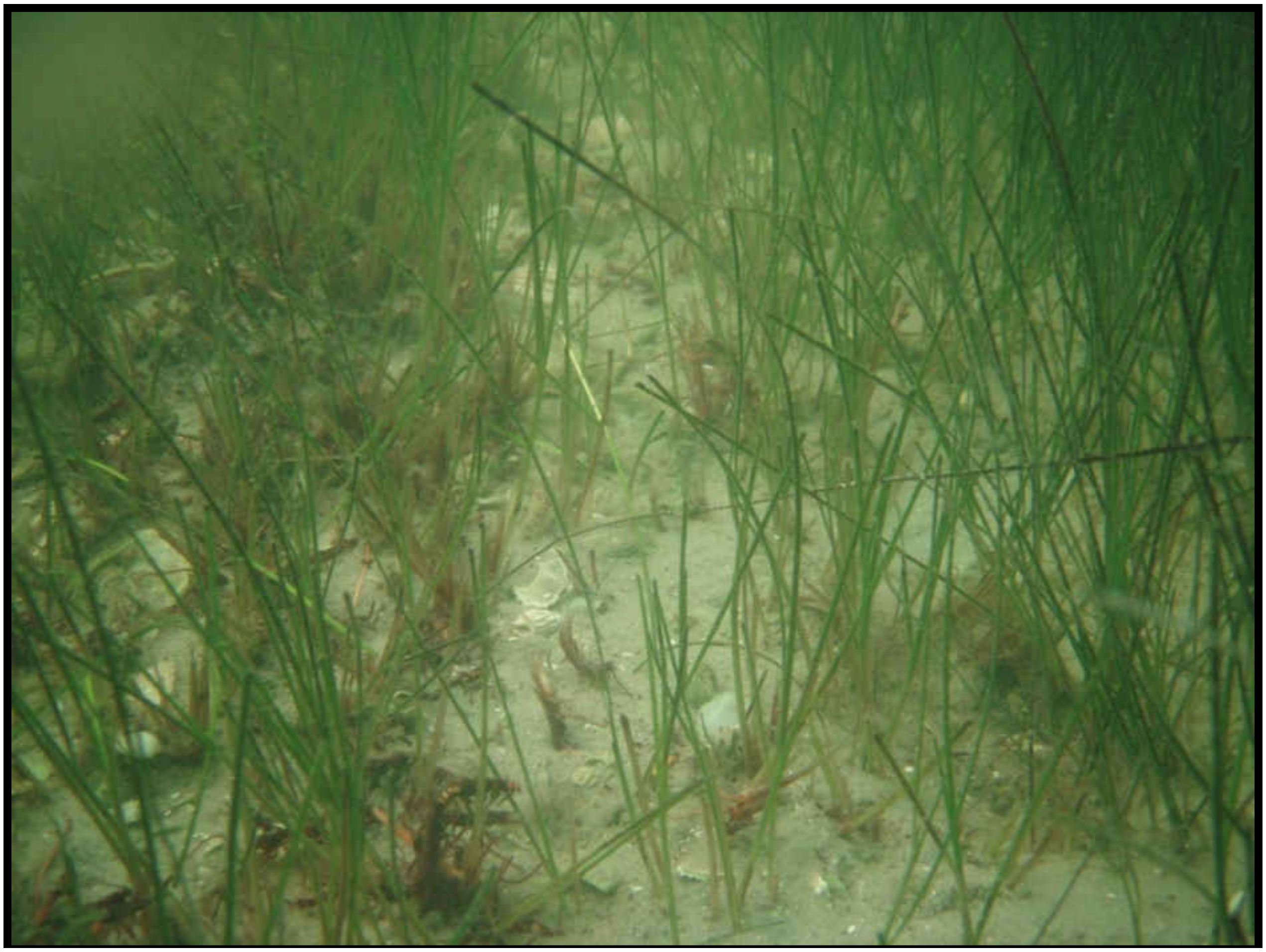

Figure 2: *Halodule wrightii* seagrass bed in Mosquito Lagoon, FL.

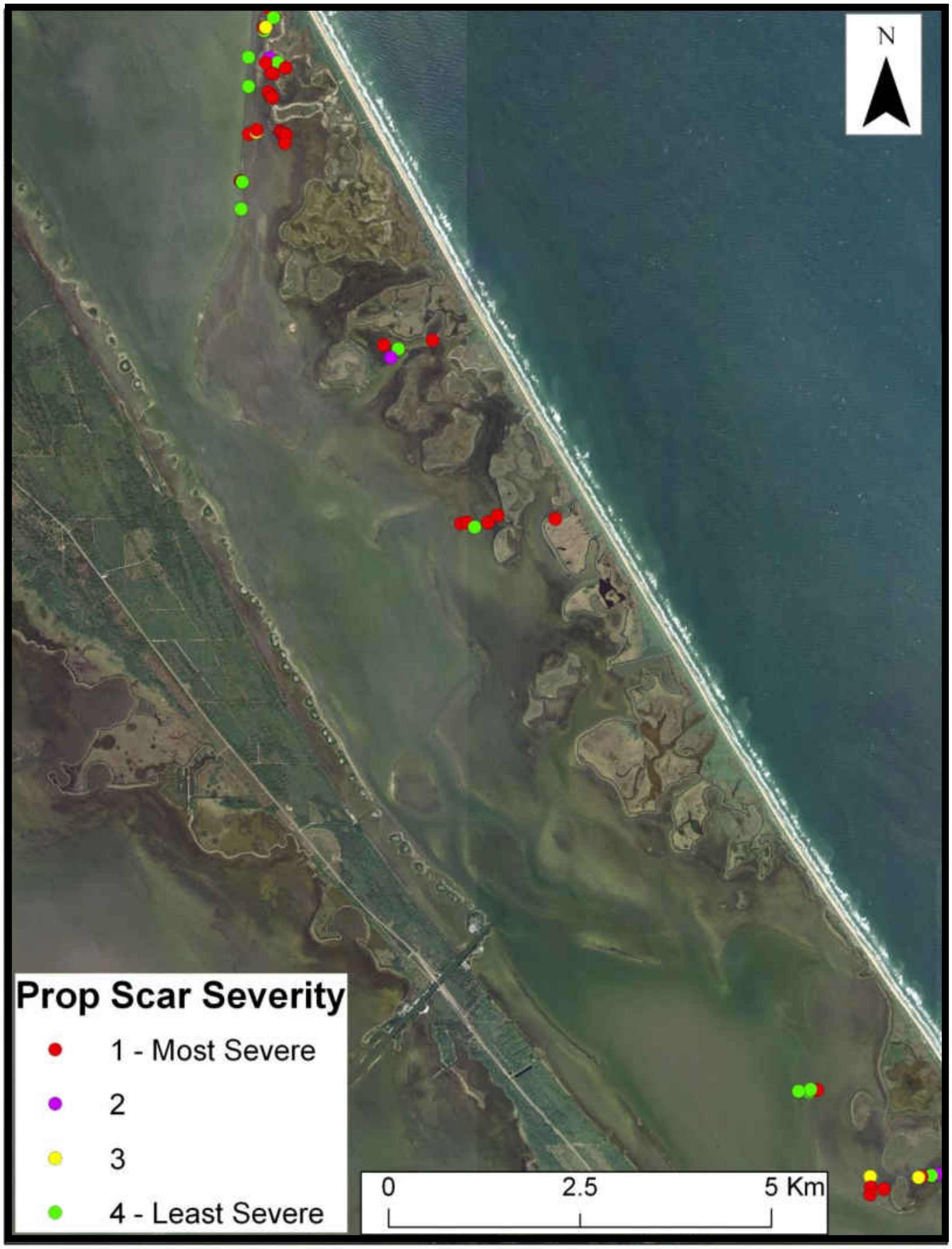

Figure 3: Location of 110 propeller scars measured in Mosquito Lagoon, FL. Scar type is color coded to show the frequency of each scar type. From this view, the entire range of measured scars is demonstrated, however not all scars can be seen due to overlap.

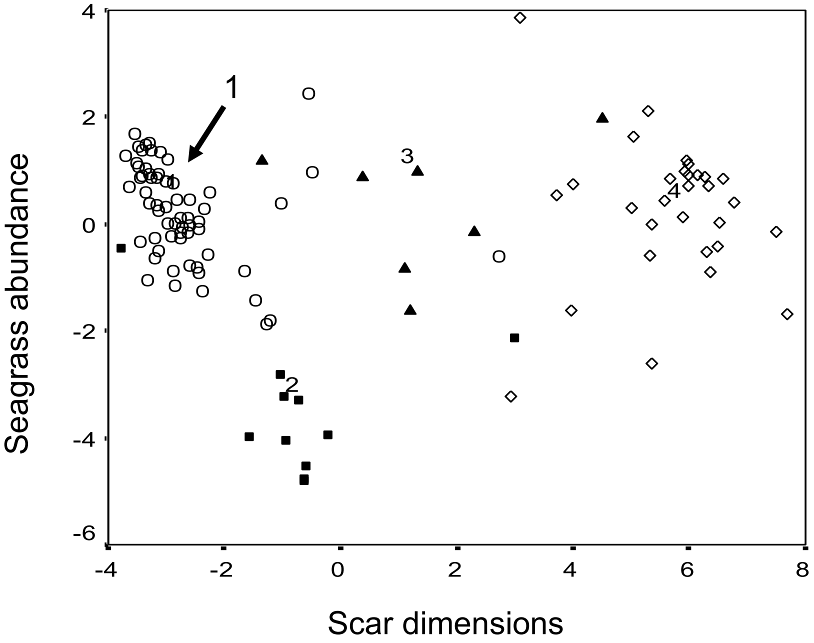

Figure 4: Canonical Discriminant Analysis classification of 110 propeller scars in Mosquito Lagoon. Scars were sorted into four groups. Type 1 scars are white circles, Type 2 scars are black squares, Type 3 scars are black triangles, and Type 4 scars are white diamonds.

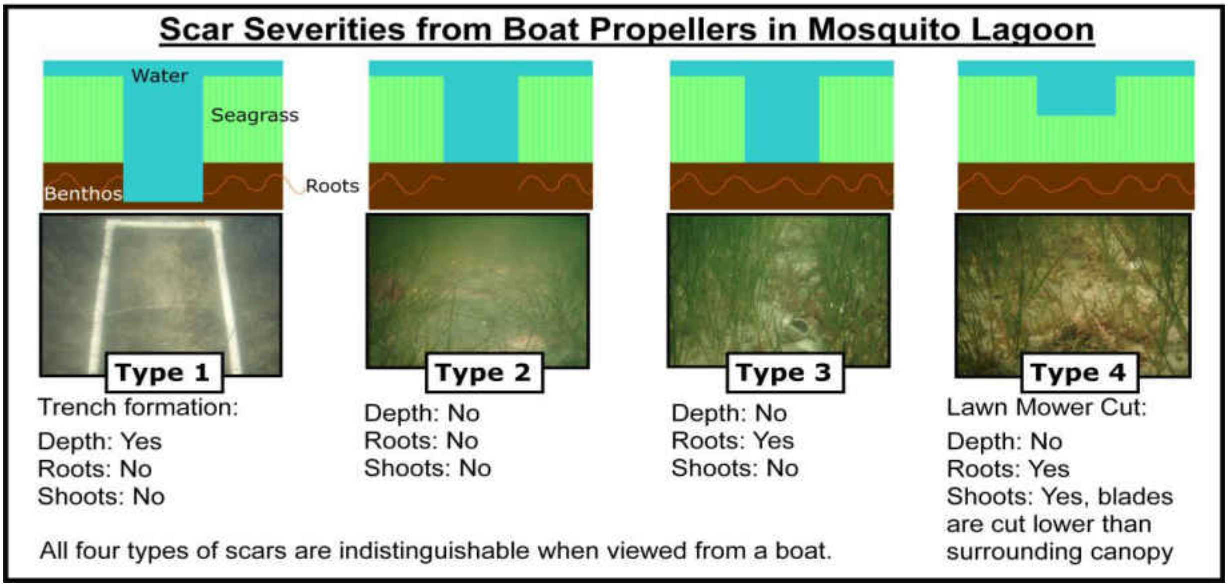

Figure 5: Scar types identified from measuring 110 scars in Mosquito Lagoon. Above diagram simplifies what was seen in each of the photographs below.

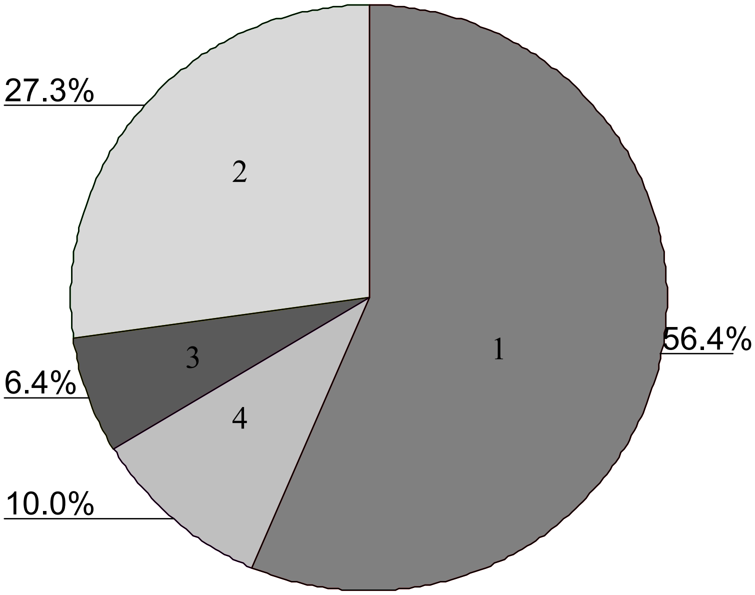

Figure 6: Frequency of scar types in Mosquito Lagoon (n = 110).

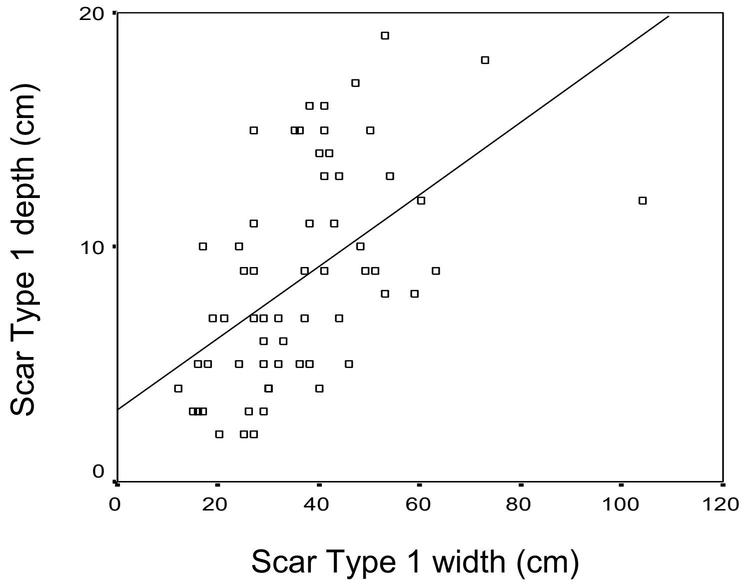

Figure 7: Regression of Type 1 scar width versus scar depth. Scar Type 1 was used to show the best correlation ($r^2 = 0.476$, $p < 0.001$), because other scar types (2-4) did not have depth.

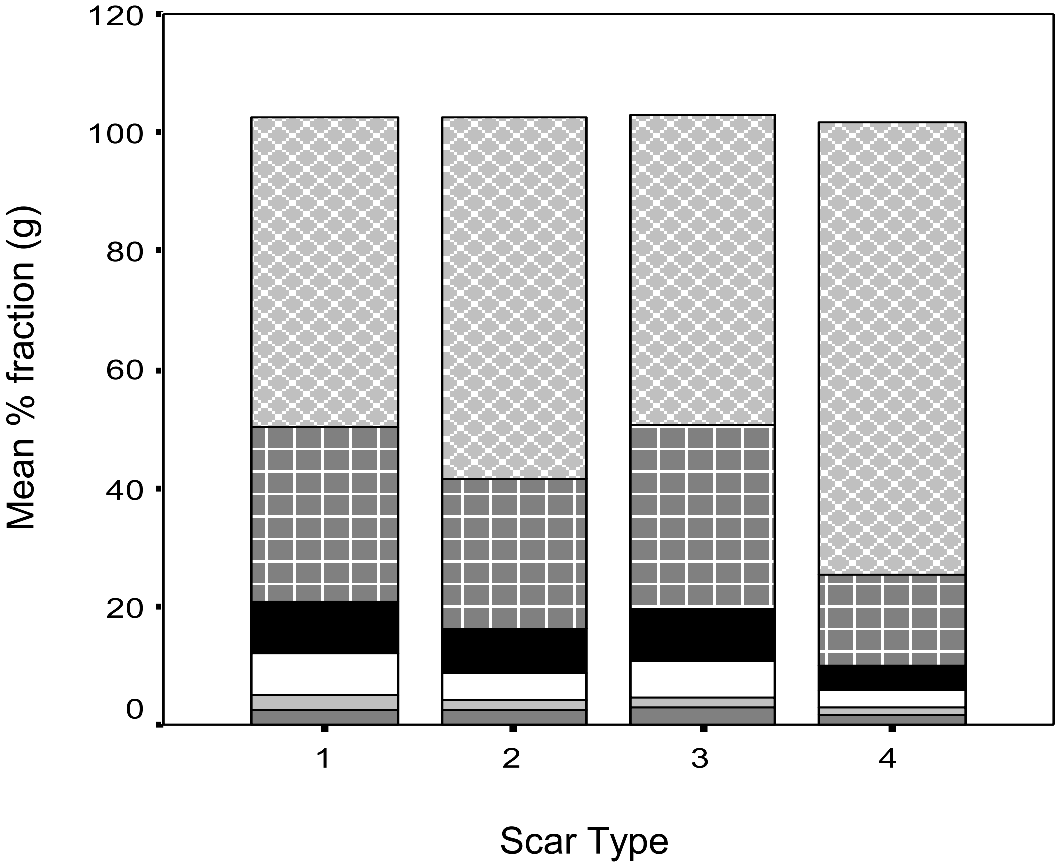

Figure 8: Mean percent of sediment grain size fractions and organic content per scar type. Percent sediment fraction sizes are listed in order < 1mm is light grey cross hatch, 1 mm is dark grey cross hatch, 2 mm is solid black, 5 mm is solid white, > 5mm is solid light grey, and percent organic content is solid dark grey. Using a one-way ANOVA, only scar Type 1 and 4 were significantly different in all fraction sizes, and size < 1mm showed the greatest difference.

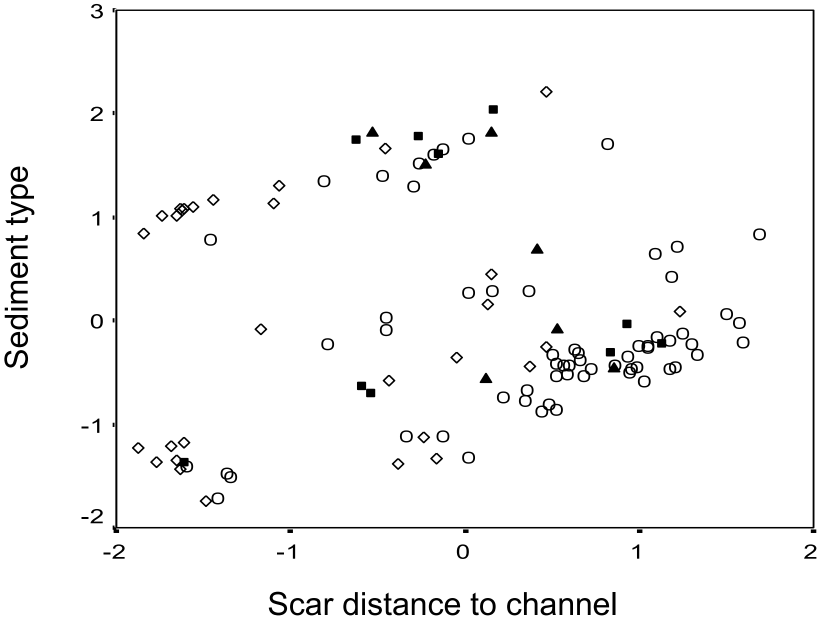

Figure 9: Canonical Discriminant Analysis classification of 110 propeller scars sediment fractions and distance measurements. Type 1 scars are white circles, Type 2 scars are black squares, Type 3 scars are black triangles, and Type 4 scars are white diamonds. Sediment types did not show a pattern in relation to distance.

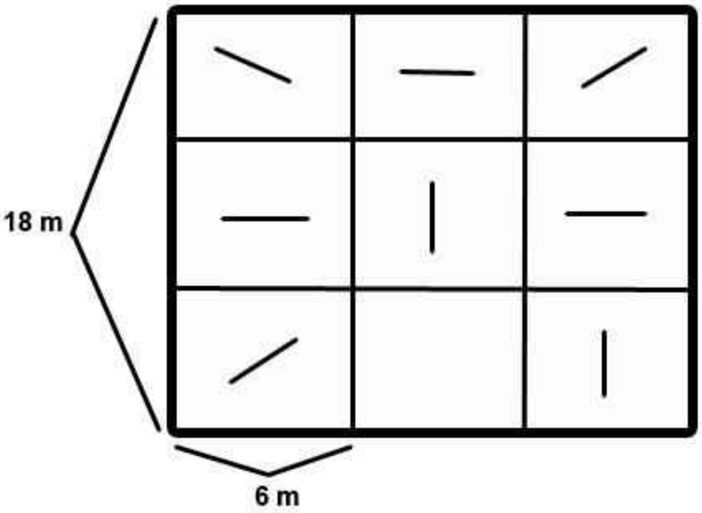

Figure 10: Layout of one block of experimental scars. Each block was 18 x18 m and was divided into 9 squares, of which only 8 had a scar treatment. A square was 6 x 6 m containing a single scar treatment in the center.

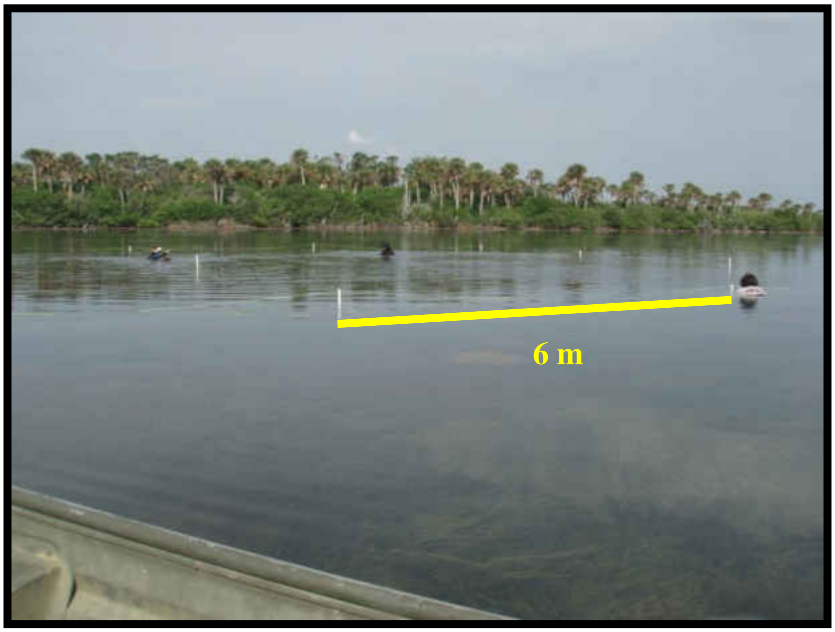

Figure 11: Setup of a one set of treatments in a large grid (block). An 18 x 18 m perimeter was marked off with yellow rope, and a PVC pole was placed every 6 m. Scars were created in the center of each 6 x 6 m square and marked with a short PVC pole at each end. All PVC grid poles were marked with a GPS location and then removed. After the scars were created, only the 2 PVC scar markers remained to mark the ends of each scar.

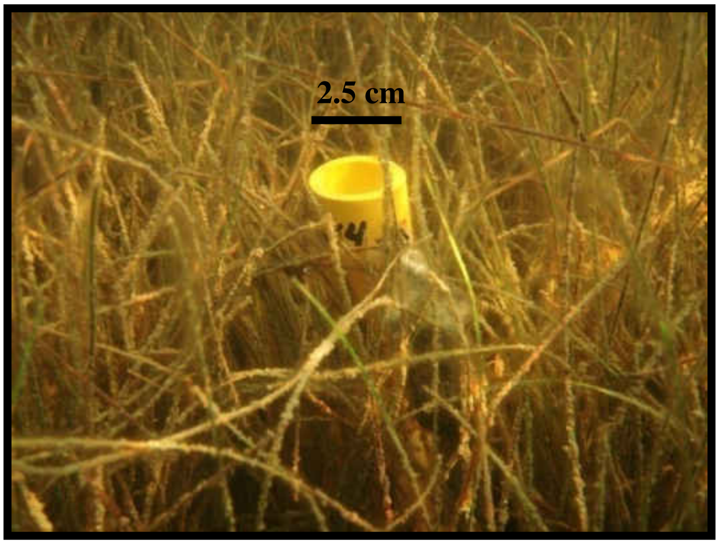

Figure 12: PVC stake marking the end of an experimental scar.

Figure 13: PVC plow 32 cm in diameter. Device used to make experimental propeller scars the same width, depth, and scar slope angle.

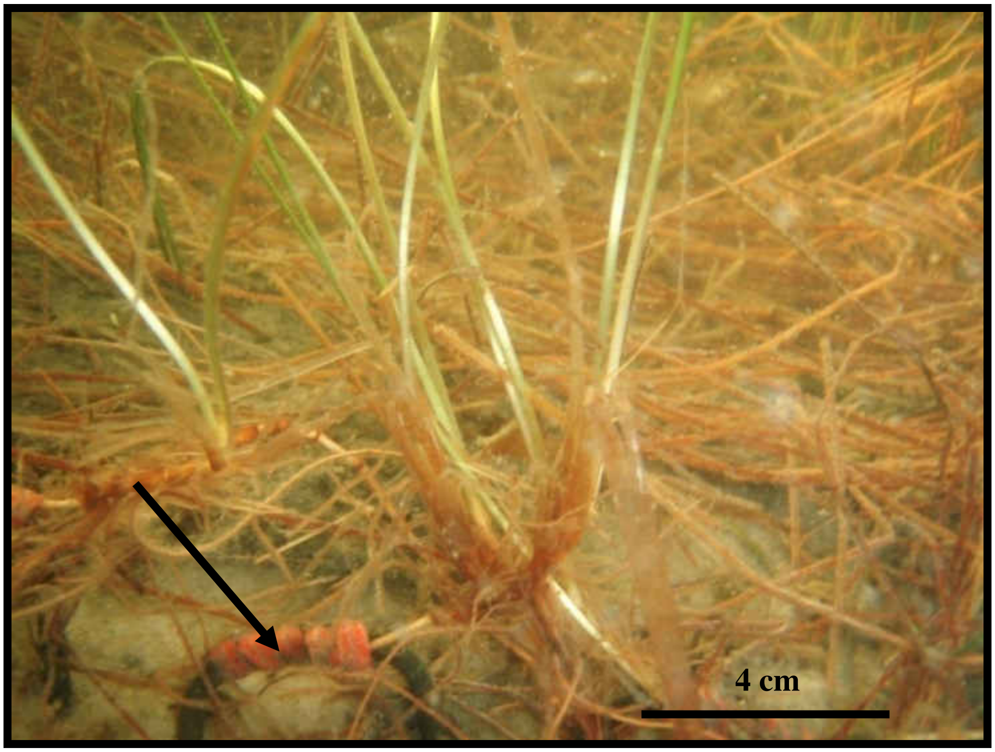

Figure 14: Arrow points to *H. wrightii* attached to garden staple with a twist tie in a scar filled with sand. This is an eroded staple, making it is easier to see how *H. wrightii* was attached with a red twist tie.

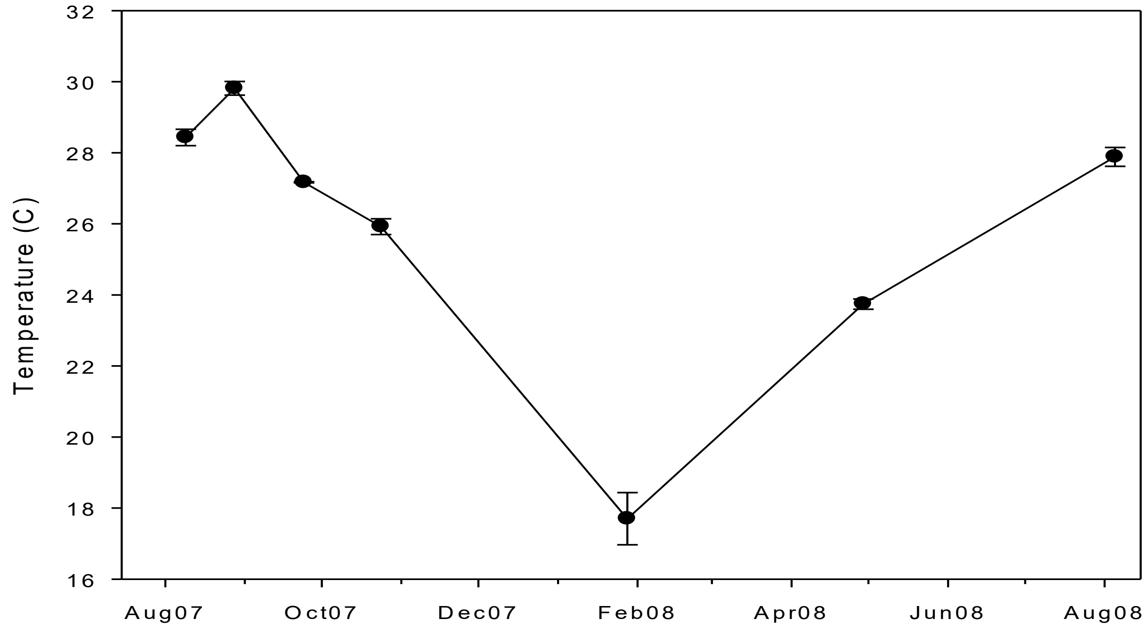

Figure 15: Mean water temperature on sampling dates (± S.E.) at location of manipulative experiments (n = 3).

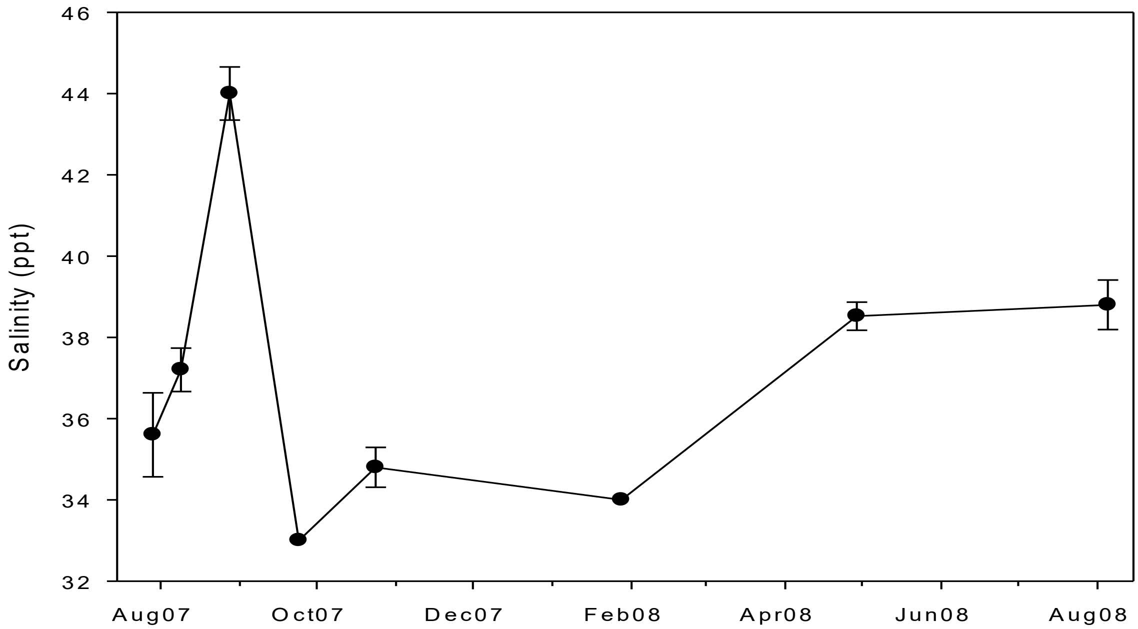

Figure 16: Mean salinity (± S.E.) at location of manipulative experiments on sampling dates (n = 3).

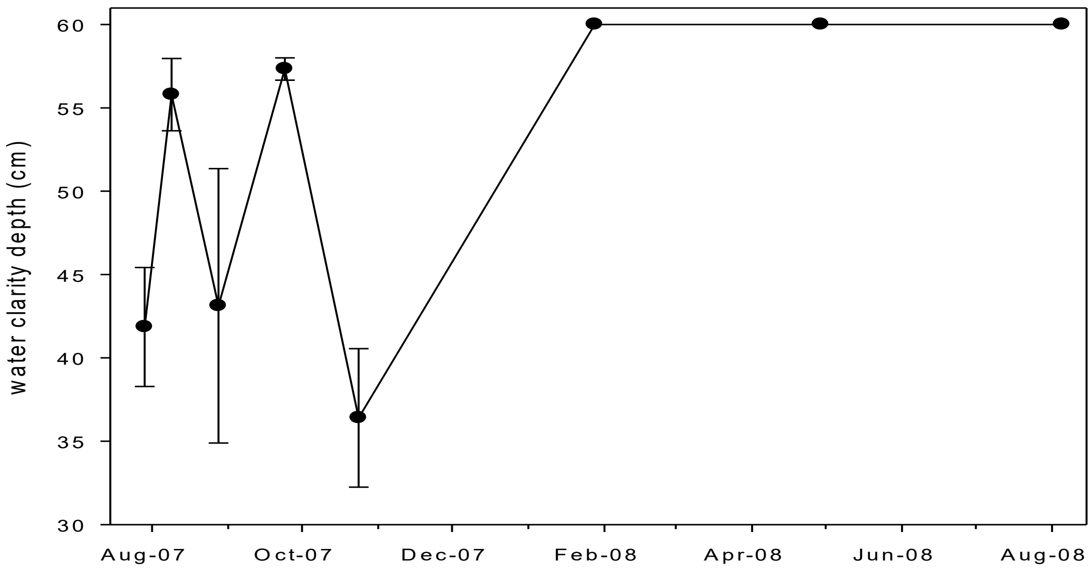

Figure 17: Mean water clarity depth (± S.E.) at location of manipulative experiments on sampling dates (n = 3). Maximum measurement possible using turbitdity tube was 60 cm.

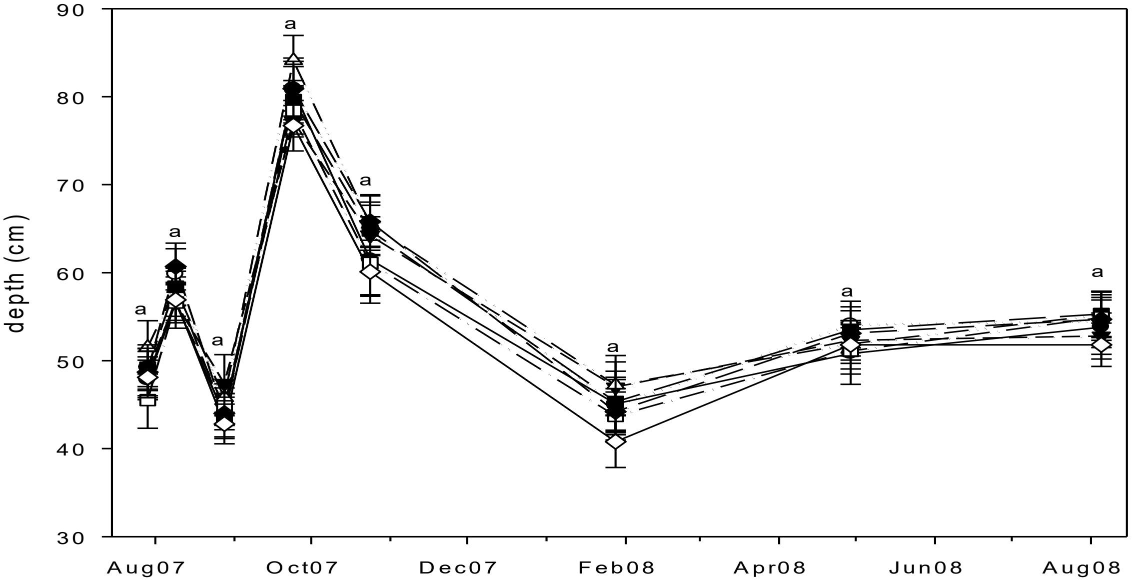

Figure 18: Mean water depth (± S.E.) of experimental scar locations of manipulative experiments (n = 10). Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

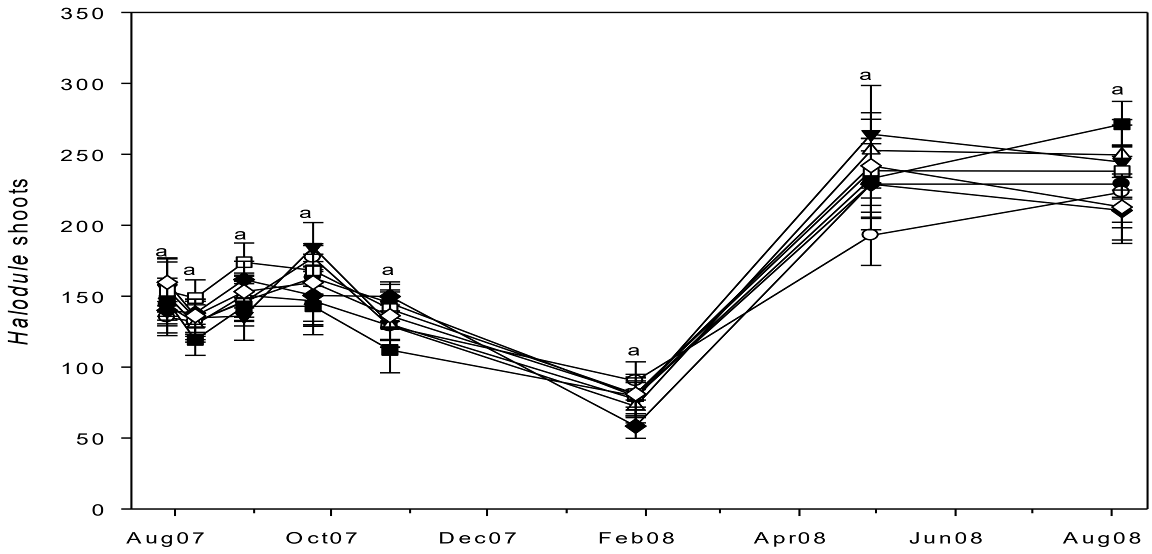

Figure 19: Mean surrounding scar *H. wrightii* density (± S.E.) per 25 x 25 cm area in experimental scar replicate blocks. Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

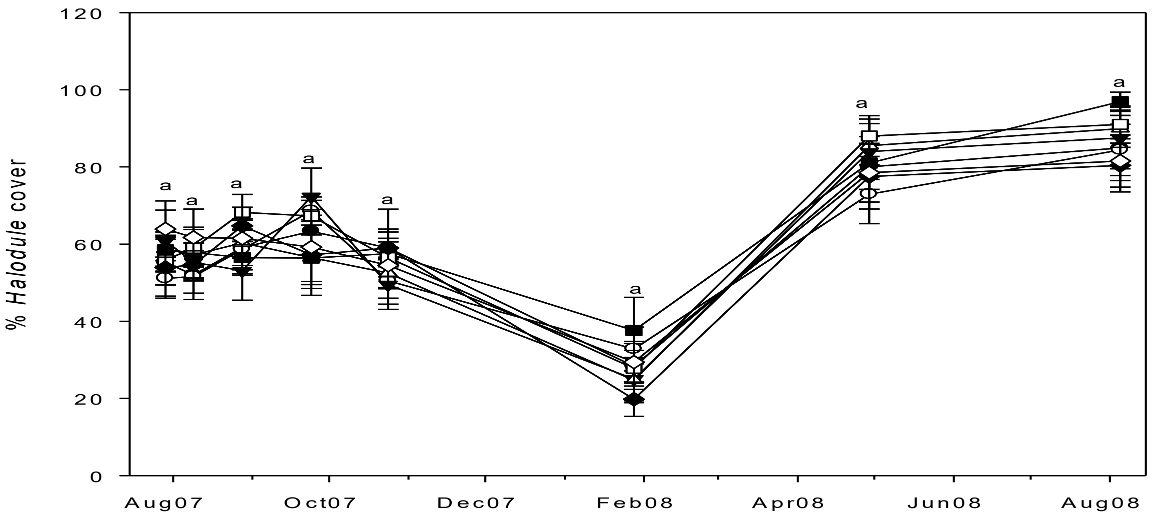

Figure 20: Mean surrounding scar *H. wrightii* percent cover (± S.E.) per 25 x 25 cm area in experimental scar replicate blocks. Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

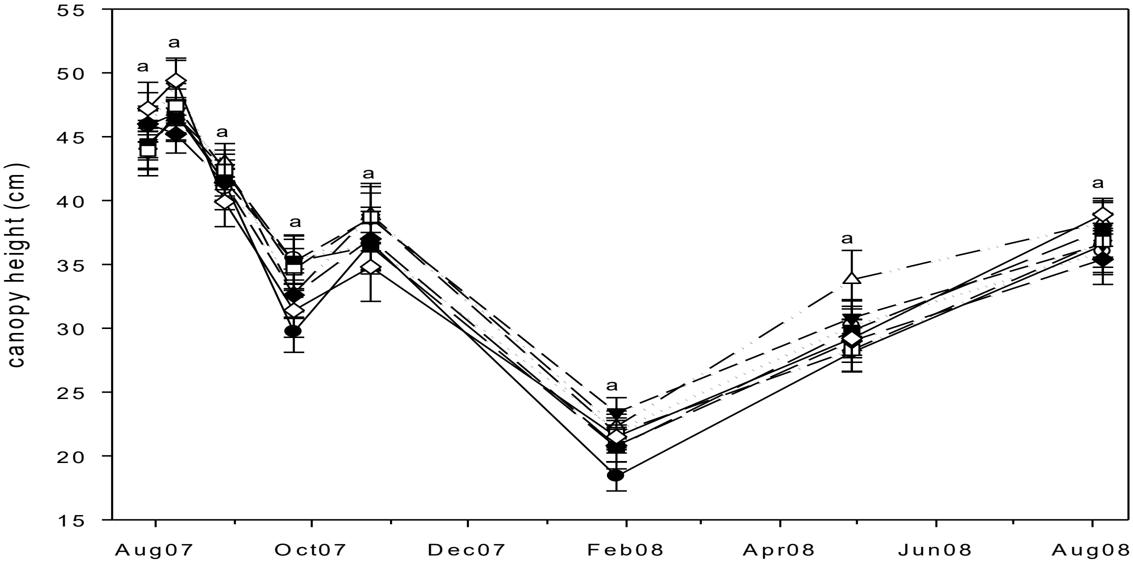

Figure 21: Mean surrounding scar *H. wrightii* canopy height (± S.E.) in experimental scar replicate blocks. Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

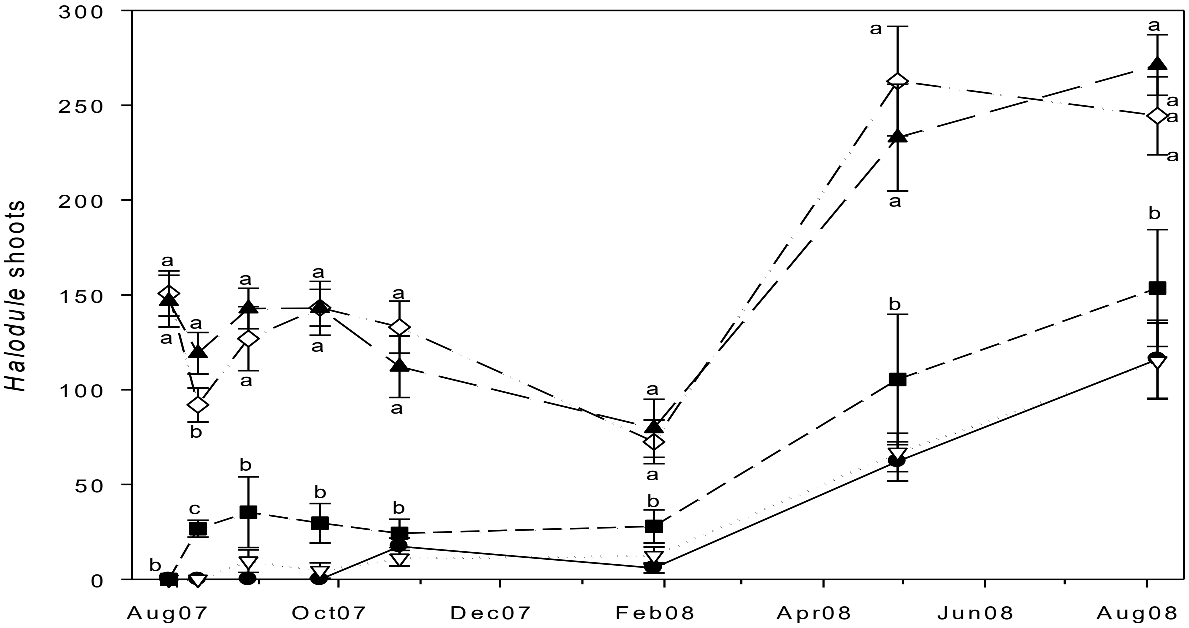

Figure 22: Natural recovery experimental scar *H. wrightii* shoot density per 25 x 25 cm area (± S.E). Type 1 are black circles, Type 2 are white triangles, Type 3 are black squares, Type 4 are white diamonds, and control are black triangles. Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

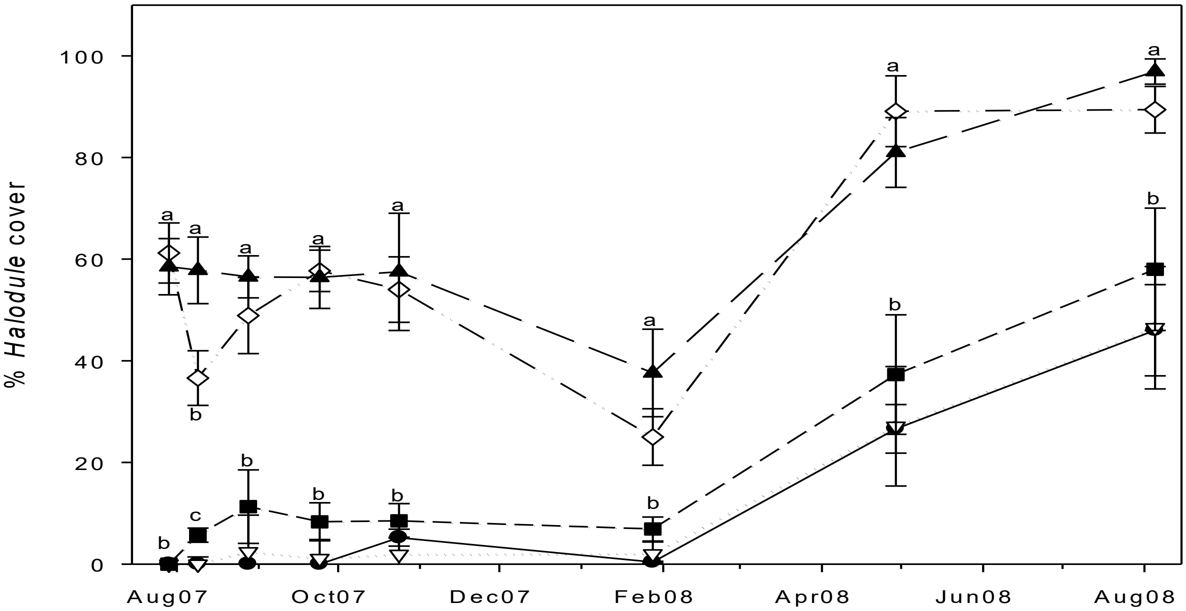

Figure 23: Natural recovery experimental scar *H. wrightii* percent cover per 25 x 25 cm area (± S.E). Type 1 are black circles, Type 2 are white triangles, Type 3 are black squares, Type 4 are white diamonds, and control are black triangles. Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

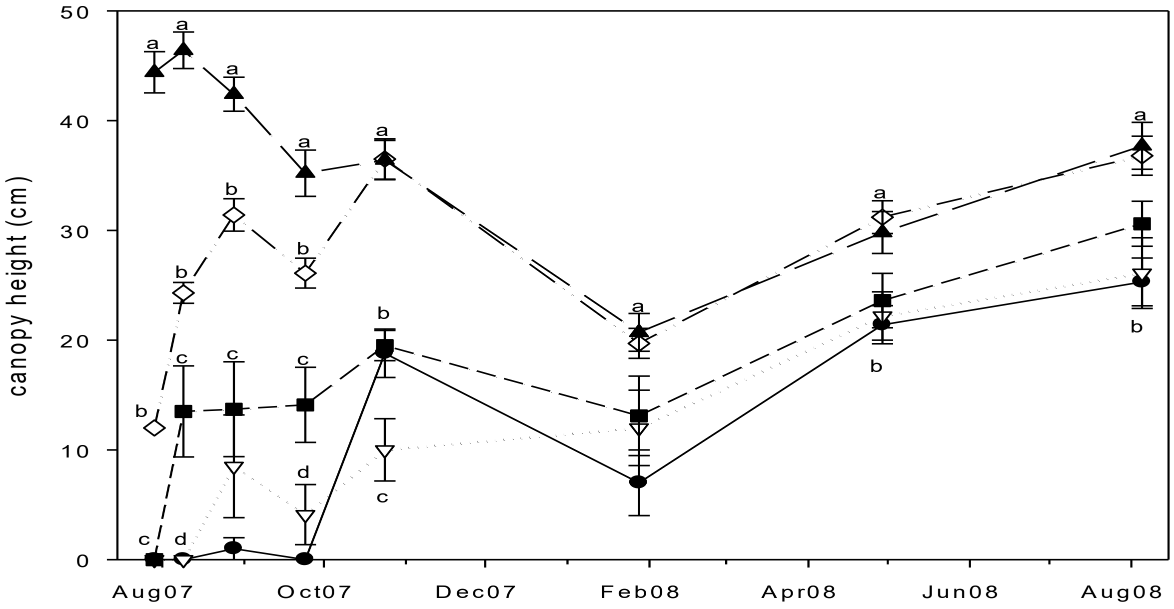

Figure 24: Natural recovery experimental scar *H. wrightii* canopy height (± S.E). Type 1 are black circles, Type 2 are white triangles, Type 3 are black squares, Type 4 are white diamonds, and control are black triangles. Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

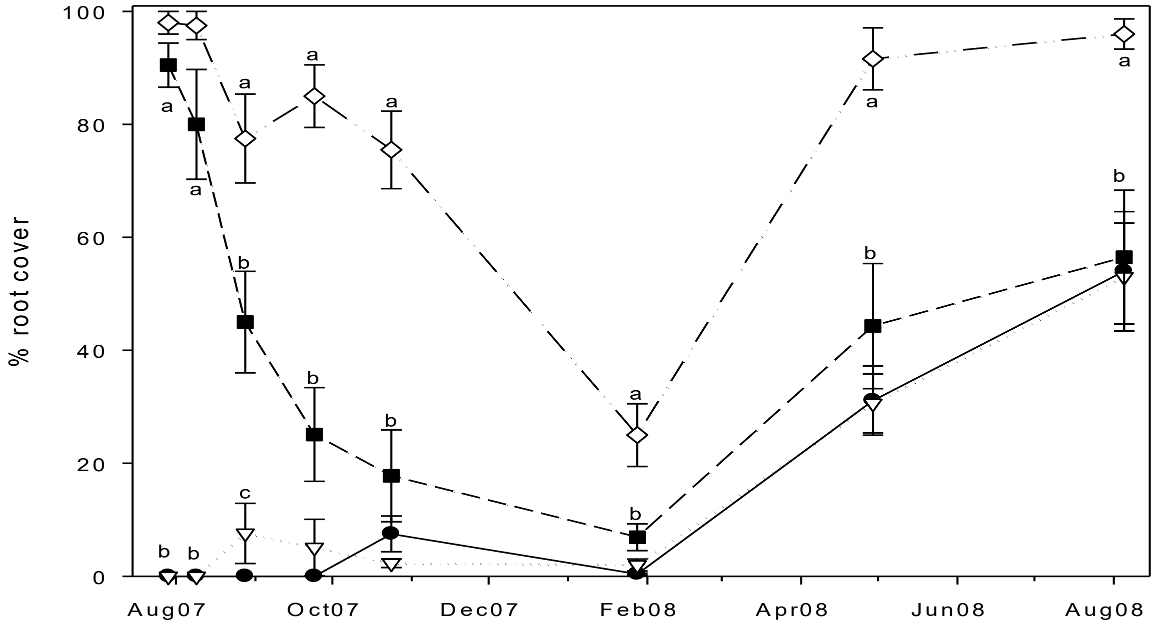

Figure 25: Natural recovery experimental scar percent root cover per 25 x 25 cm area (± S.E). Type 1 are black circles, Type 2 are white triangles, Type 3 are black squares, and Type 4 are white diamonds. Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

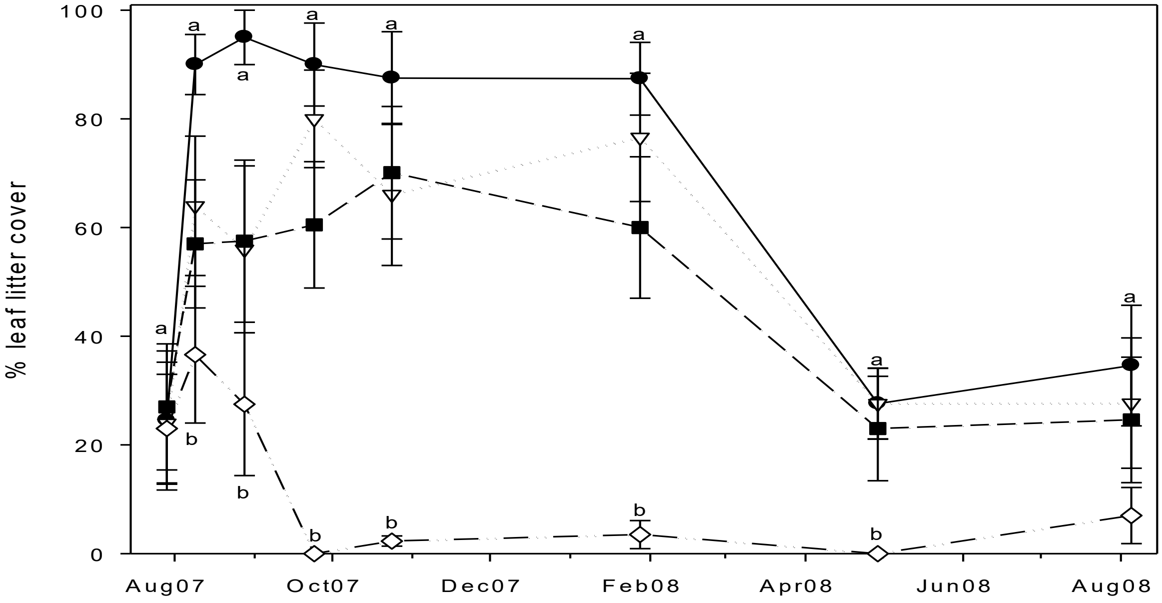

Figure 26: Natural recovery experimental scar percent leaf litter cover per 25 x 25 cm area (± S.E). Type 1 are black circles, Type 2 are white triangles, Type 3 are black squares, and Type 4 are white diamonds. Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

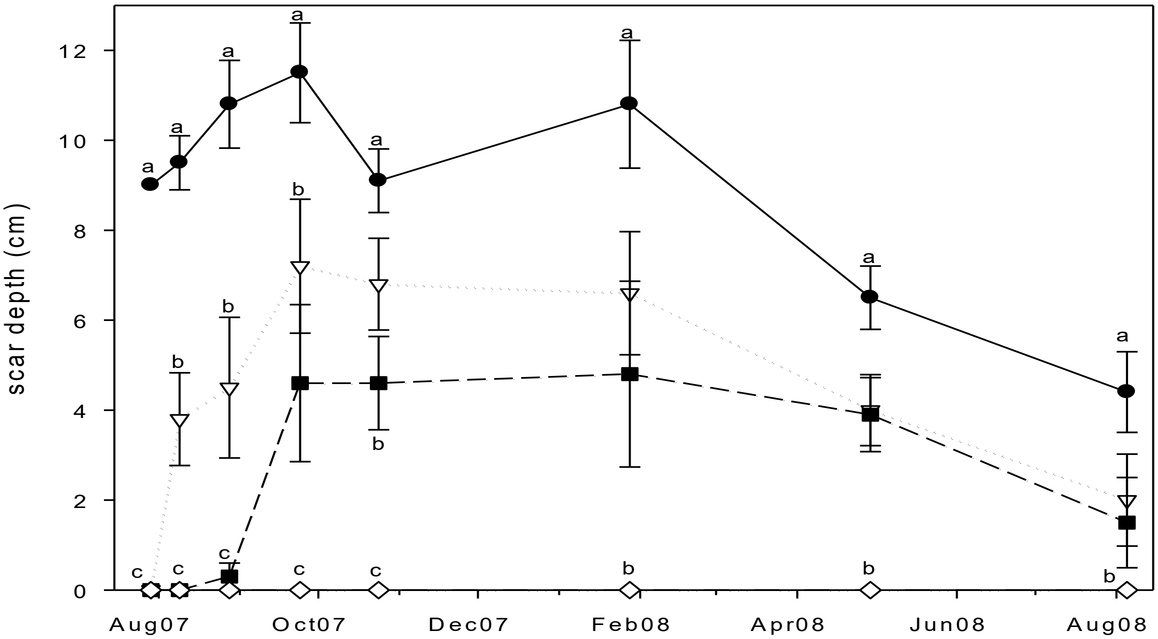

Figure 27: Natural recovery experimental scar depth (± S.E). Type 1 are black circles, Type 2 are white triangles, Type 3 are black squares, and Type 4 are white diamonds. Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

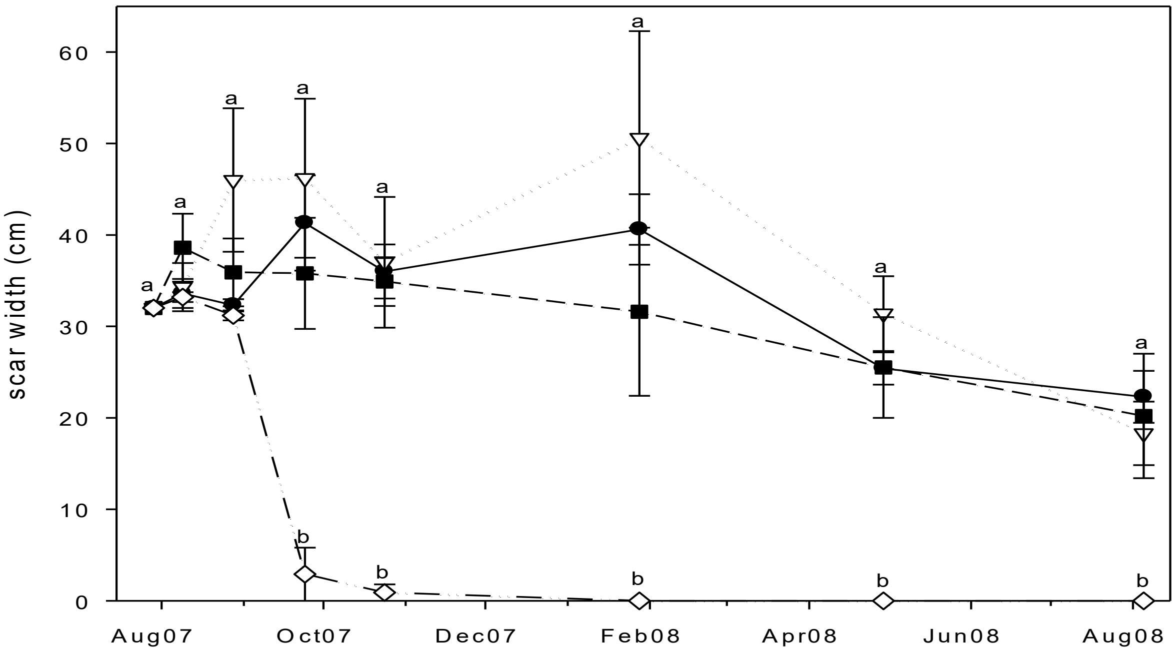

Figure 28: Natural recovery experimental scar width (± S.E). Type 1 are black circles, Type 2 are white triangles, Type 3 are black squares, and Type 4 are white diamonds. Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

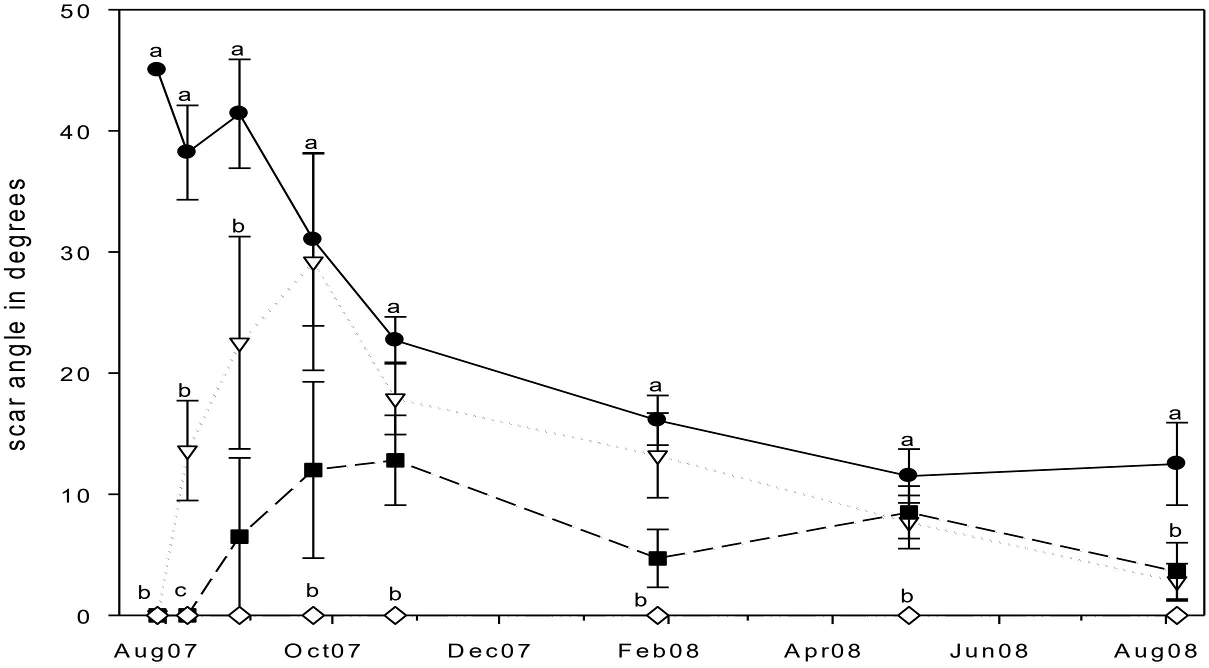

Figure 29: Natural recovery experimental scar slope angle density (± S.E). Type 1 are black circles, Type 2 are white triangles, Type 3 are black squares, and Type 4 are white diamonds. Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

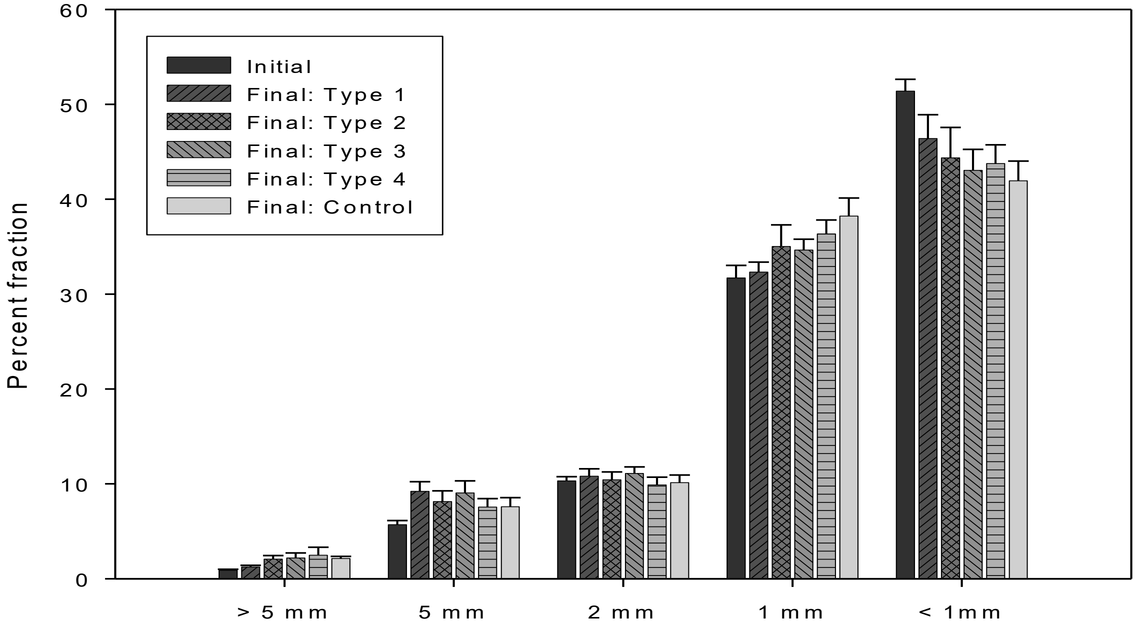

Figure 30: Natural recovery experiment mean percent sediment fractions (± S.E.) from before scar creation and from within scars after 1 year (Kruskal-Wallis: $p < 0.05$). Bar sections are labeled in order from left to right: initial, Type 1 (final), Type 2 (final), Type 3 (final), Type 4 (final), and control (final).

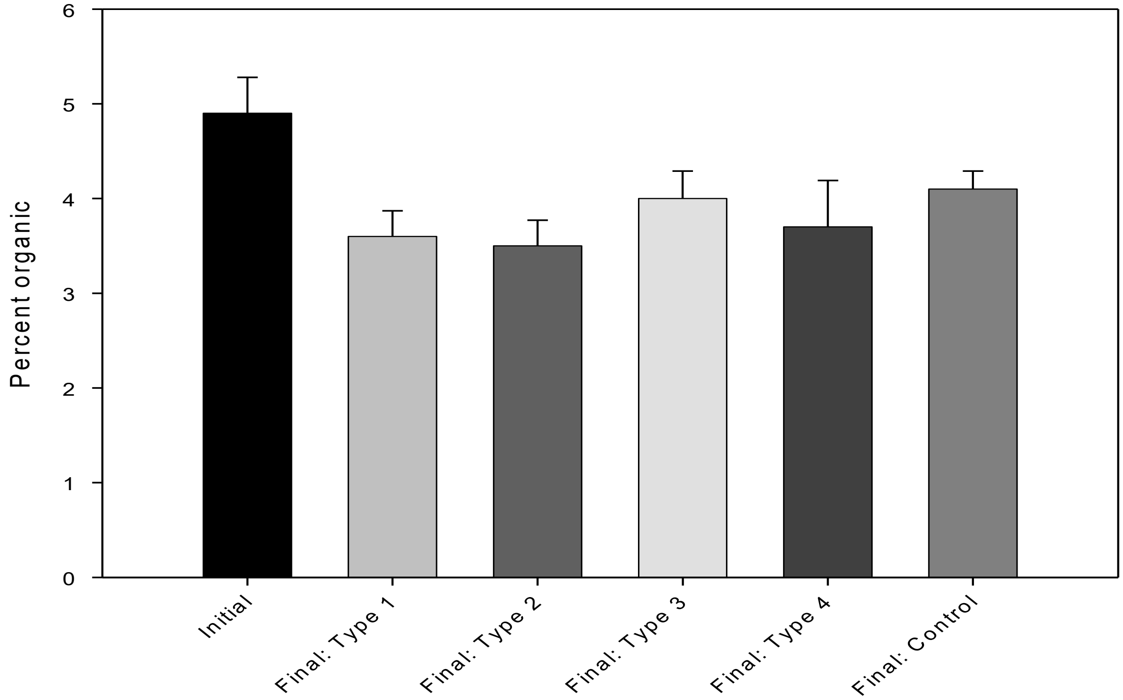

Figure 31: Natural recovery experiment mean percent organic content (± S.E) from before scar creation and from within scars after 1 year (Kruskal-Wallis: $p < 0.05$).

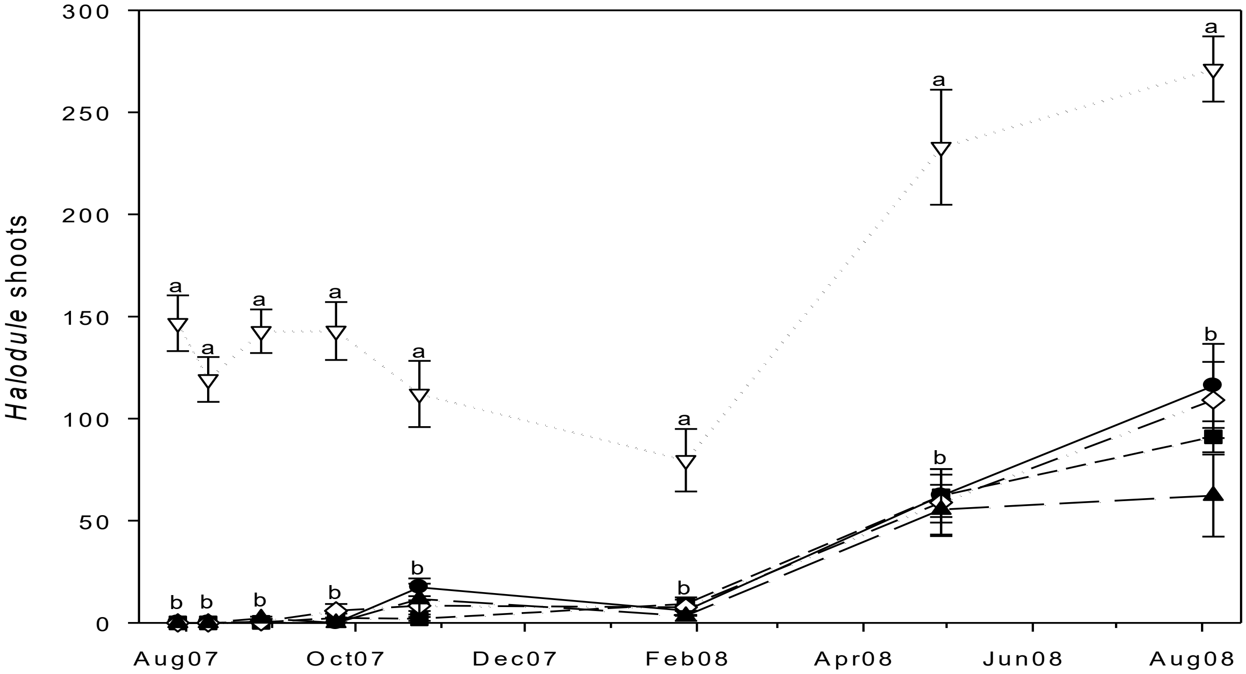

Figure 32: Restoration experimental scar *H. wrightii* density shoot density per 25 x 25 cm (± S.E). Controls are white triangles, Type 1 are black circles, plant-only are black squares, fill only are white diamonds, and plant and fill are black triangles. Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

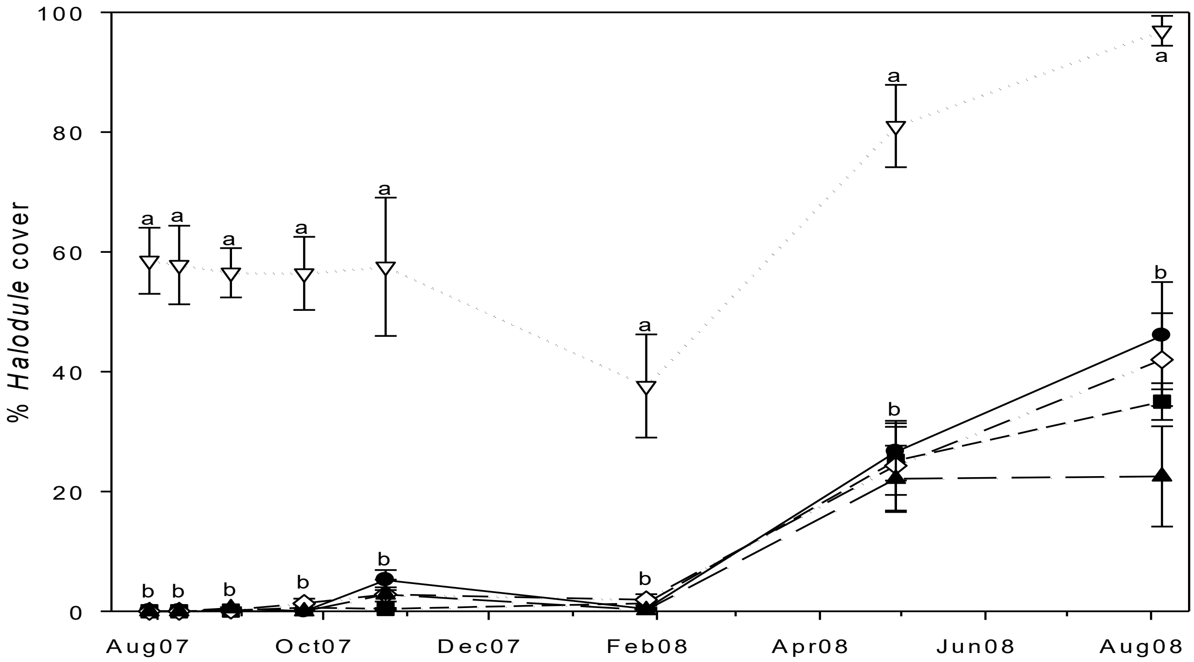

Figure 33: Restoration experimental scar *H. wrightii* percent cover per 25 x 25 cm area (± S.E). Control are white triangles, Type 1 are black circles, plant-only are black squares, fill only are white diamonds, and plant and fill are black triangles. Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

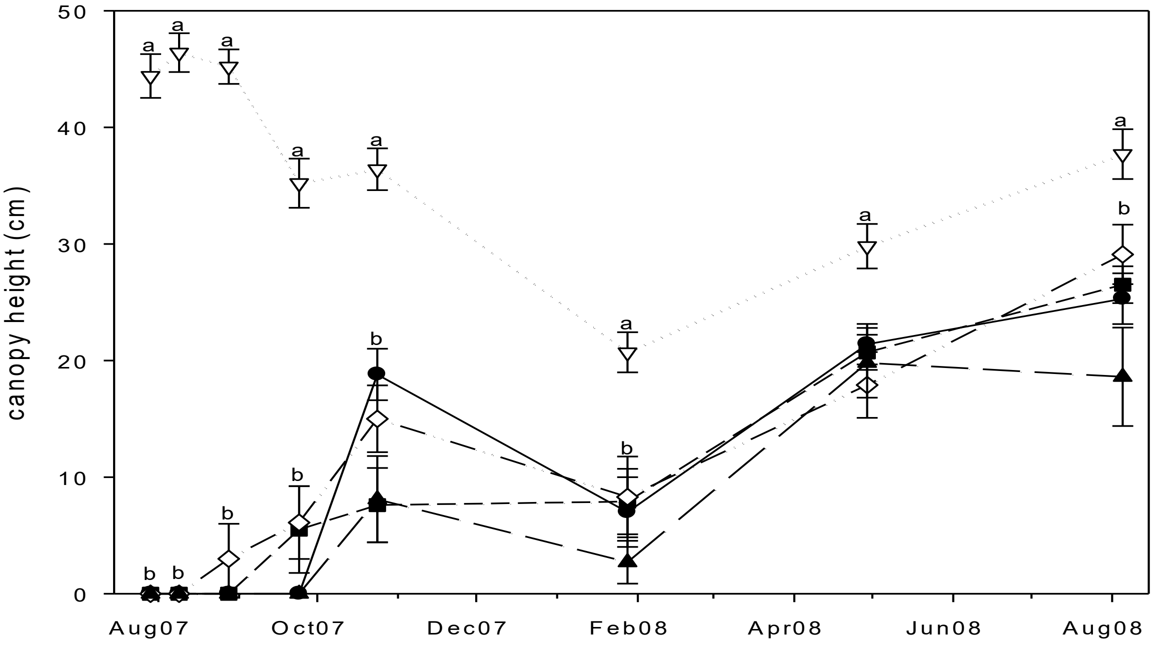

Figure 34: Restoration experimental scar *H. wrightii* canopy height (± S.E). Control are white triangles, Type 1 are black circles, plant-only are black squares, fill only are white diamonds, and plant and fill are black triangles. Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

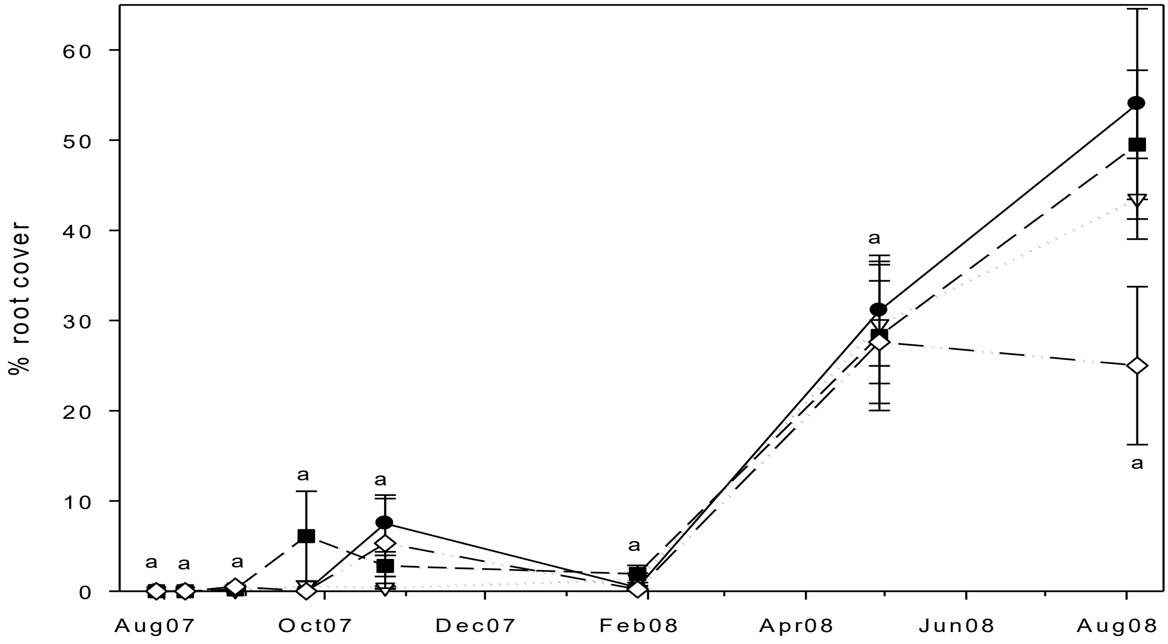

Figure 35: Restoration experimental scar percent root cover per 25 x 25 cm area (± S.E). Type 1 are black circles, plant-only are white triangles, fill only are black squares, and plant and fill are white diamonds. Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

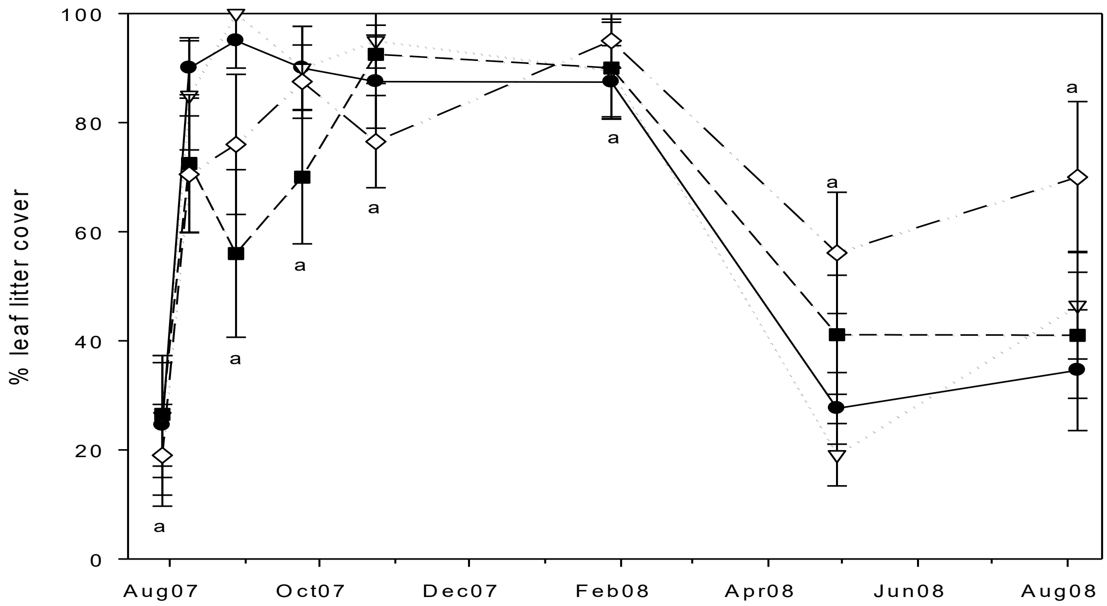

Figure 36: Restoration experimental scar percent leaf litter cover per 25 x 25 cm area (± S.E). Type 1 are black circles, plant-only are white triangles, fill only are black squares, and plant and fill are white diamonds. Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

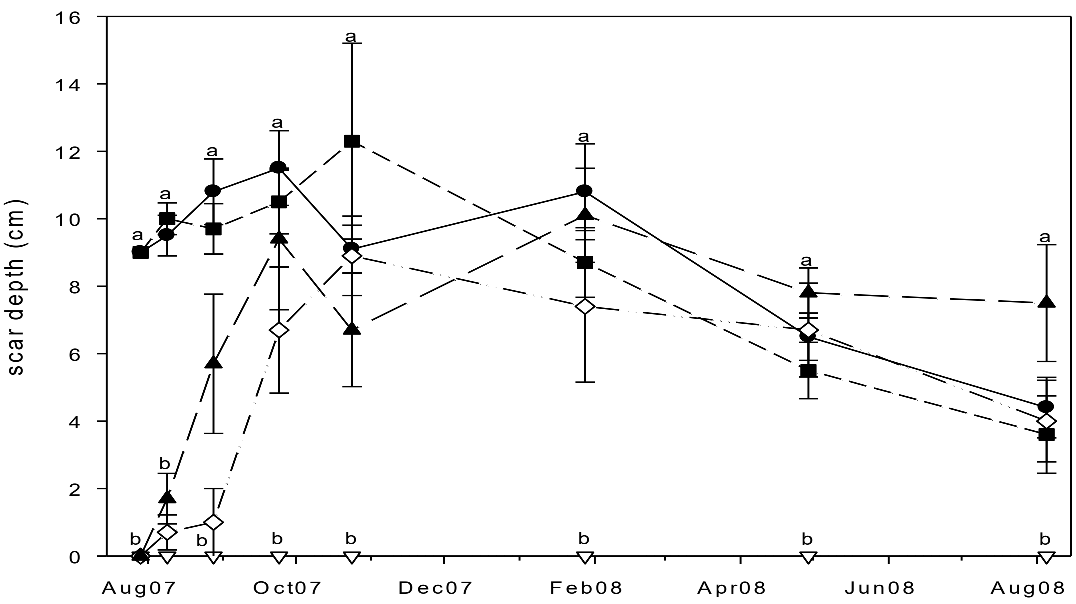

Figure 37: Restoration experimental scar depth (± S.E). Control are white triangles, Type 1 are black circles, plant-only are black squares, fill only are white diamonds, and plant and fill are black triangles. Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

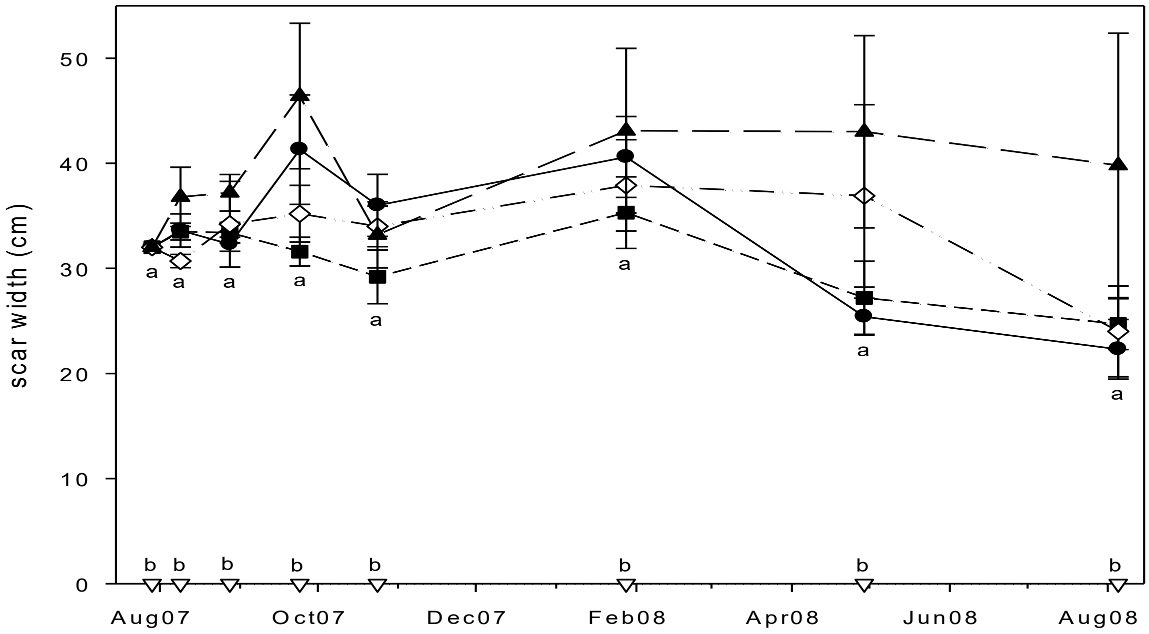

Figure 38: Restoration experimental scar width (± S.E). Control are white triangles, Type 1 are black circles, plant-only are black squares, fill only are white diamonds, and plant and fill are black triangles. Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

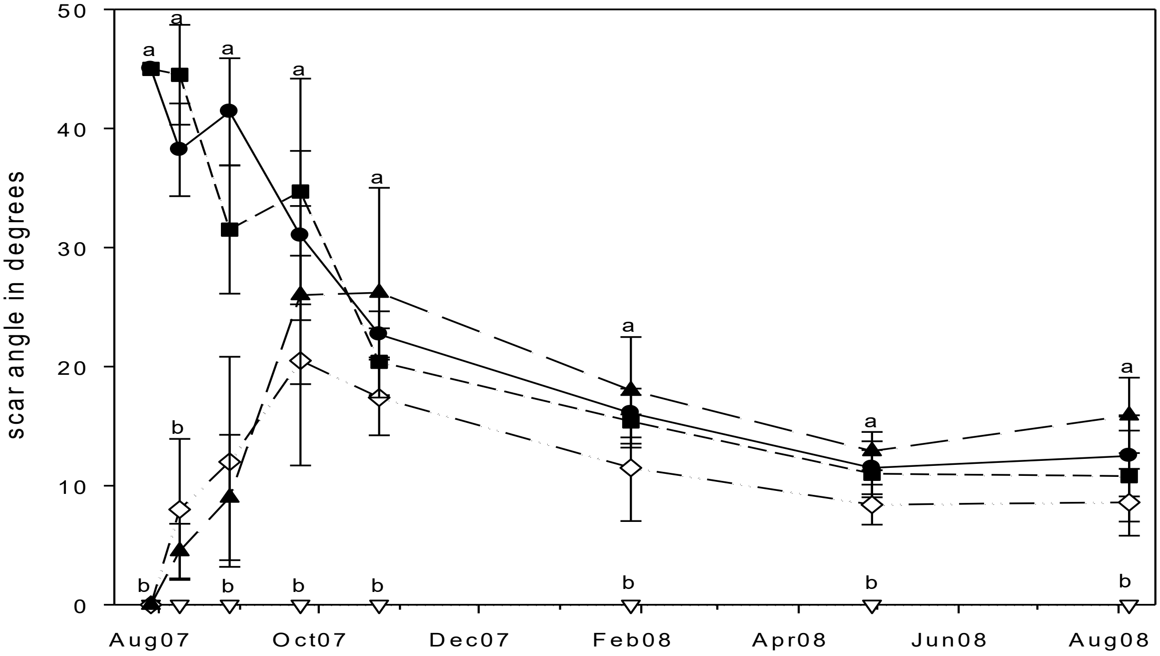

Figure 39: Restoration experimental scar slope angle density (± S.E). Control are white triangles, Type 1 are black circles, plant-only are black squares, fill only are white diamonds, and plant and fill are black triangles. Measurements were analyzed with Kruskal-Wallis rank test with a Bonferroni correction of $p < 0.006$. Treatments that were significantly different on a single day are shown with different letters.

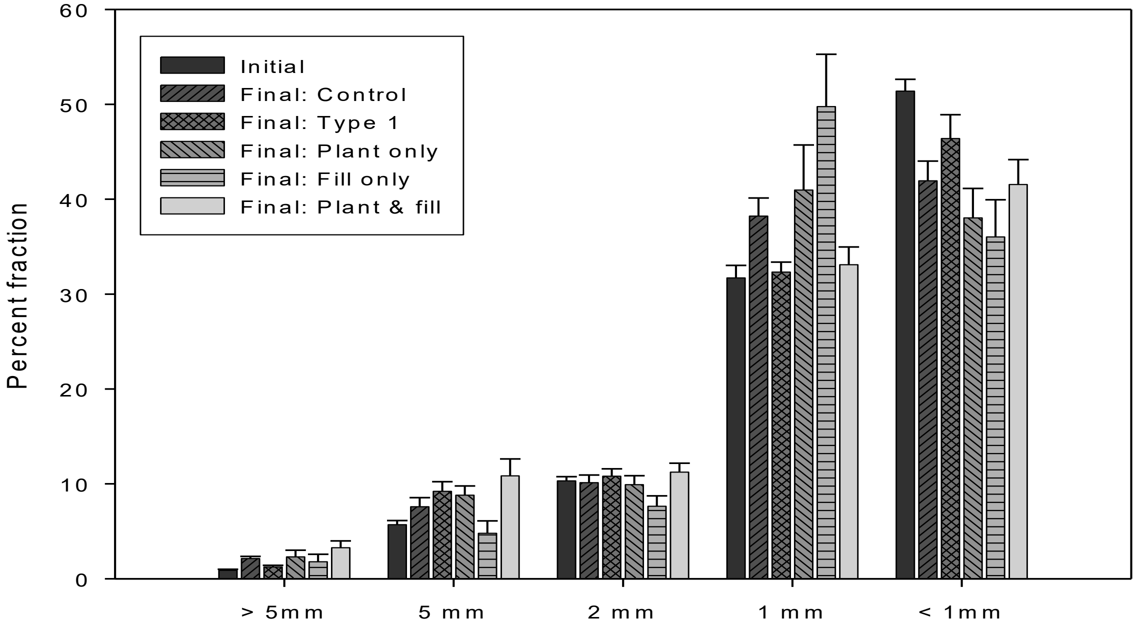

Figure 40: Restoration experiment mean percent sediment fractions (± S.E.) from before scar creation and from within scars after 1 year (Kruskal-Wallis: $p < 0.05$). Bar sections are labeled in order from left to right: initial, control (final), Type 1 (final), plant only (final), fill only (final), and plant and fill (final).

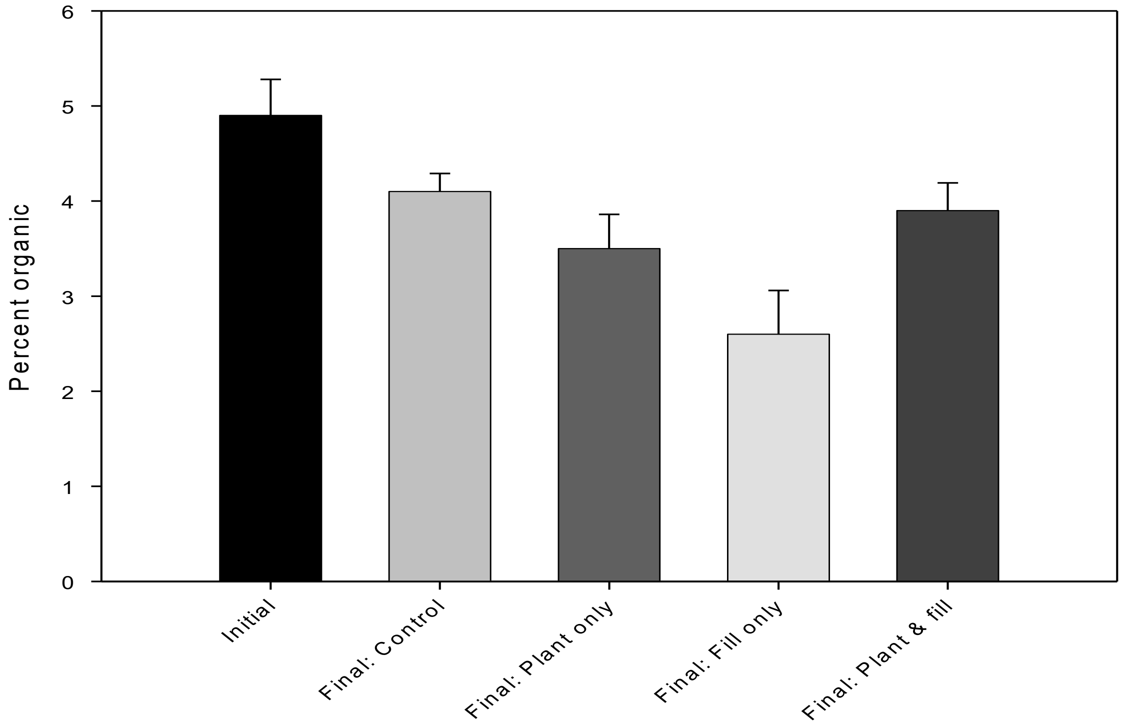

Figure 41: Restoration experiment mean percent organic content (± S.E) from before scar creation and from within scars after 1 year (Kruskal-Wallis: $p < 0.05$).

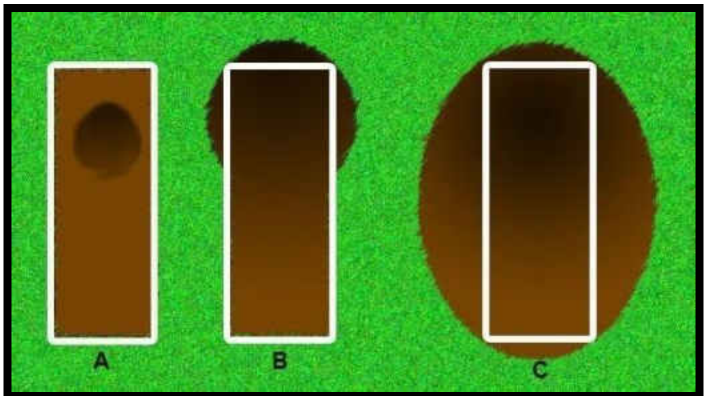

Figure 42: Types of erosion observed in experimental scars: A) holes, B) washouts, and C) sand patches. The black rectangle represents the original scar dimensions, brown is bare sediment, dark brown represents depth, and the green represents seagrass.

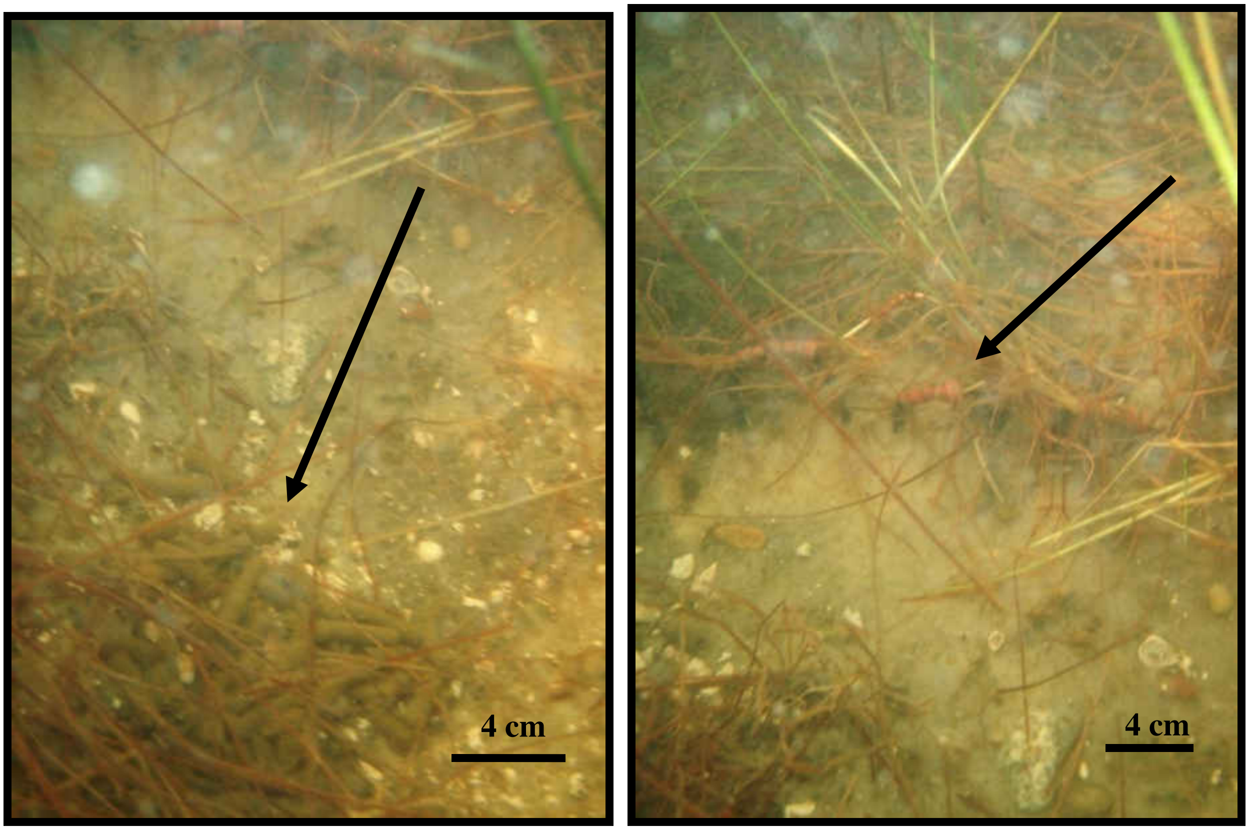

Figure 43: Bioturbation caused by a stingray. Stingray created a hole and unburied a row of *Halodule wrightii* transplants on staples, then left behind a pile of feces. In the left picture the arrow points to a close-up of excrement pile in hole, and in right picture the arrow points to a close up of the eroded staples next to the excrement pile.

Figure 44: Boater illegally using main engine motor in Pole-Troll Zone and running directly over the experiment site.

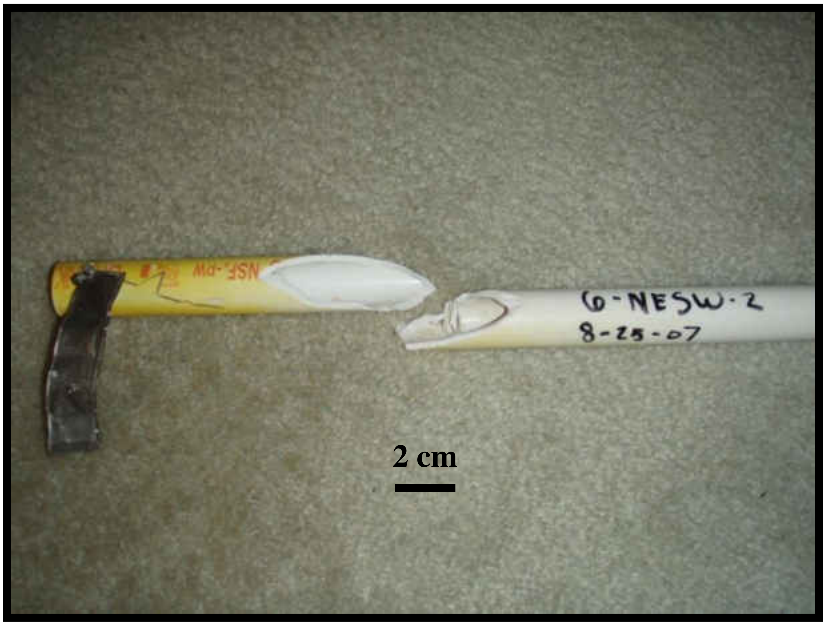

Figure 45: A PVC pole marking an experimental scar that was hit by main engine boat motor in less than 0.5 m of water.

APPENDIX B:

LIST OF TABLES

Table 1: Studies documenting existing and experimental propeller scar damage and recovery of seagrasses. No information = "-".

Species	Location	Experimental Scar(s)/ model(s)	n	Recovery time (years)	Scar depth (cm)	Scar width (cm)	Scar length (m)	Scar area (m^2)	Water depth (m)	Salinity (ppt)	Current/tidal action	Dominant sediment type	Citation
Halodule wrightii													
	Tampa Bay, FL	Yes	3	0.9 - 4.6	10	25	4	-	-	-	-	quartz-sand	Durako et al. 1992
	Tampa Bay, FL	No	41	0.6 - 1.5	-	-	-	10	0.4	30 - 32	-	-	Bell et al. 1999
	Tampa Bay, FL	No	6	0.3	0	35	40	-	-	-	-	-	Hall et al. 2006b
	Florida Keys	No	6	1	0	35	40	-	-	-	-	-	Hall et al. 2006b
	Laguna Madre, TX	No	-	-	1 - 4	32	46	-	1	≤ 50	wind driven currents	-	Martin et al. 2008
	Mosquito Lagoon, FL	Yes	10	2.1	9	32	2	0.64	0.56	33-44	tidal change = 10 cm	fine, < 1 mm	Grablow 2008
Syringodium filiforme													
	Florida Keys	model	-	3	10 - 20	100	1	1	-	-	-	-	Fonseca et al. 2000
	Florida Keys	Yes	5	0.3	10	50	1.5	-	0.1 - 1.5	-	-	-	Hammerstrom et al. 2007
	Florida Keys	Yes	5	1	20	50	1.5	-	0.1 - 1.5	-	-	-	Hammerstrom et al. 2007
	Florida Keys	Yes	5	1	40	50	1.5	-	0.1 - 1.5	-	-	-	Hammerstrom et al. 2007
Thalassia testudinum													
	Biscayne Bay, FL	Yes	2	2 -5	20	30	1	-	-	-	rapid tidal currents	slit-clay	Zieman 1976
	Tampa Bay, FL	Yes	3	3.6 - 6.4	7	25	4	-	-	-	-	quartz-sand	Durako et al. 1992
	Tampa Bay, FL	Yes	12	7.6	-	25	5	-	0.5	-	-	sand	Dawes et al. 1997
	Tampa Bay, FL	No	12	4.3	-	-	-	-	0.5	-	-	sand	Dawes et al. 1997
	Florida Keys	model	-	17.5	10 - 20	100	1	1	-	-	-	-	Fonseca et al. 2000
	Puerto Rico	No	10	-	3 - 12	25 - 76	-	-	0.5 - 1.6	-	tidal change = 15 cm	-	Uhrin & Holmquist 2003
	Puerto Rico	No	2	60	-	-	-	1200	-	-	-	-	Fonseca et al. 2004
	Florida Keys	model	-	10.5	> 20	100	-	-	-	-	-	carbonate - sand	Fonseca et al. 2004
	Florida Keys	No	1	30	150	-	-	15	-	-	-	-	Krisch et al. 2005
	Tampa Bay, FL	No	6	4	0	35	40	-	-	-	-	-	Hall et al. 2006b
	Florida Keys	No	6	4	0	35	40	-	-	-	-	-	Hall et al. 2006b
	Florida Keys	Yes	5	0.3	10	50	1.5	-	0.1 - 1.5	-	-	-	Hammerstrom et al. 2007
	Florida Keys	Yes	5	3	20	50	1.5	-	0.1 - 1.5	-	-	-	Hammerstrom et al. 2007
	Florida Keys	Yes	5	3	40	50	1.5	-	0.1 - 1.5	-	-	-	Hammerstrom et al. 2007

Table 2: Canonical Discriminant Analysis results classifying 110 propeller scar measurements into four groups. Table shows the percentage of scars correctly classified according to the most important predictor variables: shoot density, scar depth, scar % root cover, and scar canopy height.

Classification Results

		scar severity	Predicted Group Membership				Total
			1	2	3	4	
Original	Count	1	58	2	1	1	62
		2	1	9	0	1	11
		3	1	0	5	1	7
		4	0	0	1	29	30
	%	1	93.5	3.2	1.6	1.6	100.0
		2	9.1	81.8	.0	9.1	100.0
		3	14.3	.0	71.4	14.3	100.0
		4	.0	.0	3.3	96.7	100.0

91.8% of original grouped cases correctly classified.

Table 3: Mean scar measurements (± S.E.) for each scar type from 110 scars.

Scar Type	Scar Depth (cm)	Scar Width (cm)	Scar Canopy Height (cm)	Surrounding Canopy Height (cm)	Water Depth (cm)
1	9 ± 1	36 ± 2	0 ± 0	30 ± 1	44 ± 2
2	1 ± 1	42 ± 6	0 ± 0	32 ± 2	50 ± 6
3	1 ± 1	25 ± 6	2 ± 2	28 ± 2	36 ± 5
4	1 ± 1	20 ± 1	12 ± 1	28 ± 2	44 ± 3
overall	5 ± 1	32 ± 2	4 ± 1	29 ± 1	44 ± 1

Table 4: Mean scar density measurements (± S.E.) per 25 x 25 cm area for each scar type from 110 scars.

Scar Type	*H. wrightii* Shoots In Scar	*H. wrightii* Shoots Surrounding Scar	% *H. wrightii* Cover In Scar	% *H. wrightii* Cover Surrounding Scar	% Root Cover In Scar	% Drift Algae In Scar	% Leaf Litter In Scar
1	0 ± 0	157 ± 9	0 ± 0	54 ± 4	0 ± 0	4 ± 2	55 ± 5
2	0 ± 0	133 ± 14	0 ± 0	38 ± 6	0 ± 0	1 ± 1	32 ± 12
3	4 ± 4	140 ± 32	1 ± 1	39 ± 14	56 ± 15	4 ± 4	47 ± 18
4	44 ± 6	180 ± 10	25 ± 4	62 ± 5	73 ± 7	1 ± 1	10 ± 4
Overall	12 ± 3	160 ± 7	7 ± 2	54 ± 3	24 ± 4	3 ± 1	40 ± 4

Table 5: Canonical Discriminant Analysis results from classifying sediment fractions of 110 scars. This table shows the percentage of scars correctly classified according to original identifications. Sediment fractions were not a good predictor of scar types.

Classification Results

			Predicted Group Membership				
		scar severity	1	2	3	4	Total
Original	Count	1	55	0	0	7	62
		2	7	0	0	4	11
		3	7	0	0	0	7
		4	11	0	0	19	30
	%	1	88.7	.0	.0	11.3	100.0
		2	63.6	.0	.0	36.4	100.0
		3	100.0	.0	.0	.0	100.0
		4	36.7	.0	.0	63.3	100.0

67.3% of original grouped cases correctly classified.

Table 6: Mean experimental scar measurements (± S.E.) for scar types 1-4 and control in natural recovery experiment. Measurements were taken eight times from August 2007 through August 2008.

	Initial		2 weeks		1 month		2 months	
	mean	SE	mean	SE	mean	SE	mean	SE
Type 1 scars								
H. wrightii density (shoots per 25 x 25 cm)	0	0	0	0	0	0	0	0
H. wrightii canopy height (cm)	0	0	0	0	1	1	0	0
H. wrightii % cover (per 25 x 25 cm)	0	0	0	0	0	0	0	0
H. wrightii % root cover (per 25 x 25 cm)	0	0	0	0	0	0	0	0
Scar width (cm)	32	0	34	2	32	1	41	5
Scar depth (cm)	9	0	10	1	11	1	12	1
Scar angle (degrees)	45	0	38	4	41	4	31	7
% leaf litter cover	25	13	90	6	95	5	90	8
% drift algae cover	4	3	0	0	0	0	0	0
Scar side *H. wrightii* density (shoots per 25 x 25 cm)	144	15	132	12	147	18	163	12
Scar side *H. wrightii* canopy height (cm)	46	3	47	1	41	1	30	2
Scar side *H. wrightii* % cover (per 25 x 25 cm)	55	6	52	5	59	7	63	4
Type 2 scars								
H. wrightii density (shoots per 25 x 25 cm)	0	0	0	0	10	6	5	4
H. wrightii canopy height (cm)	0	0	0	0	9	5	4	3
H. wrightii % cover (per 25 x 25 cm)	0	0	0	0	2	2	1	1
H. wrightii % root cover (per 25 x 25 cm)	0	0	0	0	8	5	5	5
Scar width (cm)	32	0	34	3	46	8	46	9
Scar depth (cm)	0	0	4	1	5	2	7	1
Scar angle (degrees)	0	0	14	4	23	9	29	9
% leaf litter cover	24	11	64	13	56	15	80	9
% drift algae cover	1	1	0	0	0	0	0	0
Scar side *H. wrightii* density (shoots per 25 x 25 cm)	135	11	132	14	146	13	177	9
Scar side *H. wrightii* canopy height (cm)	46	1	49	2	41	2	36	2
Scar side *H. wrightii* % cover (per 25 x 25 cm)	51	5	52	6	59	5	69	3
Type 3 scars								
H. wrightii density (shoots per 25 x 25 cm)	0	0	27	4	35	19	30	10
H. wrightii canopy height (cm)	0	0	14	4	14	4	14	3
H. wrightii % cover (per 25 x 25 cm)	0	0	6	1	11	7	8	4
H. wrightii % root cover (per 25 x 25 cm)	91	4	80	10	45	9	25	8
Scar width (cm)	32	0	39	4	36	4	36	6
Scar depth (cm)	0	0	0	0	0	0	5	2
Scar angle (degrees)	0	0	0	0	7	7	12	7
% leaf litter cover	27	12	57	12	58	15	61	12
% drift algae cover	0	0	0	0	0	0	0	0
Scar side *H. wrightii* density (shoots per 25 x 25 cm)	155	19	135	12	136	17	185	17
Scar side *H. wrightii* canopy height (cm)	44	2	47	2	42	2	35	2
Scar side *H. wrightii* % cover (per 25 x 25 cm)	61	8	55	5	53	8	72	7

	Initial		2 weeks		1 month		2 months	
	mean	SE	mean	SE	mean	SE	mean	SE
Type 4 scars								
H. wrightii density (shoots per 25 x25 cm)	151	12	92	9	127	17	143	10
H. wrightii canopy height (cm)	12	0	24	1	31	1	26	1
H. wrightii % cover (per 25 x 25 cm)	61	6	37	5	49	7	58	4
H. wrightii % root cover (per 25 x 25 cm)	98	2	98	3	78	8	85	6
Scar width (cm)	32	0	33	1	31	1	3	3
Scar depth (cm)	0	0	0	0	0	0	0	0
Scar angle (degrees)	0	0	0	0	0	0	0	0
% leaf litter cover	23	10	37	13	28	13	0	0
% drift algae cover	1	1	3	2	0	0	0	0
Scar side *H. wrightii* density (shoots per 25 x25 cm)	151	12	130	8	151	16	147	24
Scar side *H. wrightii* canopy height (cm)	44	1	47	1	43	1	33	2
Scar side *H. wrightii* % cover (per 25 x 25 cm)	59	4	57	3	60	6	57	10
Control (dense seagrass)								
H. wrightii density (shoots per 25 x 25 cm)	147	14	119	11	143	11	143	14
H. wrightii canopy height (cm)	44	2	46	2	42	2	35	2
H. wrightii % cover (per 25 x 25 cm)	59	6	58	7	57	4	56	6

6

	3 months		6 months		9 months		12 months	
	mean	SE	mean	SE	mean	SE	mean	SE
Type 1 scars								
H. wrightii density (shoots per 25 x 25 cm)	17	4	6	3	62	10	116	21
H. wrightii canopy height (cm)	19	2	7	3	21	2	25	2
H. wrightii % cover (per 25 x 25 cm)	5	2	0	0	27	5	46	9
H. wrightii % root cover (per 25 x 25 cm)	8	8	0	0	31	6	54	11
Scar width (cm)	36	3	41	4	25	2	22	3
Scar depth (cm)	9	1	11	1	7	1	4	1
Scar angle (degrees)	23	2	16	2	12	2	13	3
% leaf litter cover	88	9	88	7	28	7	35	11
% drift algae cover	0	0	8	5	8	4	0	0
Scar side *H. wrightii* density (shoots per 25 x25 cm)	145	13	79	14	229	23	229	27
Scar side *H. wrightii* canopy height (cm)	37	2	18	1	28	1	37	2
Scar side *H. wrightii* % cover (per 25 x 25 cm)	59	5	28	6	80	6	85	8
Type 2 scars								
H. wrightii density (shoots per 25 x 25 cm)	11	4	13	5	67	10	115	20
H. wrightii canopy height (cm)	10	3	12	3	22	2	26	3
H. wrightii % cover (per 25 x 25 cm)	2	1	2	1	27	5	47	9
H. wrightii % root cover (per 25 x 25 cm)	2	1	2	1	31	5	53	10
Scar width (cm)	37	7	51	12	31	4	18	3
Scar depth (cm)	7	1	7	1	4	1	2	1
Scar angle (degrees)	18	3	13	4	8	2	3	2
% leaf litter cover	66	13	77	12	28	7	28	12
% drift algae cover	0	0	0	0	3	2	0	0
Scar side *H. wrightii* density (shoots per 25 x25 cm)	129	15	90	13	193	21	223	25
Scar side *H. wrightii* canopy height (cm)	37	2	22	2	30	2	36	2
Scar side *H. wrightii* % cover (per 25 x 25 cm)	51	6	33	6	73	8	84	7

	3 months		6 months		9 months		12 months	
	mean	SE	mean	SE	mean	SE	mean	SE
Type 3 scars								
H. wrightii density (shoots per 25 x 25 cm)	24	7	28	9	105	34	154	31
H. wrightii canopy height (cm)	20	1	13	4	24	3	31	2
H. wrightii % cover (per 25 x 25 cm)	9	3	7	2	37	12	58	12
H. wrightii % root cover (per 25 x 25 cm)	18	8	7	2	44	11	57	12
Scar width (cm)	35	3	32	9	26	6	20	7
Scar depth (cm)	5	1	5	2	4	1	2	1
Scar angle (degrees)	13	4	5	2	9	2	4	2
% leaf litter cover	70	12	60	13	23	10	25	12
% drift algae cover	0	0	0	0	4	2	0	0
Scar side *H. wrightii* density (shoots per 25 x 25 cm)	130	16	77	12	264	34	245	26
Scar side *H. wrightii* canopy height (cm)	38	2	23	1	31	1	37	2
Scar side *H. wrightii* % cover (per 25 x 25 cm)	50	6	25	6	84	7	88	8
Type 4 scars								
H. wrightii density (shoots per 25 x25 cm)	133	14	73	11	263	29	244	21
H. wrightii canopy height (cm)	36	2	20	1	31	1	37	2
H. wrightii % cover (per 25 x 25 cm)	54	6	25	6	89	7	89	5
H. wrightii % root cover (per 25 x 25 cm)	76	7	25	6	92	5	96	3
Scar width (cm)	1	1	0	0	0	0	0	0
Scar depth (cm)	0	0	0	0	0	0	0	0
Scar angle (degrees)	0	0	0	0	0	0	0	0
% leaf litter cover	2	1	4	3	0	0	7	5
% drift algae cover	7	7	0	0	0	0	0	0
Scar side *H. wrightii* density (shoots per 25 x25 cm)	129	10	72	12	253	27	250	25
Scar side *H. wrightii* canopy height (cm)	39	2	22	1	34	2	38	2
Scar side *H. wrightii* % cover (per 25 x 25 cm)	53	3	25	6	86	7	90	5
Control (dense seagrass)								
H. wrightii density (shoots per 25 x25 cm)	112	16	80	15	233	28	271	16
H. wrightii canopy height (cm)	36	2	20	2	29	2	38	2
H. wrightii % cover (per 25 x 25 cm)	58	12	38	7	81	7	97	2

Table 7: Kruskal-Wallis test for mean differences in measurements among scar types in natural recovery experiment. Since tests were repeated eight times (once for each time period), the significance level was corrected to p = 0.006 using the Bonferroni method.

		Initial		2 weeks		1 month		2 months	
	df	χ^2	Sig.	χ^2	Sig.	χ^2	Sig.	χ^2	Sig.
H. wrightii density	4	45.036	0.000	44.625	0.000	36.749	0.000	40.498	0.000
H. wrightii canopy height (cm)	4	48.503	0.000	44.806	0.000	36.460	0.000	39.237	0.000
H. wrightii % cover	4	45.083	0.000	45.137	0.000	36.838	0.000	40.657	0.000
H. wrightii % root cover	3	36.081	0.000	33.745	0.000	28.384	0.000	29.697	0.000
Scar width (cm)	3	49.000	0.000	25.141	0.000	28.983	0.000	34.778	0.000
Scar depth (cm)	3	49.000	0.000	41.937	0.000	35.660	0.000	33.625	0.000
Scar angle (degrees)	3	49.000	0.000	40.889	0.000	30.627	0.000	20.809	0.000
% leaf litter cover	3	0.079	0.994	9.514	0.023	10.891	0.012	26.631	0.000
% drift algae cover	3	2.334	0.506	6.154	0.104	0.000	1.000	0.000	1.000
Scar side *H. wrightii* density	4	2.708	0.608	0.660	0.956	0.361	0.986	4.766	0.312
Scar side *H. wrightii* canopy height (cm)	4	2.081	0.721	1.699	0.791	1.148	0.887	6.741	0.150
Scar side *H. wrightii* % cover	4	1.628	0.804	1.056	0.901	0.483	0.975	4.422	0.352

		3 months		6 months		9 months		12 months	
	df	χ^2	Sig.	χ^2	Sig.	χ^2	Sig.	χ^2	Sig.
H. wrightii density	4	33.799	0.000	28.723	0.000	29.172	0.000	24.523	0.000
H. wrightii canopy height (cm)	4	36.881	0.000	10.061	0.039	15.311	0.004	19.711	0.001
H. wrightii % cover	4	36.718	0.000	31.715	0.000	28.911	0.000	24.707	0.000
H. wrightii % root cover	3	23.692	0.000	21.120	0.000	18.628	0.000	11.397	0.010
Scar width (cm)	3	38.062	0.000	35.831	0.000	34.696	0.000	27.320	0.000
Scar depth (cm)	3	36.907	0.000	29.359	0.000	33.041	0.000	19.249	0.001
Scar angle (degrees)	3	33.152	0.000	31.336	0.000	31.326	0.000	21.598	0.000
% leaf litter cover	3	21.876	0.000	21.137	0.000	21.186	0.000	5.051	0.168
% drift algae cover	3	3.000	0.392	6.154	0.104	5.064	0.167	0.000	1.000
Scar side *H. wrightii* density	4	3.112	0.539	2.035	0.729	3.672	0.452	2.708	0.608
Scar side *H. wrightii* canopy height (cm)	4	1.588	0.811	10.075	0.039	3.854	0.426	0.567	0.967
Scar side *H. wrightii* % cover	4	2.111	0.715	2.717	0.606	3.333	0.504	3.860	0.425

Table 8: Mean experimental scar measurements (± S.E.) for three restoration treatments, and Type 1 scar control in restoration experiment. Measurements were taken eight times from August 2007 through August 2008.

	Initial		2 weeks		1 month		2 months	
	mean	SE	mean	SE	mean	SE	mean	SE
In-Scar Measurements for plant-only method								
Rooted *H. wrightii* density (shoots per 25 x 25 cm)	0	0	0	0	0	0	2	2
H. wrightii canopy height (cm)	0	0	0	0	0	0	6	4
H. wrightii % cover (per 25 x 25 cm)	0	0	0	0	0	0	1	1
H. wrightii % root cover (per 25 x 25 cm)	0	0	0	0	0	0	1	1
Scar width (cm)	32	0	34	1	33	1	32	1
Scar depth (cm)	9	0	10	1	10	1	11	1
Scar angle (degrees)	45	0	45	4	32	5	35	9
% leaf litter cover	26	11	85	10	100	0	90	8
% drift algae cover	2	2	0	0	0	0	0	0
Scar side *H. wrightii* density (shoots per 25 x 25 cm)	154	23	149	13	174	14	168	11
Scar side *H. wrightii* canopy height (cm)	44	1	47	1	42	1	35	2
Scar side *H. wrightii* % cover (per 25 x 25 cm)	56	6	59	5	68	5	67	5
In-Scar Measurements for fill only method								
Rooted *H. wrightii* density (shoots per 25 x 25 cm)	0	0	0	0	1	1	6	3
H. wrightii canopy height (cm)	0	0	0	0	3	3	6	3
H. wrightii % cover (per 25 x 25 cm)	0	0	0	0	1	1	1	1
H. wrightii % root cover (per 25 x 25 cm)	0	0	0	0	0	0	6	5
Scar width (cm)	32	0	31	1	34	4	35	3
Scar depth (cm)	0	0	1	1	1	1	7	2
Scar angle (degrees)	0	0	8	6	12	9	21	9
% leaf litter cover	27	9	73	13	56	15	70	12
% drift algae cover	2	1	0	0	3	3	0	0
Scar side *H. wrightii* density (shoots per 25 x 25 cm)	140	18	138	10	161	13	150	21
Scar side *H. wrightii* canopy height (cm)	46	1	45	1	41	1	33	2
Scar side *H. wrightii* % cover (per 25 x 25 cm)	54	8	55	4	65	5	57	9
In-Scar Measurements for fill and plant								
Rooted *H. wrightii* density (shoots per 25 x 25 cm)	0	0	0	0	0	0	0	0
H. wrightii canopy height (cm)	0	0	0	0	0	0	0	0
H. wrightii % cover (per 25 x 25 cm)	0	0	0	0	0	0	0	0
H. wrightii % root cover (per 25 x 25 cm)	0	0	0	0	0	0	0	0
Scar width (cm)	32	0	37	3	37	2	46	7
Scar depth (cm)	0	0	2	1	6	2	9	2
Scar angle (degrees)	0	0	4.5	2	9	5	26	7
% leaf litter cover	19	9	71	11	76	13	88	7
% drift algae cover	1	1	0	0	0	0	0	0
Scar side *H. wrightii* density (shoots per 25 x 25 cm)	160	17	136	12	153	12	160	27
Scar side *H. wrightii* canopy height (cm)	47	2	49	2	40	2	31	2
Scar side *H. wrightii* % cover (per 25 x 25 cm)	63	7	62	7	62	5	59	10

	Initial		2 weeks		1 month		2 months	
	mean	SE	mean	SE	mean	SE	mean	SE
In-Scar Measurements for Control, Type 1 scar								
Rooted *H. wrightii* density (shoots per 25 x 25 cm)	0	0	0	0	0	0	0	0
H. wrightii canopy height (cm)	0	0	0	0	0	0	0	0
H. wrightii % cover (per 25 x 25 cm)	0	0	0	0	0	0	0	0
H. wrightii % root cover (per 25 x 25 cm)	0	0	0	0	0	0	0	0
Scar width (cm)	32	0	34	2	32	1	41	5
Scar depth (cm)	9	0	10	1	11	1	12	1
Scar angle (degrees)	45	0	38	4	41	4	31	7
% leaf litter cover	25	13	90	6	95	5	90	8
% drift algae cover	4	3	0	0	0	0	0	0
Scar side *H. wrightii* density (shoots per 25 x 25 cm)	229	27	132	12	147	18	163	12
Scar side *H. wrightii* canopy height (cm)	46	3	47	1	41	1	30	2
Scar side *H. wrightii* % cover (per 25 x 25 cm)	55	6	52	5	59	7	63	4

	3 months		6 months		9 months		12 months	
	mean	SE	mean	SE	mean	SE	mean	SE
In-Scar Measurements for plant-only method								
Rooted *H. wrightii* density (shoots per 25 x 25 cm)	2	1	9	3	62	13	91	8
H. wrightii canopy height (cm)	8	3	9	3	21	2	27	2
H. wrightii % cover (per 25 x 25 cm)	0	0	1	1	25	6	35	3
H. wrightii % root cover (per 25 x 25 cm)	0	0	1	1	30	7	44	4
Scar width (cm)	29	3	35	3	27	3	25	3
Scar depth (cm)	12	3	9	1	6	1	4	1
Scar angle (degrees)	20	3	15	2	11	2	11	4
% leaf litter cover	95	5	90	9	19	6	47	10
% drift algae cover	0	0	0	0	14	10	0	0
Scar side *H. wrightii* density (shoots per 25 x 25 cm)	141	13	81	9	238	19	238	18
Scar side *H. wrightii* canopy height (cm)	39	3	22	1	28	2	37	1
Scar side *H. wrightii* % cover (per 25 x 25 cm)	57	5	28	5	88	5	91	5
In-Scar Measurements for fill only method								
Rooted *H. wrightii* density (shoots per 25 x 25 cm)	8	3	8	4	59	16	109	19
H. wrightii canopy height (cm)	15	3	8	5	18	3	29	3
H. wrightii % cover (per 25 x 25 cm)	3	1	2	1	24	7	42	8
H. wrightii % root cover (per 25 x 25 cm)	3	1	2	1	28	8	50	8
Scar width (cm)	34	2	38	4	37	9	24	4
Scar depth (cm)	9	1	7	2	7	1	4	1
Scar angle (degrees)	17	3	12	4	8	2	9	3
% leaf litter cover	93	5	90	9	41	11	41	12
% drift algae cover	0	0	0	0	4	3	0	0
Scar side *H. wrightii* density (shoots per 25 x 25 cm)	150	10	58	9	229	32	210	23
Scar side *H. wrightii* canopy height (cm)	37	2	21	1	29	2	35	2
Scar side *H. wrightii* % cover (per 25 x 25 cm)	59	4	20	4	78	8	80	7

	3 months		6 months		9 months		12 months	
	mean	SE	mean	SE	mean	SE	mean	SE
In-Scar Measurements for fill and plant								
Rooted *H. wrightii* density (shoots per 25 x 25 cm)	12	8	3	2	55	12	62	21
H. wrightii canopy height (cm)	8	4	3	2	20	3	19	4
H. wrightii % cover (per 25 x 25 cm)	3	2	1	1	22	6	23	8
H. wrightii % root cover (per 25 x 25 cm)	5	5	0	0	28	7	25	9
Scar width (cm)	33	3	43	8	43	9	40	13
Scar depth (cm)	7	2	10	1	8	1	8	2
Scar angle (degrees)	26	9	18	4	13	2	16	3
% leaf litter cover	77	8	95	5	56	11	70	14
% drift algae cover	0	0	1	1	3	3	0	0
Scar side *H. wrightii* density (shoots per 25 x 25 cm)	136	17	81	11	242	33	213	23
Scar side *H. wrightii* canopy height (cm)	34	3	22	1	29	2	39	1
Scar side *H. wrightii* % cover (per 25 x 25 cm)	55	6	29	5	79	8	82	7
In-Scar Measurements for Control (Type 1 scar)								
Rooted *H. wrightii* density (shoots per 25 x 25 cm)	17	4	6	3	62	10	116	21
H. wrightii canopy height (cm)	19	2	7	3	21	2	25	2
H. wrightii % cover (per 25 x 25 cm)	5	2	0	0	27	5	46	9
H. wrightii % root cover (per 25 x 25 cm)	8	8	0	0	31	6	54	11
Scar width (cm)	36	3	41	4	25	2	22	3
Scar depth (cm)	9	1	11	1	7	1	4	1
Scar angle (degrees)	23	2	16	2	12	2	13	3
% leaf litter cover	88	9	88	7	28	7	35	11
% drift algae cover	0	0	8	5	8	4	0	0
Scar side *H. wrightii* density (shoots per 25 x 25 cm)	144	15	79	14	229	23	229	27
Scar side *H. wrightii* canopy height (cm)	37	2	6	3	28	1	37	2
Scar side *H. wrightii* % cover (per 25 x 25 cm)	59	5	28	6	80	6	85	8

Table 9: Survival of three restoration treatments for Type 1 scars between August 2007 and August 2008.

	Initial	2 weeks	1 month	2 months	3 months	6 months	9 months	12 months
Plant-only method								
Mean (± S.E.) planting units per scar	16 ± 0	10 ± 2	1 ± 0	0	0	0	0	0
Fill only method								
Scars retaining sand	10	10	9	7	6	4	4	4
Fill and plant method								
mean (± S.E.) planting units per scar	16 ± 0	10 ± 2	5 ± 2	1 ± 0	0	0	0	0
Scars retaining sand	10	10	9	8	6	6	6	1

Table 10: Kruskal-Wallis test for mean differences in measurements among three restoration treatments, the Type 1 scar control, and the seagrass control in restoration experiment. Since tests were repeated eight times (once for each time period), the significance level was corrected to p = 0.006 using the Bonferroni method.

		Initial		2 weeks		1 month		2 months	
	df	χ^2	Sig.	χ^2	Sig.	χ^2	Sig.	χ^2	Sig.
H. wrightii density (shoots per 25 x 25 cm)	4	48.205	0.000	48.205	0.000	35.937	0.000	37.769	0.000
H. wrightii canopy height (cm)	4	48.209	0.000	48.205	0.000	45.046	0.000	36.363	0.000
H. wrightii % cover (per 25 x 25 cm)	4	48.209	0.000	48.205	0.000	35.660	0.000	37.789	0.000
H. wrightii % root cover (per 25 x 25 cm)	3	0.000	1.000	0.000	1.000	8.531	0.036	6.128	0.106
Scar width (cm)	3	49.000	0.000	31.142	0.000	27.981	0.000	25.628	0.000
Scar depth (cm)	3	49.000	0.000	40.950	0.000	28.122	0.000	21.858	0.000
Scar angle	3	49.000	0.000	36.084	0.000	29.703	0.000	11.431	0.000
% leaf litter cover	3	0.545	0.909	2.270	0.518	8.899	0.031	2.109	0.550
% drift algae cover	3	0.712	0.870	0.000	1.000	3.000	0.392	0.000	1.000
Scar side *H. wrightii* density (shoots per 25 x 25 cm)	4	0.791	0.940	2.069	0.723	3.942	0.414	1.485	0.829
Scar side *H. wrightii* canopy height (cm)	4	2.791	0.593	3.577	0.466	5.518	0.238	5.510	0.239
Scar side *H. wrightii* % cover (per 25 x 25 cm)	4	0.875	0.928	1.587	0.811	4.009	0.405	1.122	0.891

		3 months		6 months		9 months		12 months	
	df	χ^2	Sig.	χ^2	Sig.	χ^2	Sig.	χ^2	Sig.
H. wrightii density (shoots per 25 x 25 cm)	4	29.970	0.000	25.392	0.000	22.318	0.000	25.583	0.000
H. wrightii canopy height (cm)	4	28.728	0.000	18.018	0.000	13.797	0.008	17.175	0.002
H. wrightii % cover (per 25 x 25 cm)	4	32.811	0.000	28.582	0.000	22.611	0.000	25.735	0.000
H. wrightii % root cover (per 25 x 25 cm)	3	13.557	0.004	2.637	0.451	0.124	0.989	5.647	0.130
Scar width (cm)	3	26.306	0.000	24.504	0.000	25.985	0.000	21.467	0.000
Scar depth (cm)	3	24.277	0.000	22.528	0.000	25.059	0.000	15.900	0.003
Scar angle	3	24.932	0.000	23.063	0.000	24.975	0.000	14.907	0.005
% leaf litter cover	3	6.163	0.104	2.194	0.533	6.535	0.088	3.889	0.274
% drift algae cover	3	0.000	1.000	2.393	0.495	2.600	0.457	0.000	1.000
Scar side *H. wrightii* density (shoots per 25 x25 cm)	4	3.532	0.473	3.082	0.544	0.293	0.990	5.192	0.268
Scar side *H. wrightii* canopy height (cm)	4	1.944	0.746	4.077	0.396	1.105	0.893	2.143	0.709
Scar side *H. wrightii* % cover (per 25 x 25 cm)	4	1.322	0.858	3.538	0.472	0.582	0.965	5.775	0.217

Table 11: Mean (± S.E.) number of scars having a type of erosion per time period in each treatment.

Scar Erosion Types:	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Total
Mean number of scars with washouts per time period	1 ± 0	1 ± 0	1 ± 0	0 ± 0	0 ± 0	1 ± 0	2 ± 0	2 ± 1	8
Mean number of scars turned into sand patches per time period	0 ± 0	1 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	1 ± 0	2
Mean number of scars with holes per time period	1 ± 0	1 ± 0	1 ± 1	0 ± 0	0 ± 0	1 ± 0	3 ± 1	3 ± 1	11

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