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**Scientific evaluation of a sediment fill technique for the restoration of motor vessel injuries
in seagrass beds of the Florida Keys National Marine Sanctuary**

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Project Description: Cost-effective techniques to facilitate early intervention for the prevention of propeller scar erosion are widely needed to restore damage to Florida Keys National Marine Sanctuary (FKNMS) resources. This project used experimental manipulation to assess the effectiveness of installation of fill material to restore propeller scars in the FKNMS. The experiment was designed to test the efficacy of sediment tubes, alone and in conjunction with bird stakes and *Halodule wrightii* planting units, to re-grade injuries and therefore encourage the regrowth of seagrass from the margins of the propeller scars.

INTRODUCTION

Deterioration in seagrass habitat has been attributed to both natural and human-induced disturbance, but human-mediated disturbance is the now most serious cause of seagrass loss worldwide (Sargent et al. 1995; Short and Wyllie-Echeverria 1996). Reduction in water clarity and quality and physical damage by motor vessels are some of the most common negative impacts of human activities on seagrass beds (Sargent et al. 1995). Motor vessels are implicated in seagrass bed damage in a number of ways, including anchoring (Walker et al. 1989; Hastings et al. 1995; Creed and Filho 1999), propeller scarring (Figure 1) (Zieman 1976; Durako et al. 1992; Dawes et al. 1997; Dunton and Schonberg 2002; Kenworthy et al. 2002), and large excavations caused by hull groundings (Whitfield et al. 2002). In 1995 it was



Figure 1. Aerial photo of a shallow seagrass bank severely scarred by boat propellers.

estimated that 30,000 acres of seagrass beds in the Florida Keys National Marine Sanctuary (FKNMS) were moderately to severely scarred by boat propellers (Sargent et al. 1995).

Propeller scar damage often disrupts the seagrass rhizome matrix and excavates sediments, leaving behind unvegetated trenches that may be up to 40 cm deep, 50 cm wide and hundreds of meters long. Once the damage occurs, wind, wave, and current-induced erosion may further enlarge the trenches, creating injuries that heal very slowly (Zieman 1976; Durako et al. 1992; Dawes et al. 1997; Kenworthy et al. 2002). The resulting fragmentation of the habitat may negatively impact the macrofauna that utilize the seagrass beds (Bell et al. 2001; Uhrin and Holmquist 2003), thereby compounding the damage to seagrass ecosystems. Increased population density along the United States coasts and subsequent increased boating activity will place additional burdens on our seagrass resources. Natural resource managers therefore require restoration tools that can be implemented in a timely fashion and at reasonable cost to repair damage to seagrass communities.



Figure 2. Filled sediment tubes ready to be deployed.

Seagrass Recovery, Inc., a private company based in Ruskin, Florida, has created and patented the Sediment Tube[®], a biodegradable cotton tube that is filled with sediment and laid directly into a prop scar (Figure 2). A single tube is approximately 1.5 m long, 15 – 20 cm in diameter, and weighs 30 – 40 pounds when filled with crushed calcium carbonate screening sand. The sediment tubes serve three possible functions: 1) to restore the propeller scar to grade; 2) to deliver a desired sediment grain size; and 3) to prevent further erosion of the scar by water flow (Figure 3). The objective of this project was to test this method of propeller scar

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restoration in a variety of energy regimes and sediment types. We also combined sediment tubes with bird stakes, a proven method of enhancing seagrass growth of colonizing species (Powell et al. 1989; Powell et al. 1991; Fourqurean et al. 1995; Kenworthy et al. 2000).



Figure 3. Cross-sectional view of sediment tube deployment into an existing propeller scar.

METHODS

Study Site. The study was conducted in Lignumvitae Key Management Area in the FKNMS. The 4,050 hectare park, located in the middle region of the Florida Keys (Figure 4), is comprised of many shallow seagrass banks dominated by *Thalassia testudinum* and is a popular destination for recreational flats fisherman. The tidal range within the park is approximately 1 m, and the seagrass habitat outside the navigation channels is vulnerable to boat traffic during most of the tidal cycle. In 1993, after extensive motor vessel damage to seagrasses, approximately 2,430 hectares of seagrass meadows within the park were protected by the creation of permanent combustion engine exclusion zones. Boaters can still access these exclusion zones in kayaks, canoes, sailing craft, with trolling motors, and by poling with engines tilted up and turned off. Although legitimate boat channels are clearly marked within the park, local fishing guides have created “wheel ditches,” or propeller scars that have eroded to form new channels, in an effort to

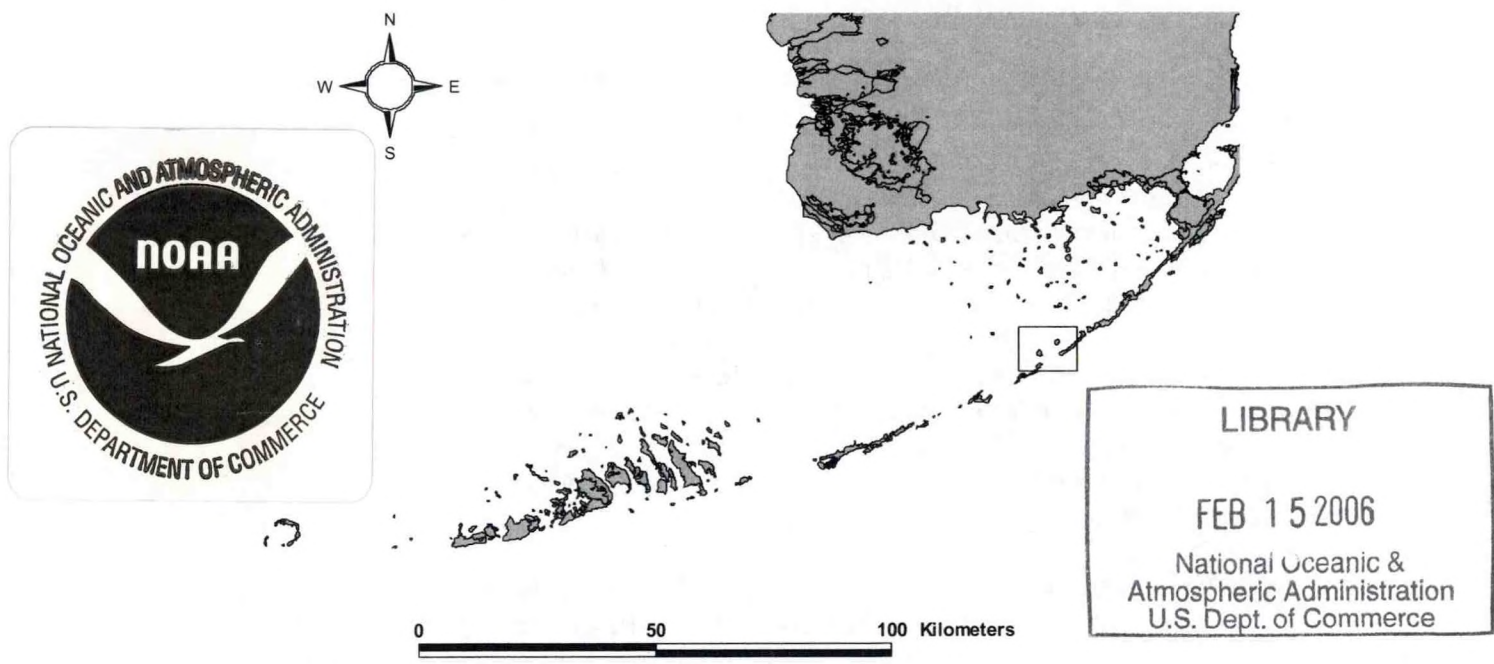


Figure 4. The experiment was deployed in the Lignumvitae Key Management Area within the Florida Keys National Marine Sanctuary. The area delineated by the box is enlarged in Figure 5.

avoid traveling around the shallow seagrass banks. Injuries also occur when boaters unfamiliar with the area, who do not know how to read charts, posted signs or the natural landmarks, accidentally go aground on the shallow banks. Park managers and the FKNMS continue to be concerned about the loss of seagrass habitat and are seeking new cost-effective and straightforward ways to restore damaged meadows.

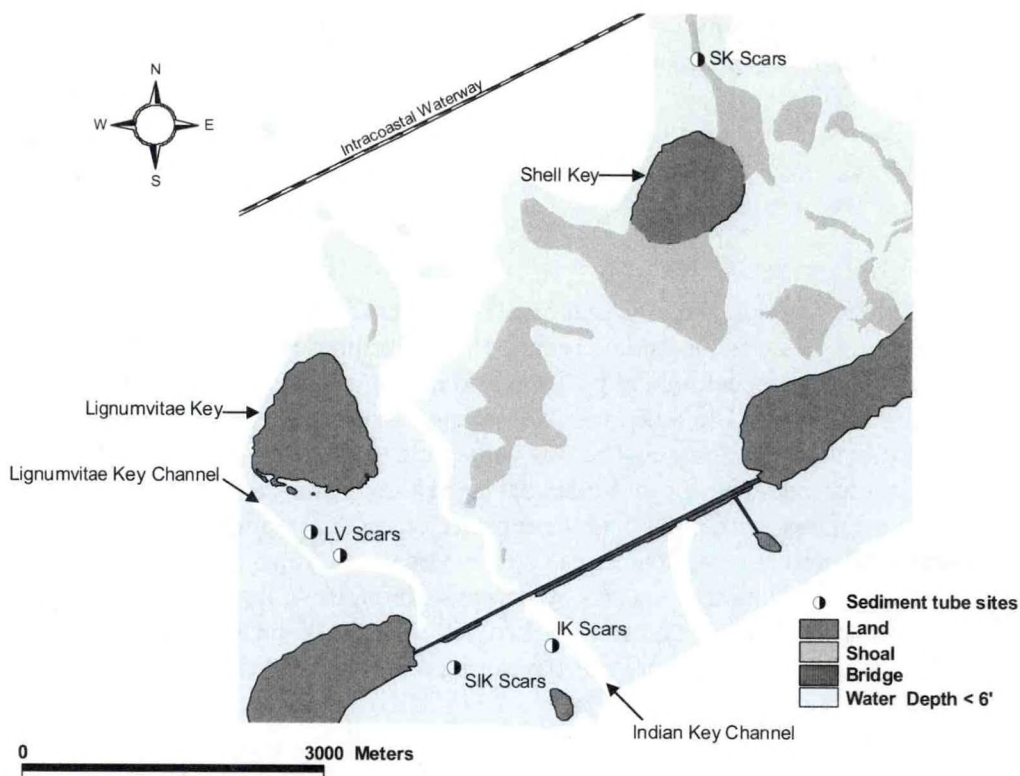


Figure 5. Lignumvitae Key Management Area. Sixteen scars were chosen in four areas of the park.

Sixteen scars within the preserve were selected (Figure 5) in four areas: Indian Key (IK), Lignumvitae Key (LV), Soft Indian Key (SIK), and Shell Key (SK). The IK area is ocean side, adjacent to the high traffic Indian Key Channel, and exposed to easterly trade winds. Sediments at the IK area are composed of *Porites* sp. coral rubble and coarse carbonate sand. The LV area is adjacent to the well-traveled Lignumvitae Key Channel, but is bayside, protected by the bridge and has little exposure to the easterly fetch. Sediment at the LV area is composed of fine carbonate mud. The SIK area is also on the ocean side, but on the more protected west side of the seagrass bank. SIK sediment is primarily fine carbonate mud. The SK area is bay side and is partially sheltered from easterly winds, but is exposed to northeast winds. The SK sediment type is coarse coral rubble. The scar locations were chosen to encompass a wide range of sediment types, wave exposures, and energy regimes. Four scars were treated in each area for a total of 16 replicate scars.

Experimental Design. The treatments included: 1) sediment tubes with bird stakes and transplants, 2) bird stakes with *Halodule wrightii* bare root transplants, 3) sediment tubes only, and 4) controls (no treatment) (Figure 6). Replicate propeller scars were 30 – 50 m long, approximately 40 cm wide and 15 – 20 cm deep. Distance between replicate scars ranged from < 10 to > 6,000 m. In each scar, four treatments were randomly assigned to 3 m sections separated by 3 m sections of untreated scar. Thus each scar contained four experimental units: 1) a 3 m sediment tube unit, 2) a 3 m bird stake + planting unit, 3) a 3 m sediment tube + bird stake + planting unit, and 4) a 3 m control unit. This was repeated in each replicate scar, for a total of 16 replicates for each treatment.

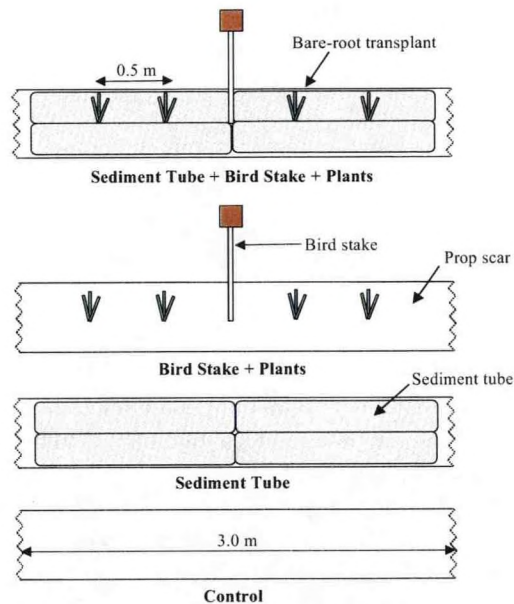


Figure 6. Experimental design. One of each treatment was deployed into each replicate prop scar.

above the water surface at mean high tide. A planting unit was composed of 3-5 runners of *Halodule wrightii*, each bearing at least 5 short-shoots and 1 apical meristem. Bird stakes were placed in the center of the treatment, 1.5 m from either treatment end, and the planting units were placed at 50 cm and 100 cm intervals from the center bird stake (Figure 6). When planting in a sediment tube, we used a dive knife to create a hole into which we inserted the planting unit, slitting about 5-10 cm of the fabric to allow horizontal rhizome growth into the tube. For “bird stake + plants” treatments, the planting units and bird stakes were spaced as above, and the planting units were inserted directly into the sediment.

The experiment was deployed in June 2001 and monitored in September 2001, February 2002, August 2002, and May 2003. Surveys included visual assessment of seagrass and macroalgal cover within the scar and in the adjacent, undisturbed seagrass bed, measurement of scar width, and digital video transects along the entire length of each experimental unit. Cover was assessed using a Braun-Blanquet scale of 0 (no cover) to 5 (> 75% cover) (Fourqurean et al. 2001). The middle 2.5 m of each treatment was surveyed using five 50 cm x 35 cm quadrats placed end to end to assess contiguous sections of the treatment. Adjacent seagrass cover was assessed in a 50 cm x 50 cm quadrat placed perpendicular to the scar treatments at a distance of 1 m into the undisturbed seagrass. Two quadrats were assessed for each treatment, one on each side, for a total of eight adjacent quadrats per scar. The replicate quadrats were averaged to obtain one value for each treatment in each scar. Adjacent quadrats were treated in the same manner. In May 2003, in addition to Braun-Blanquet assessments, we also counted the number of *Halodule wrightii* short-

Sediment tubes were filled by hand, using a funnel and a shovel. The sediment fill was composed of native crushed carbonate screening sand. Sediment grain size ranged from 0.063 to greater than 0.85 mm, with approximately 45 % of the sediment particles ≥ 0.85 mm in diameter. Approximately 5 % of the sediment was very fine silt. Filled tubes were loaded onto a shallow draft vessel and motored out the deployment sites. At the site, each tube was lowered into the water near a propeller scar and then maneuvered into place (Figure 7). Each sediment tube treatment required four tubes to complete the tube treatment (see Figure 6).

Bird stakes were created by mounting blocks of pressure-treated lumber (approximately 10 cm x 9 cm x 4 cm thick) onto 3m lengths of 2 cm PVC (1/2”). The bird stakes were driven into the substrate until the blocks were about 1 – 1.5 m above the substrate, so the blocks would be just



Figure 7. A shallow draft vessel was maneuvered close to the propeller scar and the sediment tubes were lowered into place.

shoots in each treatment. Because we used several quadrat sizes (50 cm x 50 cm, 35 cm x 50 cm, and 10 cm x 10 cm), all values were standardized to short-shoots per square meter for comparison between treatments and with values reported in the literature.

Initial scar width was recorded in several positions along the scar in June 2001. In September 2001 and August 2002, two treatment widths were measured, each 1 m from treatment ends, by laying a meter stick perpendicular to the treatment and measuring the width of unvegetated scar or treatment. Thus if seagrass began to grow into the scar from the injury margins, the width of the scar would decrease.

Data Analysis. Visual assessment data were compiled using linear regression. The recovery trajectory of three variables (*Thalassia testudinum* cover, *Halodule wrightii* cover, total seagrass cover) in the adjacent seagrass bed and within each treatment and scar was plotted as a function of time. After satisfying assumptions of variance homogeneity and normal distribution of the data, the *T. testudinum* and total seagrass slopes generated by these regressions were used as new variables in a one way analysis of variance testing the effect of treatment on scar recovery trajectory. Pairwise comparisons were conducted among treatments using Tukey's studentized range tests. Transformation of *H. wrightii* slopes and scar widths failed to resolve issues of non-normality and variance heterogeneity, so nonparametric Kruskal-Wallis tests were used to examine treatment effect on *H. wrightii* recovery trajectory, differences in scar width among treatments and in paired treatment comparisons between treatments for both recovery trajectories and widths. Finally, one way analysis of variance was used to examine cover differences among treatments in May 2003, 2 years after deployment, for *T. testudinum* and total seagrass. Differences in cover of *H. wrightii* in May 2003 were examined using Kruskal-Wallis tests due to data non-normality and variance heterogeneity.

RESULTS

A few bird stakes had to be replaced, but no other treatments were damaged during the study. Rhizophytic macroalgae quickly recruited to the sediment tubes (Figure 8). Sediment tube fabric had begun to break down by September 2001, three months after deployment. By August 2002, only the seam portions of the sediment tubes were apparent and we didn't find any evidence of existing fabric during the May 2003 survey. Despite the degradation of the fabric, most of the carbonate sand remained in the scars throughout the duration of the study.

Recovery within the scars was variable. Some scars reached total seagrass cover equal to the surrounding, undisturbed seagrass bed after 2 years, while other scars fared much worse, and still had low cover values 2 years after treatment. The wide range of recovery rates caused very high variability about the recovery trajectories.



Figure 8. Macroalgae and *Halodule wrightii* planting units in a sediment tube treatment in September 2001, three months after deployment.

One way analyses of variance revealed a significant effect of treatment on *Thalassia testudinum* cover and total seagrass cover ($p < 0.0001$ for both analyses, Table 1). Pairwise comparisons showed that the only significant comparisons were between the adjacent, undisturbed seagrass bed and the treatments inside the scars (Figure 9, 10). There were no differences in recovery rates of control, sediment tube, sediment tube + bird stake + planting units, and bird stake + planting units treatments for either *T. testudinum* or total seagrass cover.

Table 1. Analysis of variance and Kruskal-Wallis results for *Thalassia testudinum* (TT), total seagrass (TSG), and *Halodule wrightii* (HW) recovery trajectory analyses.

Dependent Variable	Independent variable	DF	F-value/Chi-Square value	P-value
TT	treatment	4	6.98	< 0.0001
TSG	treatment	4	9.99	< 0.0001
HW	treatment	4	21.82	0.0002

Kruskal-Wallis tests results for *Halodule wrightii* cover demonstrated a significant treatment effect on recovery trajectory (Figure 11). Pairwise comparisons revealed that the two treatments which included bird stakes showed higher recovery trajectories than the non-bird stake treatments, and the bird stake treatments were not significantly different from each other (Figure 11). The significant differences resulted from the presence and continued growth of the *H. wrightii* planting units. Variability in cover was high in the bird stake treatments. There was a definite trend of increasing cover over time. Although mean *H. wrightii* cover never exceeded 5 %, cover in some individual quadrats was greater than 75 % (Braun-Blanquet value of 5) in surveys conducted in May 2003. Short-shoot counts of *H. wrightii* ranged from 4.0 m^{-2} (standard deviation = 8.6) in the adjacent, undisturbed seagrass bed to 1130.1 m^{-2} (sd = 1259.9) in the sediment tube + bird stake + planting unit treatment in May 2003 (Table 2).

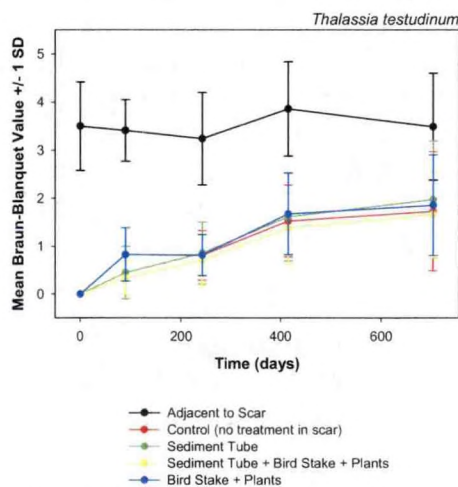


Figure 9. *Thalassia testudinum* recovery trajectories.

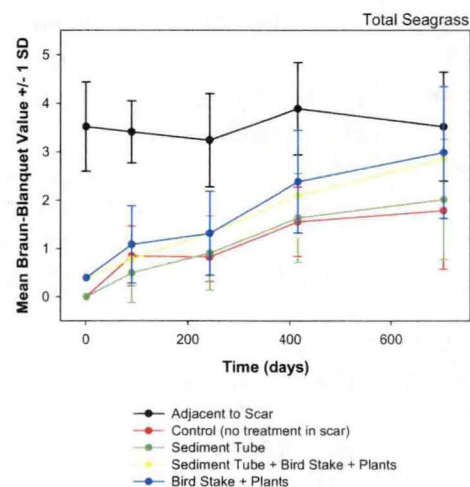


Figure 10. Total seagrass recovery trajectories.

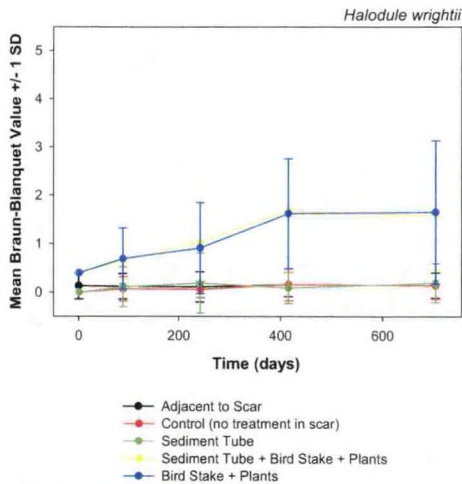


Figure 11. *Halodule wrightii* recovery trajectories.

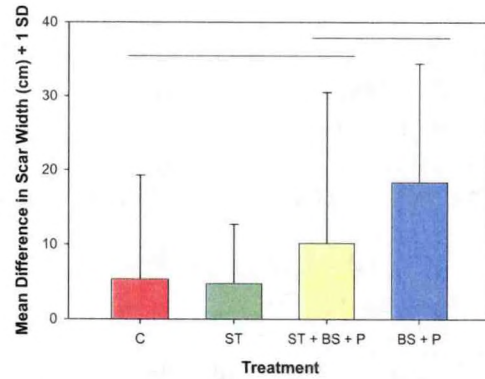


Figure 12. Mean change in scar width. C = control, ST = sediment tube, ST + BS + P = sediment tube + bird stake + plants, and BS + P = bird stake + plants. Lines over the bars indicate significant differences.

Table 2. Short-shoot counts of *Halodule wrightii* in all treatments in May 2003. All values were standardized to density per square meter.

Treatment	Mean	Standard Deviation	N
Adjacent to Scar	4.0	8.6	15
Control (no treatment in scar)	58.3	136.9	13
Sediment Tube	22.0	58.1	15
Sediment Tube + Bird Stake + Planting Units	1130.1	1259.9	16
Bird Stake + Planting Units	1076.5	1208.8	16

Initial scar width was 41.8 cm (sd = 12.02), and this declined to 27.0 cm (sd = 22.7) after two years. A Kruskal-Wallis comparison of propeller scar widths measured in treatments three months and 14 months after deployment revealed a significant effect of treatment on scar width ($p = 0.024$). Pairwise comparisons demonstrated that scar widths were significantly smaller in the bird stake + plants treatment when compared to control and sediment tube treatments. The two bird stake treatments were not significantly different from each other, and the control and sediment tube treatments were also not significantly different from each other (Figure 12). These results demonstrate that although cover of seagrasses was low, there was some evidence for bird stake treatments causing increased seagrass growth from planting units and injury margins, resulting in decreased scar width.

One way analysis of variance conducted on May 2003 (23 months after deployment) *Thalassia testudinum* cover revealed that there were no treatment differences within the scars, but that adjacent, undisturbed *T. testudinum* cover was significantly higher than *T. testudinum* cover inside the scars ($p < 0.0001$, Table 3). There were also significant differences in total seagrass cover in May 2003 ($p = 0.0012$, Table 3). Adjacent total seagrass cover was significantly greater than control or sediment tube total seagrass cover, but no other pairwise comparisons were significant. Kruskal-Wallis analyses on *Halodule wrightii* cover for May 2003 demonstrated that bird stake treatments, which were not significantly different than each other, were

significantly greater than adjacent, control, and sediment tube only treatments ($p < 0.0001$, Table 3).

Table 3. Analysis of variance and Kruskal-Wallis results for May 2003 *Thalassia testudinum* (TT), total seagrass (TSG), and *Halodule wrightii* (HW) cover.

Dependent Variable	Independent variable	DF	F-value/Chi-Square value	P-value
TT	treatment	4	7.48	< 0.0001
TSG	treatment	4	5.06	0.0012
HW	treatment	4	32.64	< 0.0001

DISCUSSION

The high level of variability in seagrass recovery resulted in no significant improvement in seagrass recovery trajectory due to the sediment tube and bird stake treatments, alone or in conjunction. Our observations revealed that sediment tubes were an effective means of deploying fine sediments into propeller scars, but the presence of tubes did not enhance seagrass growth into the scars from the scar margins. The addition of fertilizer in the form of bird feces (Figure 13), when coupled with sediment tubes, did not enhance total seagrass or *Thalassia testudinum* recovery trajectories. In May 2003,



Figure 13. Cormorants roosting on bird stakes.

two years after deployment, *T. testudinum* cover inside the prop scars had still not reached the levels of *T. testudinum* cover in the adjacent, undisturbed seagrass bed. While the results for total seagrass cover analysis on May 2003 data were somewhat different, the differences are attributable to the *Halodule wrightii* planting units coupled with bird stakes, which also influenced results of the *H. wrightii* May 2003 comparison. In all cases, the high degree of variability in seagrass cover resulted in no one experimental treatment significantly outperforming another. Conversely, presence of sediment tubes did not slow recovery, and we frequently observed seagrass shoots emerging from the sediment tube treatments (Figure 14). Also worth noting is that we used the conditions in the adjacent, undisturbed seagrass bed as a measure of what recovery in the scars should look like, yet those conditions varied from 25 to 75 % cover. Our inability to more precisely quantify what comprises ideal recovery is due to the use of our visual assessment technique, which has broad ranges of cover for each numerical category. This assessment technique may not have the necessary resolution to detect subtle differences, but it does detect larger differences and is a cost-effective and repeatable method of visual assessment (Fourqurean et al. 2001).

Scar width decreased from a mean of 41.8 cm to a mean of 27.0 cm two years later. There was some evidence to suggest that bird stake treatments may have enhanced seagrass growth enough to affect the width of the scar, but not enough that the total seagrass cover within the scar was significantly increased. The variability in scar widths was much greater in August 2002 than at the beginning of the study, suggesting that seagrass growth from the scar margins was occurring

in a patchy manner, perhaps driven more by processes acting at the local level than by the treatments themselves.



Figure 14. *Thalassia testudinum* short shoot (arrow) growing in a sediment tube treatment.

Recovery estimates of propeller scars in healthy monospecific *Thalassia testudinum* beds range from 3.5 to 9.6 years (Durako et al. 1992; Dawes et al. 1997; Kenworthy et al. 2002). In a similar study conducted within the Lignumvitae Key State Botanical Preserve, Kenworthy et al. (2002) predicted that scars in *T. testudinum* beds would recover in 5.4 to 9.6 years based on data collected on 1-2 year old scars followed for 18 months. In fact, 1 – 2 years may be required for *T. testudinum* to begin to form new rhizome apical meristems and initiate growth at scar margins (Zieman 1976).

Zieman (1976) and Kenworthy et al. (2002) postulate that several factors may cause the slow recovery of *Thalassia testudinum* in propeller scars. First, the action of the propeller excavates sediment and severs rhizomes. If new sediment is able to be deposited in the scar, it will for a time be relatively devoid of organic material and the sediment chemistry may be different than that of surrounding healthy seagrass beds (Zieman 1976; but see Dawes et al. 1997). In some cases, the energy and current regime is such that sediments will be further scoured from the original injury, thereby exacerbating the sediment loss (Whitfield et al. 2002). Disruption and damage to the rhizomes requires that new apical meristems be formed (Zieman 1976; Dawes et al. 1997), a process which requires time in a slow growing species such as *T. testudinum*. Once rhizomes are exposed at the margins of the scar, they may be less likely to grow due to light exposure and may not possess the architecture necessary to grow down into the remaining sediment (Marba et al. 1994; Duarte et al. 1997; Kenworthy et al. 2000).

Because of the clonal integration exhibited by *Thalassia testudinum*, changes in sediment chemistry probably did not significantly impact short-term recovery; new vegetative growth from the scar margins is more likely to rely on nutrient resources translocated from the intact rhizome than resources absorbed by the actively growing root and rhizome tissue. Thus it isn't surprising that the bird stake treatments did not result in higher rates of recovery for *T. testudinum* over the course of this study. In fact, given the slow rhizome elongation rates for *T. testudinum*, we might not see significant recovery after 23 months even under optimal conditions (as evidenced by control treatments that were significantly lower in cover than adjacent treatments in all scars).

There is evidence showing that sediment tubes do not prevent seagrass from growing into the scars (Table 2). In fact, in most cases the sediment tube and sediment tube + bird stake combinations performed about the same, with very similar results for both *T. testudinum* and *Halodule wrightii* (Figures 9 and 11), although sediment tube only treatments did not always reach seagrass coverage equivalent to that of the adjacent, undisturbed seagrass bed (Figure 11). Sediment tubes did allow for the introduction of fine-grained sediment to fill the scars, and in high energy environments this sediment would likely get washed away by water flow were it not encased in a sediment tube. In addition, sediment tubes would probably prevent further erosion from occurring in the propeller scars in storm events, although we did not test this hypothesis and no significant storm events occurred over the course of the study.

Halodule wrightii is a good choice for transplanting for a number of reasons. It is a smaller bodied seagrass than *Thalassia testudinum*, which makes it easier to handle the planting units and concentrate the apical meristems in those planting units. *Halodule wrightii* is also a faster growing species which frequently and opportunistically colonizes disturbed areas (Kenworthy et al. 2002). The use of bird stakes and planting units has been shown to encourage the growth of *H. wrightii* (Powell et al. 1989; Powell et al. 1991; Fourqurean et al. 1995; Kenworthy et al. 2000). The results of this experiment show that in some cases the effects of the sterility of the sediment tube fill is offset by the addition of nutrients in the form of bird feces (Figure 11). *Halodule wrightii* short-shoot counts in the bird stake treatments reached 1076 and 1130 m⁻² in May 2003, nearly 2 y after deployment. These *H. wrightii* shoot densities are in the lower range of densities reported in another bird stake study in Lignumvitae Key Management Area. Kenworthy et al. (2000) reported densities of 1000 – 3700 m⁻² in planted bird stake treatments 2 y after deployment. The fact that *H. wrightii* densities were similar in treatments with and without sediment tubes, and similar to densities in a previous experiment, adds weight to the argument that sediment tubes do not prevent the regrowth of seagrass into the scars when coupled with bird stakes. Use of bird stakes allows for “compressed succession,” in which the faster growing *H. wrightii* temporarily fills in the unvegetated propeller scars, to be replaced eventually by the slower growing *T. testudinum*.

Given these results, we would recommend that sediment tubes be used in areas where wind, wave, and current energy are such that scars are vulnerable to erosion. Sediment tubes restore the scars to grade, fill the scars with fine-grained sediment, prevent further erosion, and do not prevent the growth of seagrass from the injury margins. Although untested, we predict that damage to seagrass beds in highly erosional areas would benefit from the use of sediment tubes, especially coupled with bird stakes and *Halodule wrightii* planting units. Sediment tubes may be particularly useful in deeper scars, although this question requires further study.

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