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The Role of a Hurricane in the Expansion of Disturbances Initiated by Motor Vessels on Seagrass Banks

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ABSTRACT

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While investigating the ecology of physically disturbed seagrass and *Porites porites* coral banks in the Florida Keys National Marine Sanctuary (FKNMS), we documented the effect of Hurricane Georges on the recovery of injuries created by large motor vessels. Near the intersection of two main routes for vessel traffic in the Red Bay Bank region of the FKNMS, we found that blowholes caused by vessel groundings (n = 146), as opposed to propeller scars (n = 50), accounted for a majority of the vessel-related injuries on shallow seagrass banks. Evidence from four large motor vessel grounding sites that were mapped before and after a category 2 hurricane (Georges) with wind speeds of 96 knots (176 kmph) indicated an increase in injury size associated with the storm. At a site where a tugboat grounding had destroyed 100% of the macrophytes growing on 7,363 m^2 of a shallow bank, recovery was interrupted and reversed by Hurricane Georges. In January 1998, 4.5 yr after the original injury, macroalgae had recovered to 85% and seagrasses to 11% of the original 100% cover at the grounding site. In the second survey two months after Hurricane Georges, seagrasses had declined to $\leq$ 1% and macroalgae to 23% of the original cover. Twenty-one months later, seagrasses and macroalgae had recovered to near pre-hurricane levels, but cover was still much less than the original cover. Following the hurricane, the injured area increased from 1,576 m^2 to 2,514 m^2, a 63% increase. Three other large vessel-grounding sites exhibited at least a 65% increase in the size of their blowholes following Hurricane Georges. Our data and observations suggest that large blowholes created by vessel injuries are unstable and will continue to be vulnerable to storm events many years after the original disturbance. Depending on a bank's location, orientation, and its proximity to the reef environment, consideration should be given to a range of pro-active and post-injury responses including, but not restricted to: (1) physically regrading large blowholes to increase the physical stability of the site; and (2) strategic placement of navigational aids to direct vessel traffic away from shallow banks.

ADDITIONAL INDEX WORDS: *Seagrass, Thalassia testudinum, hurricane, disturbance, vessel groundings.*

INTRODUCTION

Seagrass meadows are well known for their ability to stabilize unconsolidated sediments and to persist under a wide range of hydrodynamic conditions (GINSBURG and LOWENSTAM, 1958; FONSECA, 1996). These important attributes are evident throughout the tropical Atlantic and Caribbean basin, where seagrass meadows dominated by *Thalassia testudinum* Banks ex König form elevated mudbanks which can exist for hundreds of years, resisting physical degradation from severe storms and hurricanes. Several studies have demonstrated that category 4 hurricanes (Saffir-Simpson scale) have only minor impacts on intact *T. testudinum* beds (THOMAS *et al.,* 1961; OPPENHEIMER, 1963; TILMANT *et al.,* 1994), even though other unvegetated parts of the systems were physically disturbed and severely eroded. In some instances, the intense wave action associated with the hurricanes removed necrotic leaves, leaving only the green, photosynthetically active seagrass blades and the appearance of a healthy, luxuriant meadow (THOMAS *et al.,* 1961; OPPENHEIMER, 1963; TILMANT *et al.,* 1994). Despite the frequency of hurricanes in the tropical Atlantic, Caribbean, and Gulf of Mexico, only one study has documented minor damage to *T. testudinum* beds (VAN TUSSENBROEK, 1994). During Hurricane Gilbert, two of the three stations investigated showed some short-shoot mortality; however, none of the sites was completely destroyed, and *T. testudinum* rapidly recovered following the storm (VAN TUSSENBROEK, 1994).

Although previous studies suggest that seagrass meadows are resistant to significant physical degradation from severe storms, natural blowouts do occur in seagrass beds and exist as ubiquitous features in some high energy environments (DEN HARTOG,

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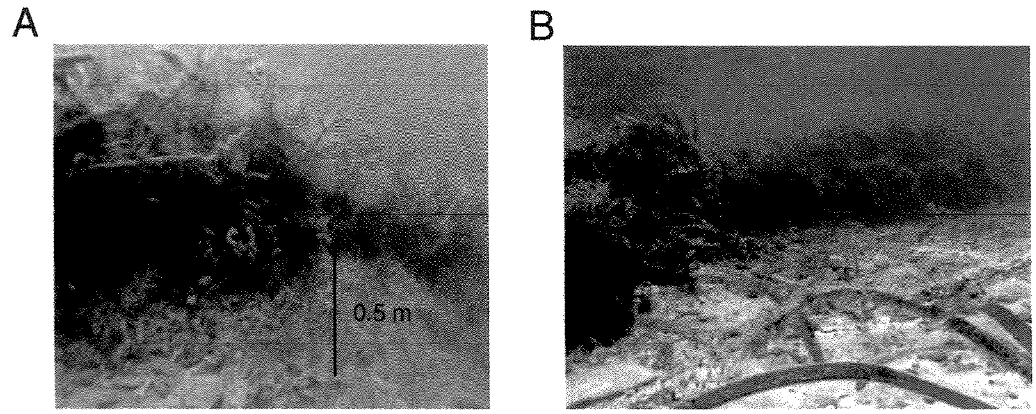


Figure 1. (A) Photograph of a deep blowhole injury margin created by a motor vessel grounding. Scale bar is approximately 0.5 m. Vertical edge shows broken rhizomes and unconsolidated *Porites porites* rubble. (B) Photograph of a slightly shallower injury. Broken rhizomes are shown at the injury margin on left. Right side of photograph is mainly unconsolidated *P. porites* rubble.

1971; PATRIQUIN, 1975; FONSECA and BELL, 1998). Aerial photographs of *T. testudinum* beds in Puerto Rico and studies of seagrass meadows in subtropical, tropical (PATRIQUIN, 1975; MARBA *et al.,* 1994), and temperate waters (FONSECA and BELL, 1998; FONSECA *et al.,* 2000) suggest that natural unvegetated blowouts and elevated patches of seagrass form and maintain physically stable shapes that migrate across the landscape in response to chronic high-wave energy conditions. For example, PATRIQUIN (1975) demonstrated how crescent-shaped blowouts migrate parallel to and into the prevailing flow. The blowouts erode at the upstream edge of the crescent and refill at the downstream edge where the seagrasses reestablish and sediments accumulate. Patchy beds may persist for long periods of time; however, recent studies have suggested that patchy and fragmented seagrass meadows may be more vulnerable to damage from severe storms than seagrass meadows with continuous cover (FONSECA and BELL, 1998; FONSECA *et al.,* 2000).

Observations regarding the vulnerability of fragmented seagrass meadows have drawn attention to the management of anthropogenic sources responsible for disturbances that create patchy seagrass meadows. A large source of disturbance in South Florida seagrass beds is derived from motor vessel groundings and propeller scarring due to the increasing number and size of boats. Several studies indicate that motor vessel impacts to seagrass beds have increased dramatically in the past two decades (ZIEMAN, 1976; FOLIT and MORRIS, 1992; SARGENT *et al.,* 1995; DAWES *et al.,* 1997). Aerial surveys of Florida's coastal waters show that approximately 70,000 ha of seagrass have been damaged by propeller scarring (SARGENT *et al.,* 1995). Propeller scars are narrow, linear features that can be either single or twin scars (see KENWORTHY *et al.,* 2002). In addition to propeller scarring, vessel groundings create large excavations known as "blowholes." Blowholes are deep excavations with large surface areas as opposed to propeller scars (Figure 1). Often, when vessels run aground on a shallow seagrass bank, the boat operator will attempt to dislodge the boat by powering off the banktop. As the engine powers up, the stern of the vessel is forced closer to the seafloor and the propellers excavate all of the seagrasses and some of the underlying sediments, creating a hole (blowhole). Sediments from the blowhole are often deposited onto the adjacent undisturbed seagrass beds, burying the seagrass (overburden). If the sediment is not removed or redistributed by a storm or currents, this part of the seagrass bed may die as well. The injury margins in blowholes are characterized by a steep, physically unstable topographic gradient, with a box-type cut that extends below the seagrass rhizome layer (Figure 1), similar to the leading edge of the crescent-shaped blowouts (PATRIQUIN, 1975). In contrast to undisturbed seagrass beds or the naturally formed crescent-shaped blowouts (PATRIQUIN, 1975), vessel-generated blowholes may be more physically unstable and vulnerable to further damage from high-energy storm events.

While investigating the recovery of previously injured seagrass banks by large motor vessel groundings, we had the opportunity to examine the effects of Hurricane Georges. Our study was designed to address three main objectives: (1) to describe the physical characteristics of large motor vessel groundings on shallow *T. testudinum* banks; (2) to determine whether motor vessel injuries initially destabilize *T. testudinum* beds and make them more vulnerable to damage by severe storms; and (3) to discuss the management and restoration options for minimizing the impacts of these injuries.

METHODS

Study Sites

To illustrate the potential impacts of hurricanes on injured seagrass banks, four vessel grounding case studies were documented. All of the injured sites were located in the Florida Keys and were impacted by Hurricane Georges in September 1998. The physical consequences of the hurricane were examined for all four case studies, and more detailed biological consequences were evaluated at the most severely impacted site.

Three of the four vessel case studies were located on Red Bay Bank, a series of elevated shallow seagrass-*Porites porites* coral banks located on the Gulf of Mexico side of Moser Channel (Figure 2). Moser Channel is the main artery for water flowing between the Gulf of Mexico and the reef track just south of the Keys and is also a major route for commercial and recreational boat traffic. In this area, the shallow elevated banks and surrounding seagrass beds are subjected to a large number of vessel injuries, including propeller scarring by relatively small boats and hull groundings by larger vessels (SARGENT *et al.,* 1995).

The seagrasses *T. testudinum* and *Syringodium filiforme* Kützing are the main stabilizing components on the banks. The bank community also includes a diverse biotic assemblage of macroalgae, sponges, gorgonians, live *P. porites,* and numerous fishes and invertebrates. Tides in this area of the Florida Keys are mixed semi-diurnal and run approximately north-south perpendicular to the orientation of the banks, with maximum current speeds up to 1.75 knots (3.2 kmph). Tidal range is approximately 0.5 m, and occasionally the tops of the banks are exposed briefly during low tide. Prevailing winds are generally southeast-northwest and parallel to the long axis of the banks. Bank sediments consist of *P. porites* rubble and other biogenically-derived calcareous materials.

The fourth vessel grounding case study was located to the southeast of Fiesta Key in a nearly monotypic *T. testudinum* bed (Figure 2A). This location is characterized by fine unconsolidated carbonate sediments and receives wave action from its exposure to the south and east.

Hurricane Georges

Hurricane Georges made landfall during mid-morning on September 25, 1998, in Key West, Florida. The Monroe County Emergency Operations Center in Marathon recorded a minimum central pressure of 982.5 mb and a maximum wind speed of 96 knots (176 kmph), indicating Georges was a category 2 hurricane on the Saffir-Simpson Scale. The Sombrero Key C-man buoy (SMKF1) located within 40 km of all the study sites (Figure 2A) recorded maximum sustained winds of 82 knots (150 kmph) with peak gusts to 92 knots (169 kmph). Hurricane force winds were recorded at the C-man buoy station for 3 hours between 1300–1600 GMT. The eye of the hurricane passed south and eventually west of all the study sites exposing each to a strong easterly wind flow. Storm surge was from 1 to 2 m in the middle and lower Florida Keys.

Case Study 1: The *Captain Joe* Grounding

In March 1993, the *Captain Joe,* a 15.4 m tugboat with a 3 m draft, ran aground on a bank just northeast of Red Bay Bank (Figure 2B). The grounding occurred when the tugboat captain missed the marked channel to the east and attempted to navigate a release channel located between two banks. The *Captain Joe* was under tow by another tugboat when it powered itself across a small bank, creating a 2–3 m deep trench and leaving mainly *P. porites* rubble as a substrate (Figure 3). In addition to the deep trench that was excavated into the bank, unconsolidated dead *P. porites* fragments and sediments were deposited on top of the adjacent seagrass bank, burying the seagrasses and creating a shallow berm on both sides of the trench.

Vertical, high-resolution color aerial photos (1:1200) of the *Captain Joe* injury were taken 3 months after the grounding on June 4, 1993. These photos along with *in-situ* observations showed 100% loss of all the seagrasses and macroalgae in a 7,363 m^2 area. Color aerial photography was subsequently obtained to characterize the recovery in February 1996 (1:1,200) and in December 1998 (1:780), three months after Hurricane Georges.

Following the hurricane, a detailed spatially referenced bathymetry survey was conducted at the

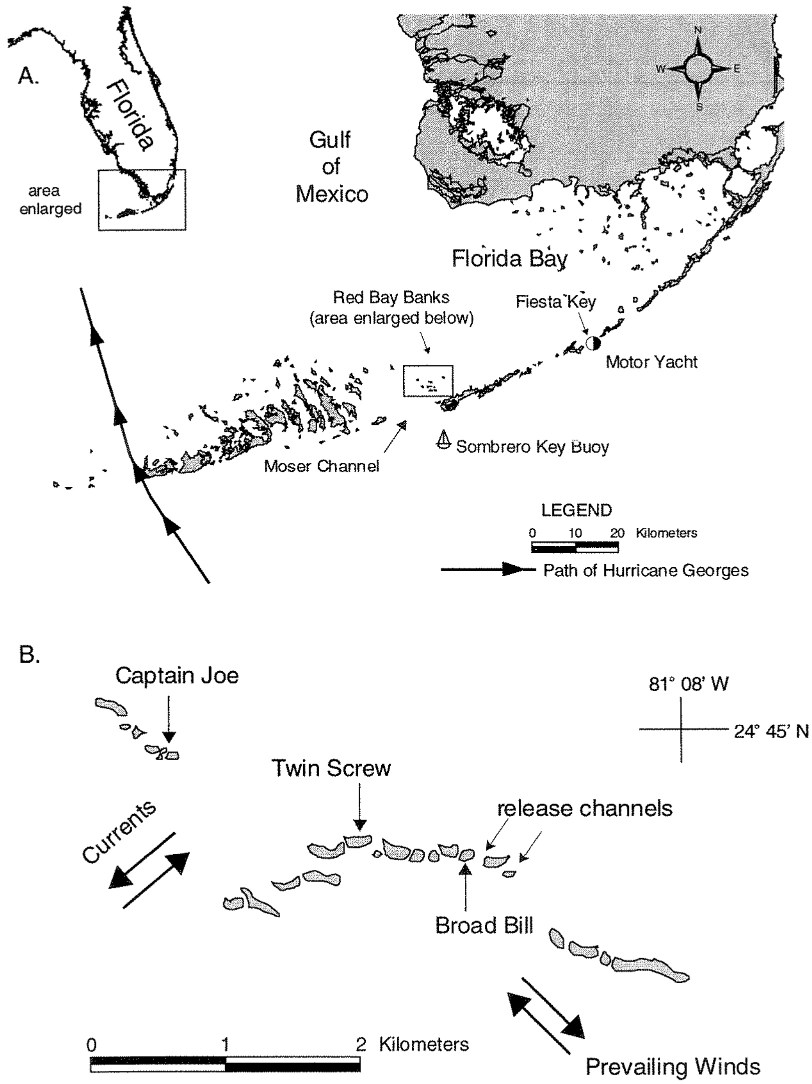


Figure 2. (A) Map illustrating the locations of the study sites, the Sombrero Key Buoy, and the path of Hurricane Georges. (B) Close up of Red Bay Bank illustrating three injury site locations along with the prevailing winds and currents.

site in November 1998 by Environmental Development Consultants Corporation (EDC, 1998). Figure 3A is the original banktop bathymetry recreated from aerial photography, and Figure 3B illustrates the bathymetric characteristics of the resulting injury. Although some of the unconsolidated sediment was redistributed back into the channel after the hurricane, the injury was still a very distinct morphological feature of the bank.

Three benthic surveys were conducted to assess the biological and physical recovery of the site. The first survey was completed in January 1998, 4.5 years after the original disturbance and 8 months prior to Hurricane Georges. Additional surveys were conducted in December 1998, and in June 2000, 3 and 21 months after Hurricane Georges, respectively.

During the first survey in January 1998, the perimeter or "footprint" of the most severely injured portion of the site was mapped from a small vessel

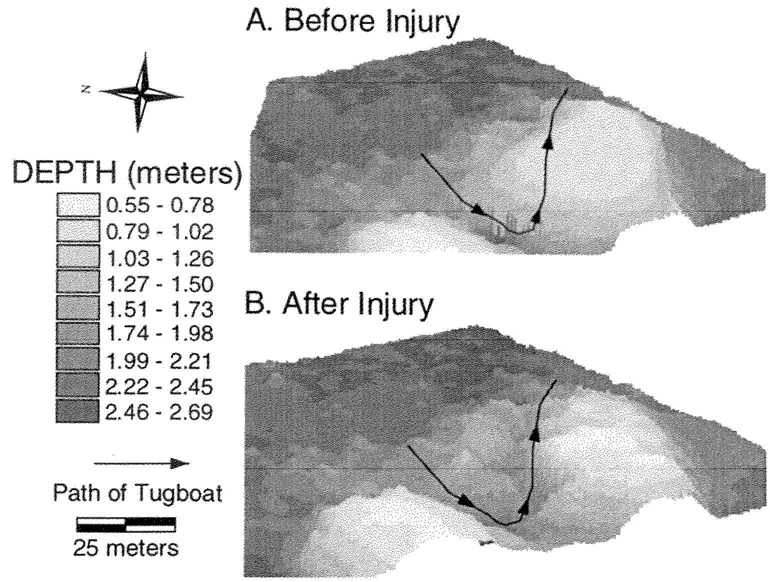


Figure 3. Three dimensional graphic of the bathymetry data for the *Captain Joe* site before the injury (A) and after the injury (B). Black line with arrows shows the path of the tugboat across the bank.

using a Trimble Pro XR Differential GPS unit (DGPS) with sub-meter accuracy. Within this perimeter, 20 random sample locations were selected to assess the percent cover of seagrasses and macroalgae. At each sample location, we placed a 1 m^2 quadrat partitioned into 400, 5 cm by 5 cm squares, and the number of squares containing seagrasses (by species) and attached macroalgae were recorded by diver. Percent cover of seagrasses and macroalgae was calculated by:

$$\text{Percent cover} = \text{total number of squares occupied} \div 400 \quad (1)$$

During the second survey in December 1998, we remapped the perimeter of the injured area with DGPS and examined 20, 1 m^2 randomly placed quadrats for percent cover of seagrasses and macroalgae. The random samples were located within the boundaries of the original perimeter mapped in January 1998. Additionally, in December 1998, vertical color aerial photographs were taken of the disturbed area. Prior to photographing the site, we secured three 1.5 m diameter targets on the bottom to serve as control points for georeferencing the photographs. We then used DGPS to accurately record the position of the targets. The photographs were georeferenced to these three points in ArcINFO to the Universal Transverse Mercator coordinate system. Henceforth, all of the spatial data we collected, such as the injury perimeters and sample locations, could be overlaid onto the photograph and examined for changes due to the hurricane. We then compared the field DGPS mapped injury perimeter from January 1998 with the injury signature on the aerial photograph to confirm the extent of physical changes due to the hurricane. In the final survey in June 2000, 21 months after Hurricane Georges, 20 randomly placed quadrats were sampled for percent cover within the dimensions of the perimeter mapped in January 1998 as described previously.

Case Study 2: *Broadbill* Injury

The *Broadbill* was a 15 m sport-fisherman-type vessel which grounded on Red Bay Bank in July 1997 (Figure 2B). While the vessel was still aground, we obtained GPS coordinates of the location. Six months later, in January 1998, we conducted our first survey of this site. Photographs taken at this time revealed a typical large vessel grounding site consisting of an inbound track onto the bank with twin propeller scars and an "island" of seagrass between the scars leading up to a deep excavation injury followed by twin propeller scars in the outbound track. The outbound track was created when the vessel was towed off the bank.

The perimeter of the injury was mapped twice with DGPS, first in January 1998, 6 months after the original grounding, and a second time in June 2000, 21 months after Hurricane Georges. Additional detailed dimensions were obtained with a tape measure during the first survey period. Detailed bathymetry measurements were obtained in June 2000 using a Garmin GPS Map Model 185 echosounder integrated with the Trimble Pro XR DGPS. Integration between the two units allowed us to collect spatially referenced bathymetry data across the injury and the adjacent undisturbed seagrass beds. The entire unit (DGPS, Echosounder and transducer) was floated in a 1 m Zodiac and towed by hand back and forth across the site. The data were downloaded into ArcView, and an inverse distance weighted surface interpolation function was used to create a surface of depth values with 0.5 m resolution. The injured area from both survey periods was calculated from the DGPS perimeter data to determine changes due to the hurricane. The volume of sediment removed from the banktop in June 2000 was also estimated using ArcView software.

Case Study 3: Twin Screw Injury

Although the exact date of this grounding is unknown, there can be no doubt that it was caused by a motor vessel. During the first survey in January 1998, there was a well-defined twin propeller scar on the inbound track with an "island" of seagrass leading up to a deep circular excavation. Overburden deposited on the adjacent seagrass bed was also visible. Since the hole was deep (2.0 m) and there was no outbound track, we think the vessel either rotated in position or simply backed off to extricate itself from the bank.

The perimeter of the injury was mapped with DGPS in January 1998 prior to the hurricane and again in June 2000, 21 months after Hurricane Georges. Additional measurements were made with a tape measure, and oblique photographs were taken during both surveys. Spatially referenced bathymetry data were also collected at this site in June 2000 using the methods previously described for the *Broadbill.* The injured areas from both survey time periods were compared for changes, and the total volume of sediment removed by June 2000 was calculated.

Case Study 4: Motor Yacht Injury

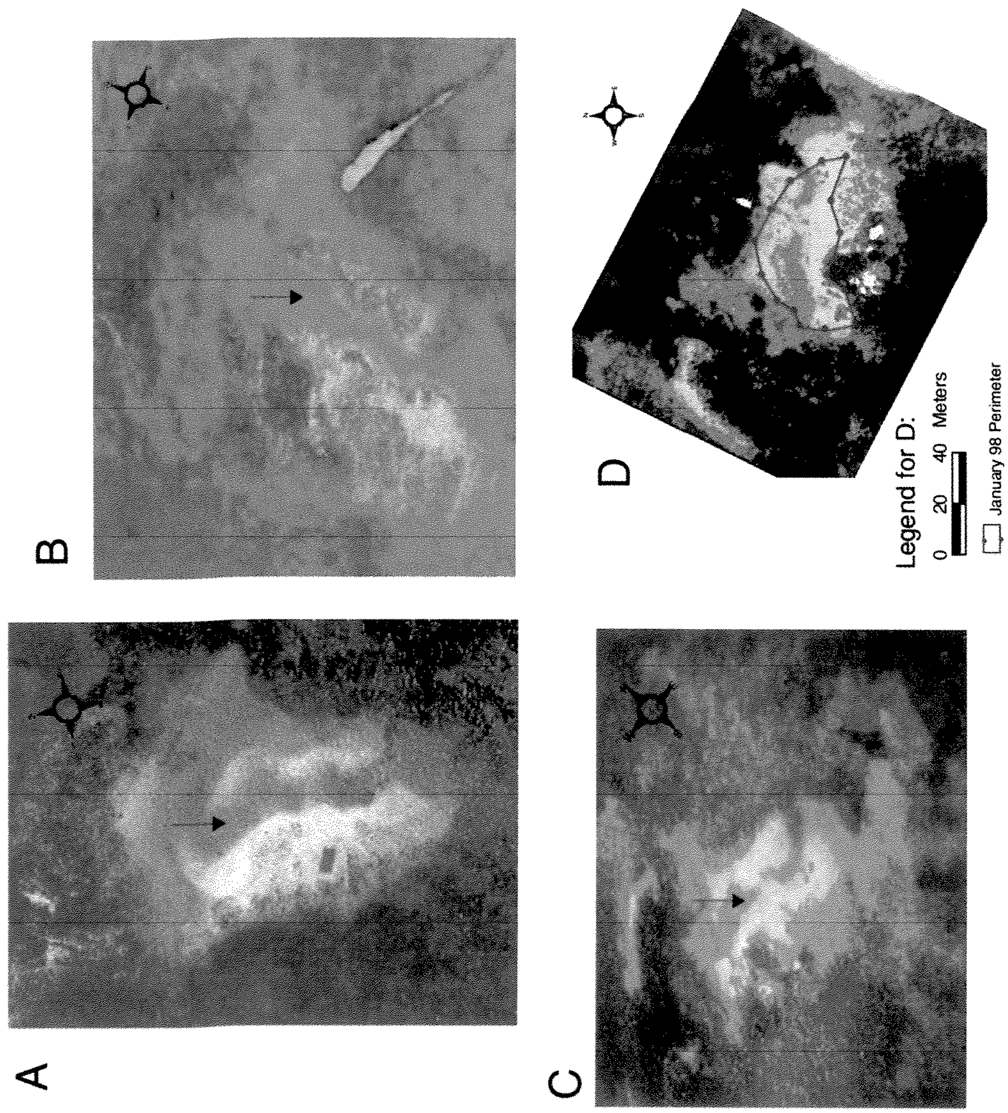
On September 4, 1998, a 19 m Viking Motor Yacht ran aground on a shallow *T. testudinum* bank on the ocean side of the Channel 5 Bridge. The grounding was characterized by an inbound twin propeller scar approximately 40 m long, a deep excavation blowhole, and an outbound path of a single propeller scar. This injury was mapped on two separate dates using a tape measure while on SCUBA. There were no DGPS data collected for this injury. The first measurements were taken September 8, 1998, a few days before Hurricane Georges, and the second set of measurements, on May 20, 1999, approximately 8 months after the hurricane. The injured area calculated from these measurements at both time periods was compared to determine any change.

RESULTS

Case Study 1: The *Captain Joe* Injury

The area of seagrass damaged by the initial physical disturbance was 7,363 m^2, as determined from the 1993 aerial photograph (Figure 4A). The footprint for the most severely damaged area remaining in January 1998 was 1,576 m^2. Thus, after 4.5 years, 5,787 m^2 of the site displayed some degree of recovery. However, after Hurricane Georges, the area of most severe damage increased from 1,576 m^2 to 2,514 m^2. The color aerial photographs (Figure 4) show a time series beginning with the original injury in which 100% of the seagrasses was lost (Figure 4A), the condition 4.5 years later (Figure 4B), and finally, the injury shortly after the hurricane (Figure 4C). Following the storm, seagrasses and macroalgae were removed from the trench and berms, setting back the recovery process. The recovery setback due to the hurricane is evident in the georeferenced color aerial photograph (Figure 4D). The white, fan-like formations extending outside the red line represent damage caused by scouring and redistribution of sediments during the hurricane. The unconsolidated sediments on the berms and in the trench were relocated into fans that extended to the east of the site.

During the 4.5 years following the grounding, the site went through a recovery process consistent with previous reports of succession in disturbed tropical seagrass ecosystems (ZIEMAN, 1982; WILLIAMS, 1990). The site was initially colonized by a diverse macroalgal community consisting of turf-like growth forms (*Batophora* sp., *Dasycladus* sp., *Chaetomorpha* spp.), several calcareous species (*Halimeda* spp., *Penicillus* spp.), and larger fleshy macroalgae (*Caulerpa* spp., *Dictyota* spp., *Hypnea* spp., *Laurencia* spp.), followed by seagrasses (*S. fil-*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iforme, T. testudinum). Within the most severely injured perimeter identified and mapped in January 1998, the percent cover of seagrass and macroalgae amounted to 11.3% (SE = ±5.2) and 85.4% (SE = ±2.7), respectively (Figure 5). *Thalassia testudinum* represented 5.9% (SE = ±2.5) and *S. filiforme* 7.1% (SE = ±4.9) of the seagrass recovery.

Three months after the hurricane, in December 1998, the seagrass and macroalgae cover had declined to < 1% (SE ±0.29) and 22.9% (SE ±6.2), respectively. The site sustained almost a complete loss of seagrasses with the exception of two *T. testudinum* seedlings, possibly new recruits. During the final survey in June 2000, 21 months after the hurricane, total seagrass cover was 12.4% (SE = ±5.6), and macroalgae cover was 62% (SE = ±6.2). Seagrasses had recovered to their original pre-hurricane values, and the macroalgae to within 20% of prestorm coverage, although the coverage was still much lower than that on adjacent, undisturbed banks.

Case Study 2: *Broadbill* Injury

In January 1998, the injured area associated with the grounding was 117 m^2 (Figure 6). In December 1998, 2 months after Hurricane Georges, the individual inbound propeller scars were no longer discernible and were replaced by one large excavation hole in the seagrass bed. The area of the original injury had increased to 194 m^2 in June 2000, an expansion of 65%.

The bathymetry of the site in June 2000 revealed a 1 m deep excavation where the original propeller scars were before the hurricane (Figure 7). The northern portion of the original blowhole appeared to have regraded, and the outbound propeller scars had been recolonized by seagrasses and macroalgae. However, the rest of the injured area appeared to be expanding, as evidenced by the perimeter comparisons between the two time periods (Figure 6). A total amount of 25 m^3 of sediment was removed from the banktop by June 2000 due to the combined effects of the injury and the hurricane.

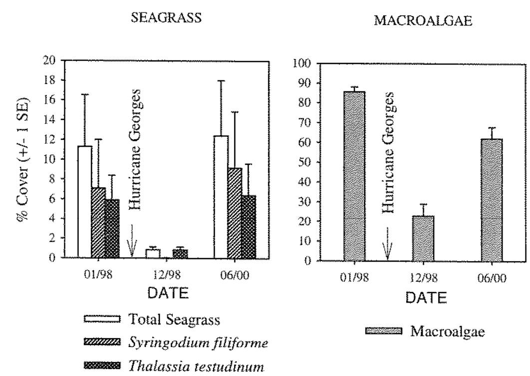

Figure 5. Biological data collected at the *Captain Joe* site, once before the hurricane (01/98) and twice after the hurricane (12/98 and 06/00).

Case Study 3: Twin Screw Injury

During the first survey in January 1998, prior to the hurricane, the injured area was 58 m^2 (Figure 8). The circular excavation measured 4.3 m × 2.9 m, and was 0.75 m deep. Twenty-one months after the hurricane (June 2000), the injured area was 136 m^2, more than twice the area of the original injury. The changes were similar to those observed at the *Broadbill* site. The blowholes and the propeller scars had coalesced into a large polygonal-shaped excavation. The bathymetry data illustrate the extent of the sediment scour that occurred due to the hurricane (Figure 9). The whole injury in June 2000 was 1–1.5 m deep. Approximately 65 m^3 of sediment have been excavated from the banktop as a result of the combined effects of the injury and the hurricane.

Case Study 4: Motor Yacht Injury

The area of the original injury was 77 m^2 in September 1998 prior to the hurricane. Eight months after Hurricane Georges (May 2000), the area had doubled to 140 m^2 (Figure 10). This site appeared to have deteriorated in a manner similar to the

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Figure 4. Oblique time series color photographs of the *Captain Joe* injury. In May 1993 (A), February 1996 (B), in October 1998 after Hurricane Georges (C). Georeferenced vertical photograph of the site two months after the hurricane (D). The lightest parts of the photographs are the shallow berms separated by a deep, 2–3 m trench. The arrows in each photograph illustrate the location of the trench between the north and south berms. The darker areas on the north and south berms represent recovery by seagrasses and macroalgae (C). The red dotted line represents the January 1998 perimeter (D). The white fan formations that extend outside of the red perimeter represent damage sustained due to the hurricane.

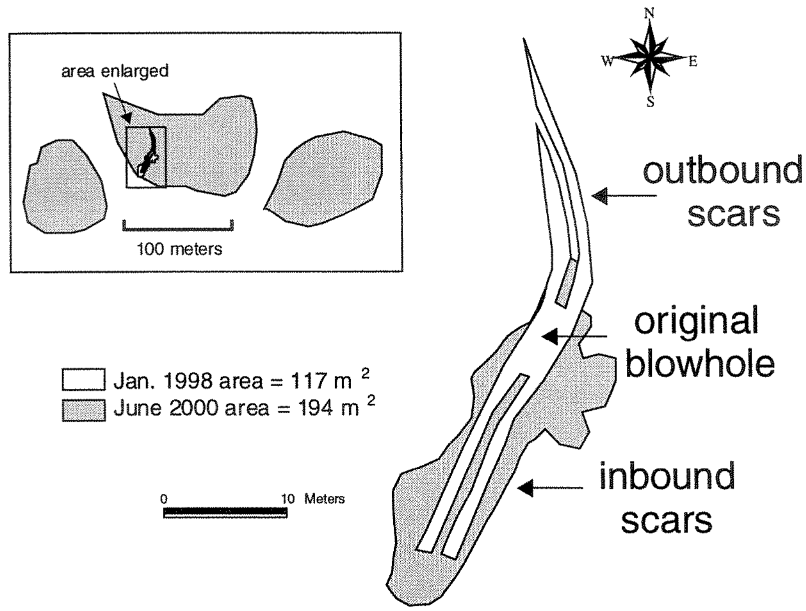

Figure 6. The *Broadbill* injury perimeters from January 1998 and June 2000 overlaid. The area enclosed in the square represents the location of the injury on the bank.

Broadbill and the Twin Screw case studies. The blowhole was seven times larger, and the island of seagrass between the twin propeller scars had also blown out and enlarged due to the formation of new excavation holes in the inbound track.

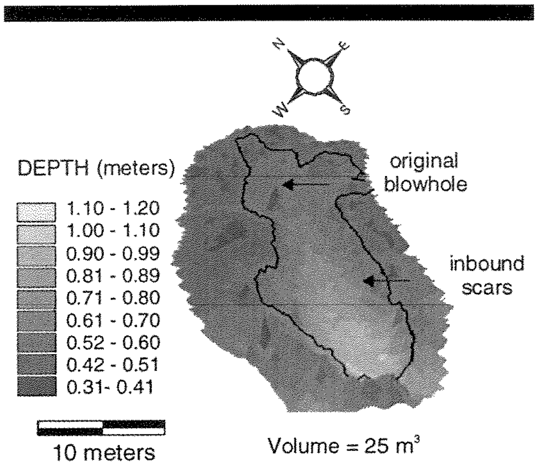

Figure 7. Three dimensional graphic of the bathymetry data for the *Broadbill* injury. The arrows point to the locations of the original inbound scars and blowhole. The volume of sediment scoured out was 25 m^3.

DISCUSSION

The four motor vessel injuries described in this paper increased in size by 65–135% following Hurricane Georges. These results show that motor vessel groundings destabilize seagrass beds and increase their vulnerability to further damage by severe storms.

In the three smaller injuries (the *Broadbill,* Twin Screw, and Motor Yacht), the deep blowholes created from the vessel groundings were enlarged by the hurricane. Our data also suggest that islands of seagrass separated by twin propeller scars are unstable. Seagrass islands between the propeller scars were completely lost in the inbound tracks of both the *Broadbill* and the Twin Screw injuries and were partially replaced by deep excavation holes. At the Motor Yacht grounding site, seagrass islands in the inbound track deteriorated due to the formation of three new blowholes as a result of the hurricane. Immediately following the vessel impacts, all three of the injuries were roughly linear in shape. The Motor Yacht, the most recent injury, maintained a more linear shape but appeared to be progressively deteriorating in the same manner as reported for the *Broadbill* and the Twin Screw injuries. These data sug-

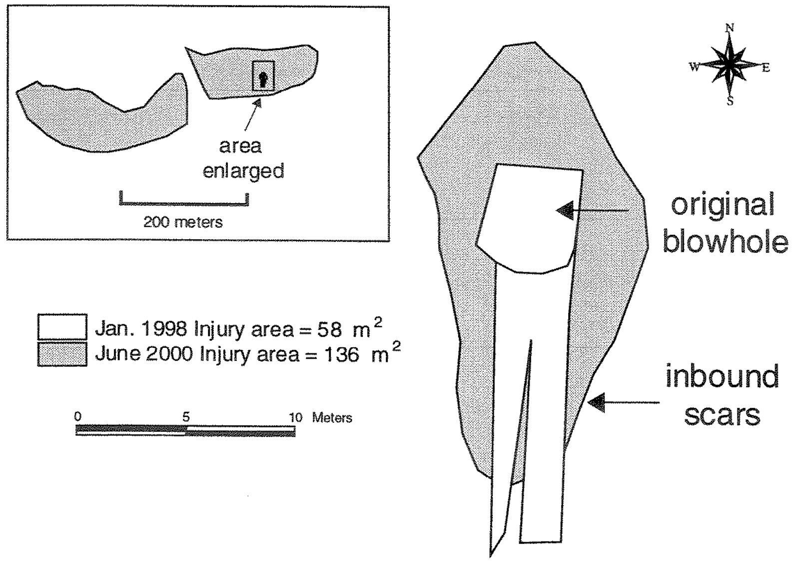

Figure 8. The Twin Screw injury perimeters from both time periods, January 1998 and June 2000. The arrows point to the locations of the original inbound scars and blowhole. The area enclosed in the box is the location of the injury on the bank.

gest that linear shaped injuries may continue to erode and form blowholes.

In the small injuries, we saw no evidence for recovery of blowholes. The only twin propeller scar that showed significant recovery was located in the outbound track of the *Broadbill* and was not distinguishable from the seagrass bank at the time of the second survey (Figure 6). One possible explanation for this recovery may be that during the storm surge, wave energy approaching from the south scoured and redistributed sediments out of the inbound propeller scars and into the original blowhole and the outbound scars, effectively regrading the site at the north end. Our suggestion is supported by the bathymetry data (Figure 7). This figure shows that the inbound propeller scars became the deepest part of this injury, and portions of the original blowhole (the north end) were regraded to within 20 cm of the surrounding seagrass bed. Overall, despite this isolated occurrence of post-hurricane recovery, the three smaller injuries enlarged considerably.

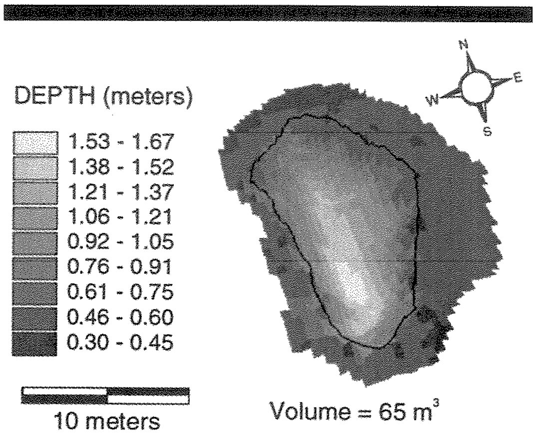

Figure 9. Three dimensional graphic of the bathymetry data for the Twin Screw injury. The area scoured from the banktop is 65 m^3.

All of these grounding sites were unstable, regardless of their location (*i.e.,* ocean vs. Gulf sides) or sediment regime (authors' personal observations), suggesting that the potential effects of hurricanes on vessel impacted seagrass banks could be widespread in a more severe storm. The bank on which the Motor Yacht grounded was a fine-grained carbonate sediment. The two similar sized groundings on Red Bay Bank, the *Broadbill* and the Twin Screw, occurred where the sediments consisted of a greater fraction of *P. porites* rubble, a much larger and heavier sediment texture. Our original concern for the potential impacts of vessel groundings was reaffirmed after an extensive in-

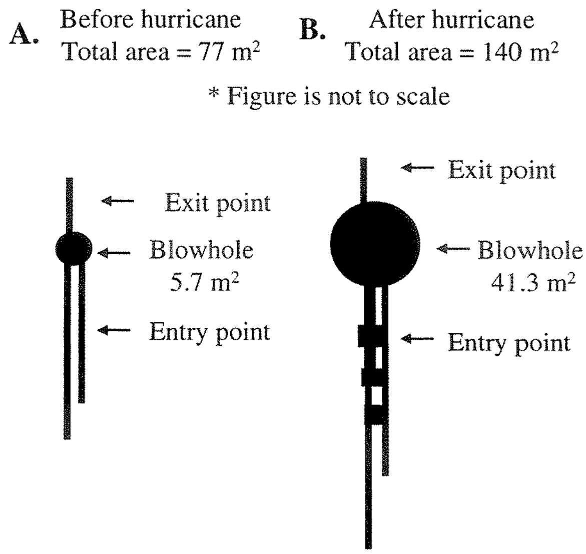

Figure 10. Injury area for the 19 m motor yacht injury before (A) and after (B) the hurricane.

spection of aerial photography and *in-situ* ground truthing in and around Red Bay Bank and the Middle Keys region following the hurricane. In contrast, there was no evidence from ground truthing or aerial photography that undisturbed seagrass beds were damaged by Hurricane Georges, supporting the long-held paradigm that healthy, intact meadows are resistant to storm damage (THOMAS *et al.,* 1961; OPPENHEIMER, 1963; TILMANT *et al.,* 1994).

Similar to the other three case studies, the *Captain Joe* injury was also enlarged after the hurricane. Biological data collected before and after the hurricane show that recovery rates were three times faster after the hurricane than after the original injury. The recovery rates during the 4.5 year period between the time of the original grounding and 9 months prior to the hurricane indicate seagrasses were recovering at a rate of 2.5% per year, and macroalgae were recovering at a rate of 18.9% per year. This is in contrast to the recovery rates of seagrasses and macroalgae after the hurricane, which were 7% and 23% per year, respectively. These data raise an interesting question: Why did the seagrass component recover faster after the hurricane than after the original grounding?

There are several possible explanations for the differences in seagrass recovery times before and after the hurricane. The storm may have helped to regrade the injury by redistributing unconsolidated sediments from the berms back into the trench, effectively smoothing the topographic gradient along the margins of the disturbance and improving conditions for recovery by vegetative growth into the site from the surrounding healthy seagrass beds. Furthermore, in the original grounding, all of the seagrass was scoured out or buried under a very deep *P. porites* rubble layer. After the hurricane, some *T. testudinum* beds were buried under a thinner layer of mixed, unconsolidated sediments (authors' personal observations). These conditions may have been much more suitable for growth than the mostly *P. porites* rubble deposited immediately after the grounding. MARBA *et al.* (1994) documented the ability of *T. testudinum* to withstand some degree of burial by sediments. Following Hurricane Gilbert, the vertical growth of *T. testudinum* enabled some plants to recover under moderate burial conditions (MARBA *et al.,* 1994). At the *Captain Joe* site, *T. testudinum* buried by Hurricane Georges may have recovered in the same manner as documented by MARBA *et al.* (1994).

Finally, faster seagrass recovery could be attributed to the smaller area of the injury after the hurricane relative to the original injury area. The original grounding injury was three times as large (7,363 m^2) as the injury area following the hurricane (2,514 m^2). Because the perimeter-to-area ratio was much greater after the hurricane than following the original grounding, it should take less time for vegetative growth to re-establish into the smaller injury. Despite the faster recovery rates following the storm, the cover of seagrasses and macroalgae was still well below the coverage on the undisturbed banks nearby. The footprint of the original injury was a distinct morphological feature of the bank eight years after the grounding occurred.

Unlike the crescent-shaped seagrass bed patterns resulting from naturally formed blowouts in tropical seagrass systems (PATRIQUIN, 1975) and high energy bedforms described in temperate regions (FONSECA and BELL, 1998), injuries created by motor vessel groundings are physically unstable. Typically, crescent-shaped natural blowouts are oriented with the long axis perpendicular to the prevailing wind or current and the convex side directed upstream (PATRIQUIN, 1975). Erosion at the upstream edge is caused by flow separation that increases the physical instability at the scarp face and contributes to the formation of the blowout (PATRIQUIN, 1975). Downstream of this scarp face, the blowout is recolonized by seagrasses propagating along the leeward slope. Eventually, baffling effects of seagrasses cause sedimentation on the leeward edge to increase faster than erosion at the scarp, and the blowout fills in.

In contrast, the shape and orientation of vessel-generated disturbances are such that they continue to erode throughout the injury margin. For example, the long axes of the *Broadbill* and the Twin Screw injuries were oriented parallel to the current (south to north) and originally extended from the top edge of the banks to the southerly fringe. This orientation left the injuries exposed to the wind-driven waves from the hurricane which came out of the south. The uneven surfaces created by the deep box-cut edges that extend beneath the seagrass rhizome layer are physically unstable like the upstream scarp of a natural blowhole. However, this unstable edge usually extends around the entire blowhole and is easily scoured and undercut, further increasing the instability of the feature.

In addition to problems with physical instability, the deep box-cut edges that extend deeper than the rhizome layer severely inhibit regrowth of *T. testudinum*. The dimorphic rhizome system of *T. testudinum* is programmed to grow horizontally or branch vertically upward (TOMLINSON, 1974). The rhizomes are thicker and more rigid than either *S. filiforme* or *H. wrightii* rhizomes and do not commonly grow down the walls of steep box-cut excavations created by motor vessels.

Since this is the first long-term study which examined large motor vessel injuries to seagrass beds, it is difficult to predict total recovery time. It is, however, likely to be more than 10 years. Previous studies addressing mechanical damage by propeller scarring alone indicate that *T. testudinum* will take 3–26 years to recover in a typical scar depending on the substrate type and the depth of excavation (ZIEMAN, 1976; DURAKO *et al.,* 1992; SARGENT *et al.,* 1995; DAWES *et al.,* 1997; KENWORTHY *et al.,* 2002). Additionally, propeller scars have a higher perimeter to area ratio than blowholes, and there is usually much less sediment excavated from a propeller scar. Therefore, we expect that recovery of deep excavation injuries will take much longer than recovery of single linear propeller scars.

MANAGEMENT IMPLICATIONS

Motor vessel disturbances have become ubiquitous in vegetated shallow water areas throughout South Florida and elsewhere in the Caribbean. Many of these injuries may recover very slowly or not at all. We recommend implementing a timely and aggressive damage assessment approach that would include, but not be limited to, four management options. These options could be used either in conjunction or separately: (1) physically regrading large blowholes to pre-injury levels through backfilling; (2) removing overburden from the adjacent undisturbed seagrass bed back into the blowhole; (3) replanting the blowholes with fast growing opportunistic seagrass species; and (4) implementing preventive measures, through strategic placement of navigational aids, updates of nautical chart nomenclature, and vessel operator training.

Backfilling has previously been used as a successful primary restoration strategy to mitigate the damage caused by excavating a trench for the placement of an aqueduct pipe in Lake Surprise (LEWIS, 1987), and in an 80 m long by 5 m wide propeller excavation in the Lignumvitae State Management Area (KENWORTHY *et al.,* 2000); both of these projects are located in the Florida Keys. Regrading increases the physical stability of the site by eliminating the box-cut edges, and it minimizes the potential for further expansion. Secondly, in cases where vessel groundings result in significant berm formation by the deposition of excavated sediments onto adjacent shallow banks, the replacement of the overburden back into the blowhole as soon as possible by hand raking or with a diver-operated water dredge, is recommended. Removal of the overburden minimizes the mortality of seagrass due to burial. Where applicable, both regrading (backfilling) and removal of the overburden back into the blowhole should be used in conjunction to increase stability and minimize damage.

In smaller injuries or less dynamic environments, transplanting primary colonizing species, such as *S. filiforme* and *H. wrightii,* into blowholes may be the best option. These species recruit and grow much faster than *T. testudinum* (FONSECA *et al.,* 1987; KENWORTHY *et al.,* 2002) and readily colonize unstable topographical features like the edges of blowholes (PATRIQUIN, 1975). This method of "compressed succession" uses the faster growing species to temporarily substitute for the climax species while stabilizing the injury and accelerating the eventual recovery of *T. testudinum* (DURAKO and MOFFLER, 1984; FONSECA *et al.,* 1998). This approach is currently being used to restore small propeller scars in the Lignumvitae State Management Area in the Florida Keys (KENWORTHY *et al.,* 2000). In this approach, growth of the colonizing species can be enhanced by fertilization so that dense seagrass cover can be attained in 1–3 years (FOURQUREAN *et al.,* 1995; KENWORTHY *et al.,* 2000).

Due to the high cost of restoration and the potential longevity of lost ecological services at injury sites, prevention may be the most desirable course of action. One option is establishing gated navigational aids (Red and Green) to mark channel boundaries on both sides. Many motor vessel groundings result from confusion on the part of the boat operators and their inability to read the water signatures (*e.g.,* color, surface characteristics, direction of flow), necessitating a foolproof marking system. Often the operators do not know which side of the navigational aid to pass. In the Red Bay Bank area, there are only single markers (one green or one red) that form a line leading north between the shallow banks. The location of the channel would be more apparent with gated markers. Nautical chart nomenclature could also be updated to reflect the dangerous nature of navigating in and around these shallow vegetated ecosystems. The nautical charts should include some dialog on the unique nature of the ecosystem and suggest avoidance or extreme caution while navigating in the area. Any information or additional training that increases boat operator awareness is crucial to preventing these injuries.

CONCLUSIONS

This is the first paper which examines large motor vessel impacts and their role in destabilizing seagrass beds by making them more vulnerable to severe storm effects. In the Red Bay Bank area alone, there were 146 blowholes and 50 propeller scar injuries found on 25 of the banks we examined. There are long-term implications for losses of seagrass habitat caused by motor vessel impacts, especially in the tropical climax communities dominated by *T. testudinum,* where recovery rates are very slow and the period of instability and vulnerability to severe storms is long. It is also noteworthy that as a category 2 hurricane, Georges was not very powerful. The impacts by a category 3 or greater hurricane would likely be even more devastating and longer lasting, depending on the storm surge and direction of passage (TILMANT *et al.,* 1994).

In the near future, large vessel groundings will continue to occur in shallow waters throughout the Florida Keys. At best, the most severe vessel injuries will recover very slowly. During periods of time when hurricanes are frequent, some grounding sites may never recover to pre-injury conditions. In order to avoid further damage and longer recovery periods, the use of several different management strategies is recommended to emphasize both prevention and restoration.

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