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Boating impacts to seagrass in Florida Bay, Everglades National Park, Florida, USA: links with physical and visitor-use factors and implications for management

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Abstract. Recreational motor boating in shallow water can damage submerged natural resources through propeller scarring and these impacts represent one of many factors that affect the health of seagrass ecosystems. Understanding the patterns of seagrass scarring and associations with physical and visitor-use factors can assist in development of management plans that seek to minimise resource damage within marine protected areas. A quantification of seagrass scarring of Florida Bay in Everglades National Park, using aerial imagery, resulted in the detection of a substantial number and length of seagrass scars. Geospatial analyses indicated that scarring was widespread, with the densest areas found in shallow depths, near navigational channels, and around areas most heavily used by boats. Modelling identified areas of high scarring probability, including areas that may experience increased scarring in the future as a result of a reallocation of impacts if management strategies are implemented. New boating-management strategies are warranted to protect seagrass in Florida Bay. An adaptive approach focusing on the most heavily scarred areas, should consider a variety of management options, including education, improved signage, new enforcement efforts and boating restrictions, such as non-motorised zones, or temporary closures. These methods and recommendations are broadly applicable to management of shallow water systems before and after resource impacts have occurred.

Additional keywords: groundings, marine protected areas, propeller, scarring, recreational impacts.

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Introduction

Globally, physical damages caused by boating are recognised among the multiple stressors contributing to the decline of seagrass (Orth *et al.* 2006). Human-caused seagrass damage has been identified in shallow coastal areas throughout Florida and other shallow-water marine habitats through multiple studies (e.g. Kuss 1991; Kruer 1994; Sargent *et al.* 1995; Engeman *et al.* 2008). In addition to nutrient inputs, altered hydrology, and anthropogenically induced algal blooms, physical damage to seagrass by boats has occurred for many years in Florida Bay, Everglades National Park, Florida, and contributes significantly to the disturbance of seagrass meadows (Zieman 1976; Sargent *et al.* 1995).

Everglades National Park (ENP) encompasses ~607 000 ha at the southern tip of peninsular Florida. Included within the park boundary are over 200 000 ha of marine environments, including portions of Florida Bay (~162 000 ha). The bay, as part of ENP, is internationally significant, with designations as an International Biosphere Reserve, a World Heritage Site 'in danger', a Wetland of International Importance under the 1987 Ramsar Convention, and as part of the National System of Marine Protected Areas in the United States. Most of Florida Bay was designated by the United States as part of the Everglades Wilderness in 1978; thus, the area is subject to administration under the provisions of the Wilderness Act of 1964 (Fig. 1). It is characterised by extensive areas of shallow water (<1.0 m at low tide), punctuated by deeper natural basins separated by banks with natural and man-made channels connecting them and it supports submerged aquatic vegetation made up of seagrasses (e.g. *Thalassia testudinum* and *Halodule wrightii*) and marine algae. Vegetated areas serve as nursery habitat for commercially important fisheries, such as spiny lobster (*Panulirus argus*), stone crab (*Menippe mercenaria*), pink shrimp (*Farfantepenaeus duorarum*) and a variety of reef-fish species. The bay and its submerged vegetation also provide habitat and feeding grounds for state- and federally listed species such as manatees (*Trichechus manatus*) and many sea turtles. Florida Bay represents one of the premier shallow-water boating and fishing destinations in the world and recreational fishermen utilise small and medium-size boats to access prime fishing grounds to pursue fishes such as bonefish (*Abula vulpes*), redfish (*Sciaenops ocellatus*), snook (*Centropomus undecimalis*), spotted seatrout (*Cynoscion nebulosus*), and tarpon (*Megalops atlanticus*).

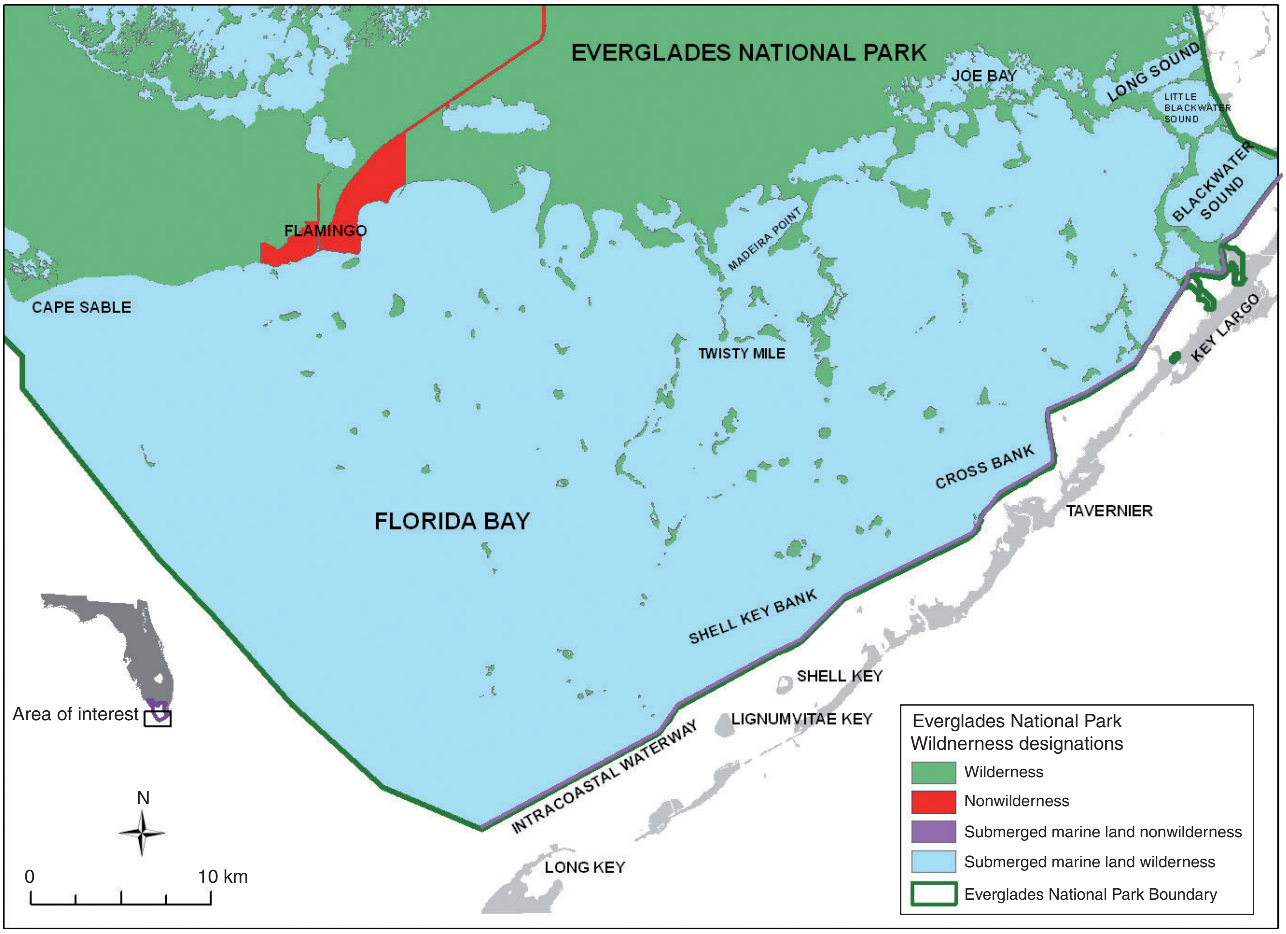

Fig. 1. Wilderness areas within Florida Bay, a marine protected area within Everglades National Park, Florida, USA.

Recreational angling and boating are becoming increasingly popular within ENP. Ault *et al.* (2008) estimate that boating use within the boundaries of ENP has increased from 2 to 2.5 times between the 1970s and 2007, largely following the increase in population within south Florida and boat registrations in local counties covering ENP have also increased substantially since 1995 (Florida Fish and Wildlife Conservation Commission 2007). Increased boating activity, often by boaters with little or no previous experience in navigating the numerous shallow flats and complex of narrow channels of Florida Bay, make parts of the bay very susceptible to visitor impacts resulting from the operation of motorised watercraft. Damage from boats generally occurs when a boat propeller (prop) contacts either the submerged vegetation or the vegetation and the bay bottom. In addition, prop scarring occurs when boaters use the prop to dredge new channels or maintain existing, man-made channels.

Prop scars lead to direct loss of seagrass and sediment excavated by boat props within channels can form berms adjacent to channels that may bury seagrass, causing mortality and an increase in susceptibility of seagrass beds to damage from hurricanes (Duarte *et al.* 1997; Whitfield *et al.* 2002). Estimates of recovery time for prop scars vary depending on the severity of the scar and the seagrass species that is damaged, ranging from as little as 0.9 years (Sargent *et al.* 1995) to 7.6 years (Andorfer and Dawes 2002). Recent model-derived estimates of scarring recovery in *T. testudinum* beds suggest that some areas in the Florida Keys may require 60 years for recovery (Fonseca *et al.* 2004).

Prop scarring has been observed throughout Florida Bay in shallow flats, bights, bays and banks and in other high-use areas (Fig. 2). Historical photographs show evidence of prop scarring over the years; however, no detailed study had quantified the extent of seagrass damage in Florida Bay before the present effort. Previous systematic efforts to map prop scars in ENP have been limited. Sargent *et al.* (1995) included Florida Bay in their state-wide assessment of Florida's seagrass beds and identified 814 ha of scarred seagrass beds within ENP. However, recent anecdotal observations indicated that scarring was more widespread than previously identified.

To implement effective marine management strategies that conserve seagrass meadows and recover damaged areas, while maintaining public access, managers must understand existing prop-scarring conditions and potential associations with physical factors, such as water depth and presence/absence of aids to navigation, along with public-use factors that explain how, where, and to what extent Florida Bay is visited. Little

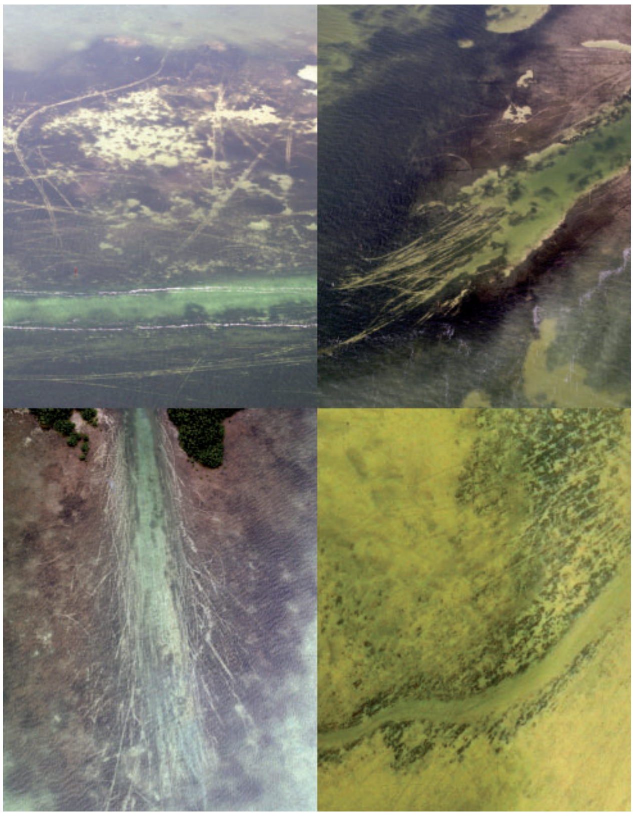

Fig. 2. Examples of propeller scarring photographed in 2006 and 2007 at Upper Cross Bank, Twin Key Bank, The Boggies and the mouth of Alligator Creek, Florida Bay, Everglades National Park, Florida, USA.

information on the locations, patterns and relative density of prop scarring had been available for Florida Bay. In the present study, we sought to

(1) characterise seagrass scarring throughout Florida Bay,
(2) determine whether levels of prop scarring were increasing or decreasing at specific locations,
(3) assess potential relationships between prop-scar density and location of seagrass scarring when analysed against water depth, proximity to shorelines, proximity to marine facilities, proximity to navigational channels, and patterns of fishing and boat use in Florida Bay,
(4) develop a statistical model by relating scar density with physical and visitor-use factors to aid in prevention of scarring in undamaged areas, and
(5) utilise results of the analyses and model to recommend marine management strategies that permit boat access to traditionally used areas, but reduce the potential for damage to marine resources.

Materials and methods

Scar mapping

Georeferenced digital imagery at 0.5-m resolution of Florida Bay from April 2004 was used to digitise propeller scarring throughout the Florida Bay portion of ENP. Images were created from 1 : 24 000-scale true-colour raw scans (Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute 2004), georeferenced and reviewed for spatial accuracy according to National Map Accuracy Standards (United States Geological Survey 2007). Previous assessments of propeller scarring (e.g. Sargent *et al.* 1995) have indicated that imagery at this scale will not show all propeller damage to seagrass beds. However, review of the images indicated that enough scarring was evident to identify and map heavily scarred areas as well as some individual scars in areas with less damage. Therefore, the images were used to develop a conservative estimate of scarring, determine relative scarring densities and visualise spatial scarring patterns.

Images of the ENP portion of Florida Bay were reviewed in 10–25-ha increments for visible scars in ArcMap version 9.2 (ESRI 2006). Each visible scar was digitised by tracing as an individual line segment. Generally, images were viewed at the greatest magnification possible that allowed a clear view of the bay bottom. At magnifications greater than 1 : 1000–1 : 2000 image quality prevented discerning and mapping prop scars. No attempt was made to ground-truth individual scars that were identified in the imagery used in the present study; however, observations conducted during several helicopter flights confirmed heavily scarred areas identified in aerial photography. Scar line data were overlaid with 100-m^2 grid cells to calculate scarring density (m m^{-2}). The areas with the greatest density of scarring (top 10%) were selected and mapped to examine possible priority areas to focus on in the development of marine management strategies. To determine whether the analysis under- or over-estimated scarring when compared with more recent and higher-resolution imagery, we utilised a partial set of higher-resolution imagery for north-central Florida Bay to quantify scarring. The high-resolution imagery was collected in 2006 at 0.30-m resolution; however, it was available only for a small portion of Florida Bay, so it could not be used for most of the study area.

Prop-scar change analysis

Partial sets of 1 : 24 000 digital imagery of Florida Bay from 1999, 2004 and 2006 were used to conduct a change analysis among these time periods. We analysed three areas of Florida Bay where scarring was visible in the same location on aerial photographs taken over multiple years and separated by some period of time. The aerial extent and suitability for use in mapping varied greatly, limiting the amount of potential area that could be mapped for comparative purposes. Imagery from 1999 consisted of digital orthographic quarter-quads in MrSID format. Imagery from 2006 was prepared for the 2006 Monroe County Florida Orthophoto Project in MrSID format (Woolpert Inc. 2007). All three digital image sets were at 0.5-m-pixel resolution. Areas within Florida Bay identified as suitable for comparative mapping were as follows: Twisty Mile, an area located south of Madeira Point; Shell Key Bank, north of Shell Key; and Cross Bank, east of Tavernier. Twisty Mile and Shell Key Bank were mapped using 1999 and 2004 imagery and the Cross Bank area was mapped using 1999, 2004 and 2006 images. In all cases, scar data were compared among years and unique scars were identified by their similarity of shape and location to determine the percentage of scars remaining in the subsequent photo. In addition to mapping individual scars, we attempted to measure the change in area of a new channel that was established through repeated prop scarring and boat travel, on Shell Key Bank. The channel was mapped using 1995 (.jpg and 0.5-m resolution), 1999 and 2004 imagery. Polygons were drawn around the area denuded of vegetation in each of the three photos, to estimate the area devoid of seagrass.

Geospatial analyses

We explored the relationship between scarring and water depth and proximity to several types of features (e.g. shorelines, boat activity). Proximity was generated in 100-m increments for all factors except water depth. The following data layers were used:

Water depth

Bathymetry data in North American Vertical Datum 1988 (NAVD88) for Florida Bay were obtained from a 1990 fathometer survey (Hansen and DeWitt 1999). Transects ran mostly north–south, typically ~500–600 m apart, with depth measurements collected in feet approximately every 3 m along the transect. Ordinary kriging with anisotropy was used to create a continuous gridded surface of interpolated bathymetry for the bay (RMS = 0.07 m, average s.e. = 0.17 m) at 100-m resolution. NAVD88 vertical datum is ~0.41 m above mean low water (MLW) in the Florida Bay area (Hansen and DeWitt 1999).

Channels

Centrelines of marked and unmarked channels in Florida Bay were traced using a National Park Service Map and Guide (National Park Service and Florida Keys Fishing Guides Association 2006). Marked channels were identified as those with aids to navigation installed along the sides of the channel.

Marine facilities

Location data were compiled for marine facilities including docks, boat ramps, marinas and other areas at which boats may congregate or launch (Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute 2006). Attributes of the point data include location and characteristics of the following facilities: boat ramps, bridges, fish camps, jetties, marinas, parks and piers. Because the marine facilities were well distributed along the Florida Keys, they generally represent the distance of scarring from the Florida Keys and Flamingo, the primary boat launch site within ENP (Fig. 1).

Boat use

Boat-use data were collected for all marine waters in ENP between fall of 2006 and fall of 2007, using aerial methods (Ault *et al.* 2008). We used motorised watercraft data based on two categories, namely, fishing and transiting. Because ENP fishing reports over many years demonstrate that more than 90% of boating activity in the park has been associated with recreational fishing (National Park Service 2006), it was presumed that most transit activity was associated with a boat going to or from a fishing-related activity, or as a recreational or commercially guided trip (Fig. 3).

Shorelines

Shoreline data were obtained from the official ENP map. These data included shorelines for all islands in Florida Bay and the entire northern coastline of ENP, from Cape Sable to Long, Little Blackwater, and Blackwater Sounds (Fig. 1).

Areas in which seagrasses cannot be damaged because submerged rooted vascular (SRV) cover was not present were excluded from the analysis by screening the imagery with benthic cover-type data (Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute 2005). Benthic cover-type data included 47 descriptive classes for sea bottom and an upland class. These classes were aggregated into two classes relevant to the present study: areas of continuous or discontinuous SRV plants and areas without SRV cover, including hard bottom, turbid plume, unconsolidated sediments, attached macroalgae, upland, and others. Areas with water depth greater than 2.0 m MLW were also excluded because 99% of prop scarring occurs in water depths shallower than 2.0 m MLW (Fig. 4).

We sought to evaluate the relationship between scarring and physical and visitor-use factors by using logistical regression; however, we determined that it could not be performed because, although variables were normally distributed, a large number of outliers caused substantial heteroscedasticity and transformations were not effective in achieving homoscedasticity. As an alternative, we used non-parametric generalised additive models for location, scale and shape (GAMLSS) (Rigby and Stasinopoulos 2005) with a Poisson distribution for fitting scar-density relationships to each of the following nine variables using the R statistical software package (R Development Core Team 2007):

(1) water depth (Depth),
(2) proximity to all channels (ChanPx),
(3) proximity to marked channels (MChanPx),
(4) proximity to marine facilities (DockPx),
(5) proximity to shorelines (ShorePx),
(6) proximity to boats engaged in fishing (FishPx),
(7) proximity to boats transiting between locations (TransitPx),
(8) proximity to recreational boats (RecPx), and
(9) proximity to commercial boats (ComPx).

A scatter plot of scarring density *versus* proximity to boats engaged in fishing demonstrated that scarring tends to increase as distance to boats engaged in fishing decreases (Fig. 5). At any given distance, however, all scarring densities from zero to the maximum at that distance were also present, thus, causing poor correlation. This issue is common to all the variables and was resolved by refocusing the analysis on the most heavily scarred areas. Management efforts are likely to concentrate on these areas because high-density scarred areas may also be more likely to include areas of deep scarring. Deep scarring is of particular management concern because seagrass recovery rates may be much slower at these sites. Models tracking maximum scarring with distance appear to have a stronger trend, so maximum scarring data were identified as the top 10% of scar-density values within each 100-m interval over the range of proximity data (e.g. Fig. 5). For depth data, the top 10% of scar-density values was selected within each 0.03-m interval

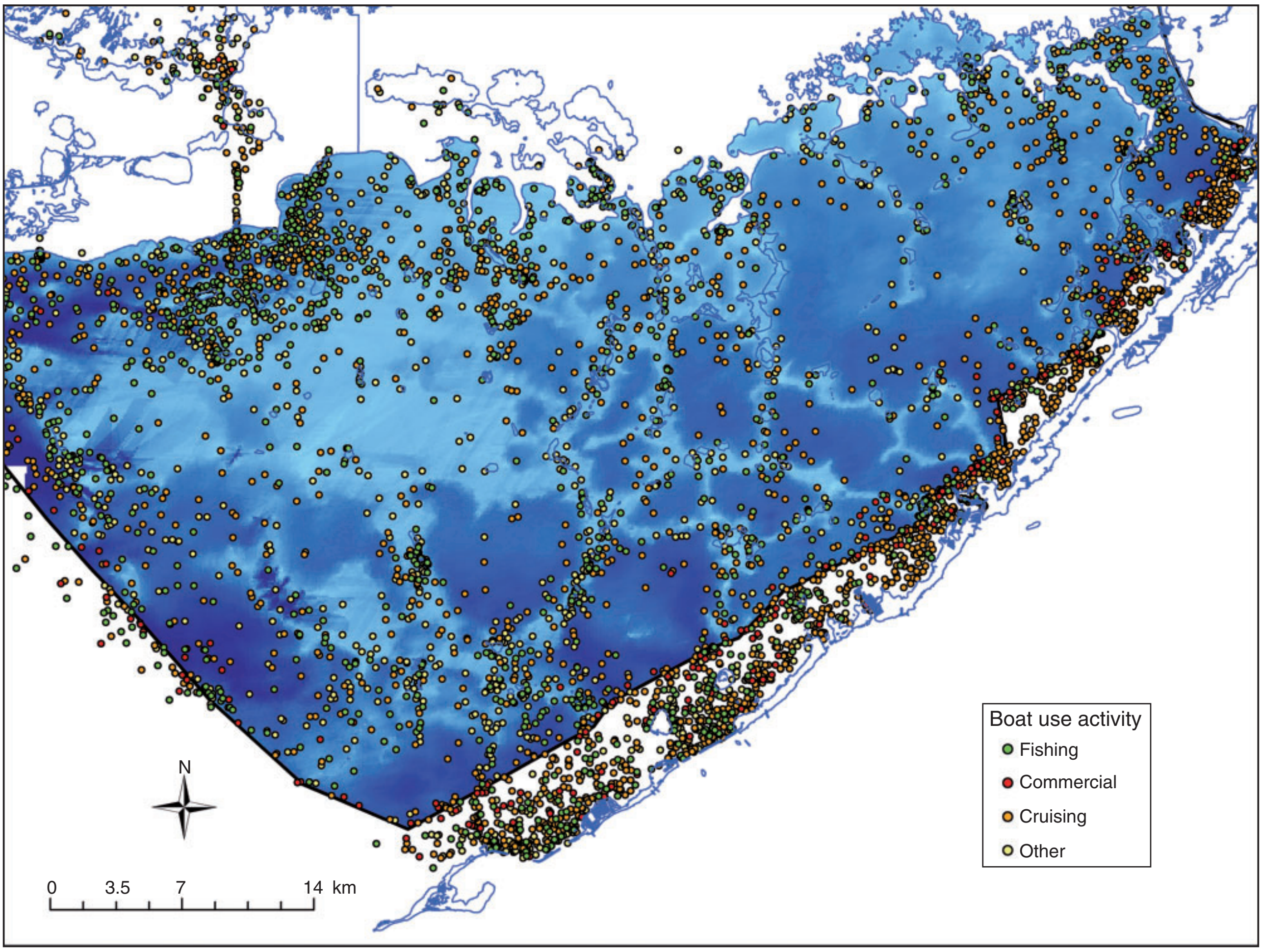

Fig. 3. Distribution of boating activity from 2006–2007 in Florida Bay, Everglades National Park, Florida, USA (from Ault *et al.* 2008).

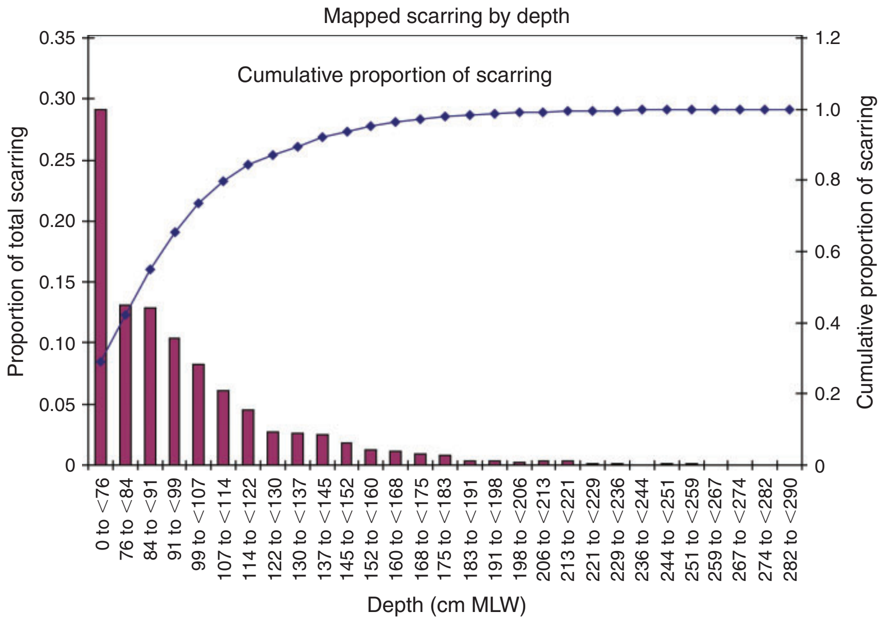

Fig. 4. Proportion of total scarring and cumulative proportion of scarring (line) *versus* water depth at mean low water (MLW) in Florida Bay, Everglades National Park, Florida, USA.

over the range of depths. A compromise between the best statistical match and over-fitting the data was achieved by constraining the GAMLSS not to exceed nine effective degrees of freedom.

We also developed a composite index model to help identify areas with the highest probability of scarring, using factors that managers could focus on in future management strategies, including management by water depth, areas of high boat use, areas around navigational channels, and areas near shorelines. Multiple regression techniques were not used because data values selected as a running maximum will, in the majority of cases, be selected from different locations for one explanatory variable than they are for another one. The difficulty created is that any attempt at multiple regression analysis will have values at a location for one variable but most likely not for the other variables at that location. Rather than attempt complex 'missing value' data manipulations, an overall estimate of maximum likely scar densities was created by calculating the mean of several mapped data layers into a composite index model to estimate areas within Florida Bay that have a high probability of scarring. Spearman's rank correlation analyses were performed for each unique pair of the nine variables to eliminate redundant variables (Table 1). Spearman's rank correlations for each unique pair of variables demonstrate that FishPx, RecPx and TransitPx were highly correlated, as were ChanPx and MChanPx, thus indicating that any one of these three boating variables or two channel variables could be used for the model (Table 1). We chose FishPx *versus* ComPx because fishing is the primary activity associated with boating in Florida Bay and ChanPx *versus* MChanPx to include the variable associated with both marked and unmarked channels. The final selection for the combined index uses the following four of the variables: Depth, FishPx, ShorePx and ChanPx. Maximum estimated scar density was mapped in ArcGIS version 9.2 (ESRI 2006) for each spatial data layer on the basis of the GAMLSS curves predicted for that variable.

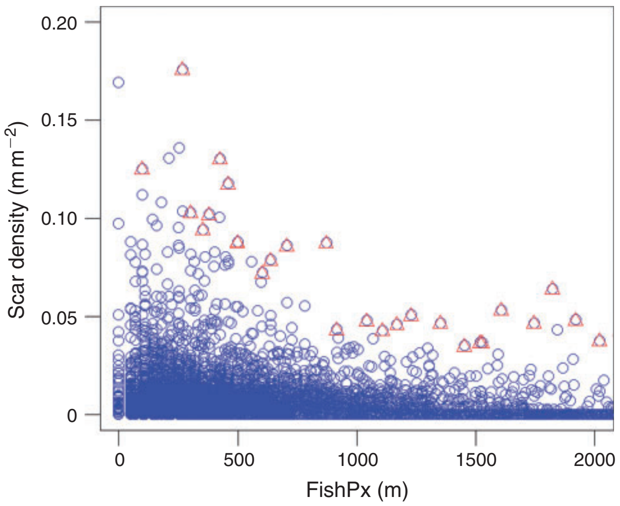

Fig. 5. Seagrass scarring density (m m^{-2}) in relationship to distance from boats engaged in fishing. Circles represent all observations, whereas red triangles represent the most densely scarred cells as defined by the top 10% of observations for each 100-m distance interval.

Results

Scar mapping

In total, 11 751 line segments representing 527 498 m of propeller scars were mapped throughout Florida Bay (Fig. 6). In some cases, scars cut across patchy grass flats or traversed deeper areas or were otherwise not continuous. Mapped scars ranged in length from 2.1 m to 1680 m, with a mean length of 44.5 (s.d. ± 52.7) m. Scar densities ranged from 0 to 0.025 m m^{-2}, with the majority (>75%) of the 100 × 100 m grid cells mapped with scarring less than 0.0125 m m^{-2}. Scar-density mapping suggested that scars cover a large portion of the shallow water area, and patterns generally matched those of the shallow flats and mud banks. In one small area of the Bay, comparison of the 2004 imagery with the higher-resolution imagery of 2006 resulted in detection of 340 scars, totalling 23 443 m by using the 2004 imagery *versus* 3975 scars totalling 155 550 m by using the 2006 imagery.

Change analysis

The number and total length of prop scars increased between 1999 and 2004 at all three sites (Table 2). All sites had four to five times more scars in 2004 than in 1999. Between 9.8% and 15.6% of scars that were present in 1999 were still visible 5 years later. At Cross Bank, where imagery from 2006 was available, the number and total length of scars decreased between 2004

Table 1. Spearman's rank correlations for all pairs of variables ($n = 197\,628$)
$P \leq 0.001$ for all correlations

Variable	ChanPx	MChanPx	DockPx	ShorePx	FishPx	TransitPx	RecPx	ComPx
MChanPx	0.72							
DockPx	−0.06	0.32						
ShorePx	0.39	0.37	0.30					
FishPx	0.24	0.29	0.11	0.28				
TransitPx	0.17	0.35	0.22	0.16	0.44			
RecPx	0.27	0.35	0.16	0.29	0.82	0.72		
ComPx	−0.34	0.42	0.44	0.23	0.12	0.33	0.14	
Depth	0.34	0.11	−0.03	0.49	0.11	−0.14	0.07	−0.62

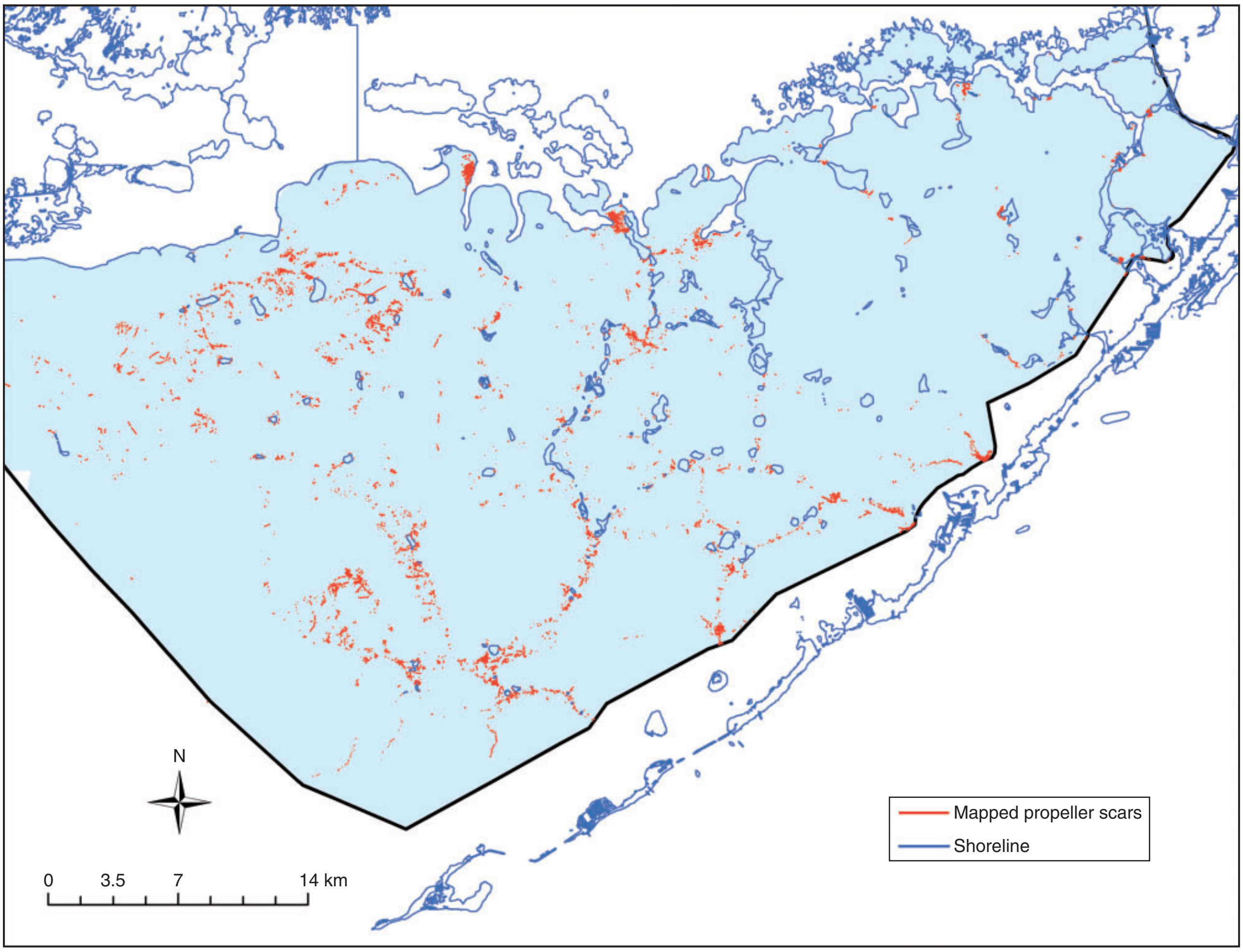

Fig. 6. Propeller scarring mapped from 2004 aerial imagery in Florida Bay, Everglades National Park, Florida, USA.

Table 2. Number, total length and percentage of seagrass scars remaining at three locations in Florida Bay, Everglades National Park, Florida, USA

Location	Year	No. of scars	Length (m)	Percentage of scars remaining
Cross Bank	1999	83	4342	n.a.
Cross Bank	2004	387	14 395	15.6
Cross Bank	2006	311	11 959	36.7
Shell Key Bank	1999	52	3475	n.a.
Shell Key Bank	2004	225	9986	15.4
Twisty Mile	1999	61	2936	n.a.
Twisty Mile	2004	300	12 360	9.8

and 2006 by 20% and 17%, respectively, yet in this same time, 36.7% of the scars that were visible in 2004 were still visible in 2006 (Table 2). The area of impacted vegetation at the channel on Shell Key Bank increased from 0.15 ha in 1995, to 0.33 ha in 1999, to 0.52 ha in 2004.

Geospatial analysis

A wide range of scar densities occurred at all distances for the proximity variables and at all depths for the water-depth variable (Fig. 7). A larger number of cells had dense prop scars when they were in shallow water depths and in close proximity to channels, shorelines and locations with relatively high levels of boating activity, including fishing or transiting associated with recreational and guided trips. For all variables, GAMLSS results were significant ($P \leq 0.001$) towards higher densities of scarring as distance decreased or with decreasing water depth (Fig. 7). The composite index model indicates that large parts of Florida Bay are susceptible to scarring and also indicates that scarring data generally overlap areas that were predicted by the model to be scarred (Fig. 8).

Discussion

Results of the prop-scarring analyses documented that scarred areas are extensive and ubiquitous throughout the shallow waters of Florida Bay. High-density scarring was limited to shallow areas (≤2.0 m), but did not appear to be restricted to any

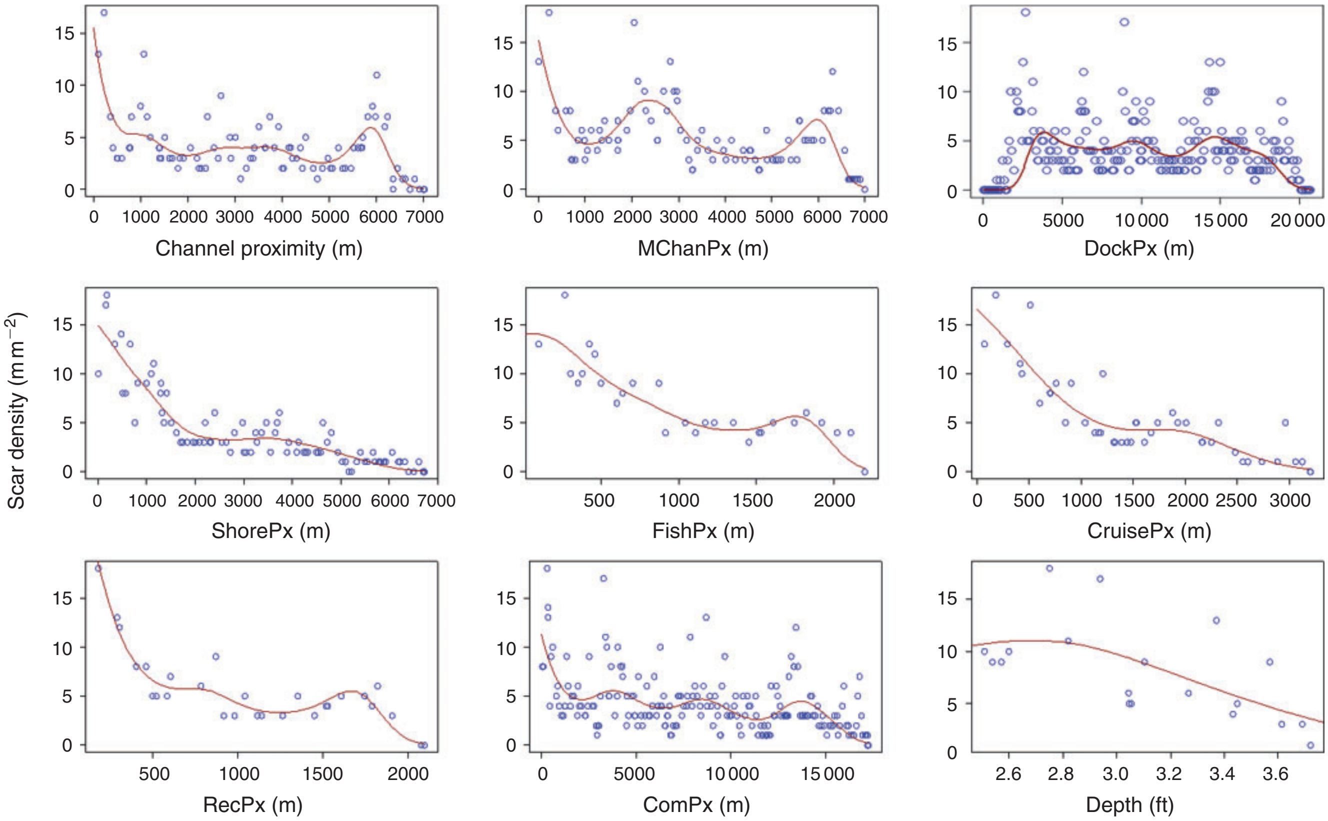

Fig. 7. Generalised additive models for location, scale and shape (GAMLSS) with a Poisson distribution for fitting the top 10% of scar densities (m m^{-2}) in relationship to proximity to all channels (ChanPx), marked channels (MChanPx), marine facilities (DockPx), shorelines (ShorePx), fishing boats (FishPx), transiting boats (TransitPx), recreational boats (RecPx), commercial boats (ComPx) and water depth (Depth). All models are significant ($P \leq 0.001$).

particular bottom feature, e.g. on banks, near channels or near the Florida Keys. Scarring presence was substantially greater than that reported by Sargent *et al.* (1995) and our methodology for quantifying scar density was different; we used a 100-m^2 grid-cell layer to calculate density, as opposed to using a density scale and hand-drawn polygons around scarred areas. We recommend the grid-based approach for future studies because it eliminates ambiguity associated with where scarred areas begin or end. Our comparison of the 2004 imagery with the higher-resolution imagery of 2006 in north-central Florida Bay suggested that we may have substantially underestimated the number and length of scars. Factors affecting underestimation included the difficulty in differentiating scars in heavily damaged areas and areas where drift algae may have filled in and obscured scars, and photo-quality issues, such as surface glare, wind-related disturbance and water transparency. For example, few scars were found in north-eastern Florida Bay (Fig. 6); however, poor water transparency during imagery acquisition may have influenced our results. Consequently, our results represent a conservative estimate of scarring presence, mean length, total length and density. Nevertheless, results are useful to describe relative scar density, patterns of scarring density as they relate to visitor-use factors and areas where management strategies can be focussed to avoid future impacts and implement restoration. The change analysis documented that some prop-scarred areas are, at best, stable in terms of the number and length of scars (i.e. there is no net recovery); however, data also suggested that in some locations the quantity of prop scars and their length may be increasing over time. The substantial increases in mapped scars between 1995 (Sargent *et al.* 1995) and 2004 throughout the bay, the persistence of scars at all change-analysis sites, the increase in the southern Florida population, and the increase in motor-boat registrations suggested that prop scarring is likely to remain a prominent resource concern in shallow-water areas.

Recovery of scarred seagrass is uncertain and our results indicated that scars persist over time and may be influenced by the scar severity and species composition. The rhizome architecture of *T. testudinum*, for example, is not flexible enough to grow down into the remaining sediment (Marbà *et al.* 1994), and deep excavations are more susceptible to secondary continued erosion and expansion of scars from currents, winds, waves and storms (Zieman 1976; Kuss 1991; Durako *et al.* 1992; Rodriguez *et al.* 1994; Hastings *et al.* 1995; Dawes *et al.* 1997; Kenworthy *et al.* 2002; Whitfield *et al.* 2002). In addition, drift algae filling scars may also slow recruitment or recovery of seagrass species (Hammerstrom *et al.* 2007). Recovery may be influenced by the impacts of sediment suspension and wave activity that is caused by motor-boat wakes by reducing light transmittance. However, boat wakes have been found to have small impacts on sediment suspension and water quality relative to natural wave action (Koch 2002).

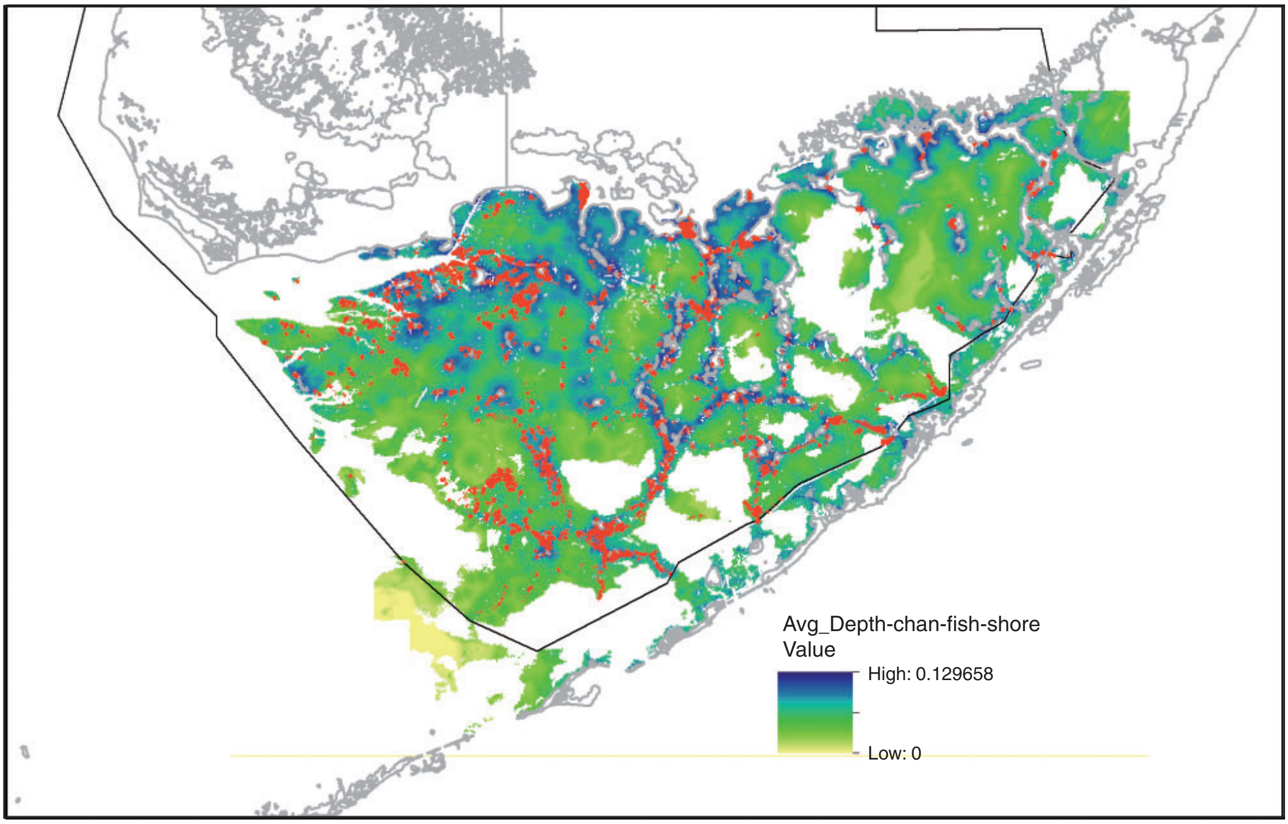

Fig. 8. Modelled maximum expected boat propeller scarring using shoreline-proximity, fishing-proximity, channel-proximity and water-depth data for Florida Bay, Everglades National Park, Florida, USA. Observed scars are overlaid in red.

Prop scarring is directly related to water depth and is greatest in shallow areas. Consequently, marine-resource protection plans may consider the use of depth thresholds to manage access of motorised watercraft in areas that are most susceptible to prop scarring or other human-caused impacts, such as damage to coral reefs. Results indicated that scarring is denser near shorelines; thereby, suggesting that zoning in areas within some proximity of shorelines may be an effective management tool. The relationship between scarring and proximity to navigational channels suggested that resource managers should place some focus on strategies that increase navigation awareness in and around shallow water areas. There was no clear difference in this relationship when examining marked and unmarked channels, although we initially hypothesised that areas around marked channels would have a lower density of scarring. This finding may be a result of a more intensive use of marked than unmarked channels. Improving aids to navigation will probably help reduce scarring in areas that are proximal to the channel; however, it is not likely that these markings would result in bay-wide reductions in scarring.

Ault *et al.* (2008) found that boats are well distributed throughout Florida Bay and our results indicated that scar patterns align according to the level of boating activity. This finding confirmed that outreach and education focussed towards recreational anglers is warranted and marine facilities are obvious locations to implement these programs, given the number of recreationists that originate from these areas. Scarring was also significantly related to proximity to marine facilities, but observations of scarring (Fig. 6) and the GAMLSS results (Fig. 7) suggested that scarring levels can be high throughout the bay and that management effort, such as zoning, should be considered bay-wide. Other strategies should consider factors such as boat size, potential draft, hull shape, horsepower, and the use of adjustable outboard motor mounts, e.g. jack plates. In Lignumvitae Key Submerged Lands Management Area, boat size was not related to an increase in the area of damage, but it was related to damage severity (Engeman *et al.* 2008). Generally, managers should consider the notion that boats with larger-horsepower motors, larger propellers, longer outboard motor shafts, and boats with deeper draft depths have the potential to result in greater resource damage in shallow waters.

Studies on the secondary impacts of seagrass damage in shallow-water ecosystems have presented mixed results. Negative ecological impacts of prop scars have been observed. For example, Uhrin and Holmquist (2003) observed lower abundances of crabs and molluscs in and around scars, and Burfeind and Stunz (2007) observed a decrease in shrimp growth in scarred areas. In contrast, several studies have indicated no impact to fish in scarred areas (Bell *et al.* 2002; Uhrin and Holmquist 2003; Burfeind and Stunz 2007) and no impact to overall nekton communities (Burfeind and Stunz 2006). Fonseca and Bell (1998) observed rapid loss in structural complexity of seagrass habitat when fragmentation exceeded

50% coverage. Although secondary impacts of boat-induced seagrass damage may be limited, reducing or eliminating benthic damages should contribute to promoting natural resilience, an important adaptation strategy for areas susceptible to climate change (Falkenberg *et al.* 2010).

Prop scarring may have an impact on user experiences in marine protected areas. As a premier sport-fishing destination, Florida Bay is extremely important to the recreational fishing community, including professional fishing guides in the southern Florida area. These stakeholders have a vested interest in providing visitors from all over the world with a quality experience in the park. User satisfaction during recreational fishing trips may be affected by aesthetics and fishing success. Just as diver-induced coral damages affect reef aesthetics (Tratalos and Austin 2001), aesthetic values of seagrass beds are affected by damages caused by boats. Users, especially those seeking wilderness values, such as opportunities for solitude, wildlife viewing, paddling, sight-fishing, interpretive and education programs, and camping may be negatively influenced by the aesthetic impacts caused by prop scarring.

Although challenging in large marine protected areas with permeable boundaries, education is an important component in the protection of sensitive marine resources. Education is not a substitute for on-the-water experience and local knowledge. Duarte *et al.* (2008) reported that seagrass ecosystems receive the lowest level of coverage in the media when compared with other ecosystems such as mangroves and coral reefs; thus, it is not surprising that public awareness is limited in coastal areas. Regulatory requirements such as those that require users to participate in mandatory safe-boating courses paired with education may be an effective combined approach.

Slow-speed and idle zones may be used to slow motorised watercraft and reduce the potential for seagrass damage. These zones are widely used in Florida in an attempt to reduce collisions between boaters and wildlife. However, boats generally draft more water when idling. Therefore, idling or slow-speed transit may also result in some level of scarring and associated turbidity. Implementation of non-motorised zones, often called 'pole and troll zones', warrant consideration because these zones greatly reduce or eliminate the possibility of prop scarring by allowing only human-powered transit via push poles, very low horsepower electric motors, and paddles for boat locomotion. Pole and troll zones are likely to present solutions that have a high probability of reducing prop-scar impacts while still allowing access. However, simply restricting motor-boat access does not guarantee that scarred areas will recover or that the area of damage will decline. For example, Engeman *et al.* (2008) reported a continual increase in benthic damages despite the establishment of a no-motor-zone area in Lignumvitae Key, Florida. Enforcement or other means of ensuring compliance with regulations should be considered a critical component of a successful marine-resource recovery program.

Management strategies should be tailored to specific goals for recovery of seagrass and other sensitive marine resources. Monitoring should be carried out with the intent of determining how well implemented strategies meet the following objectives:

(1) reducing the likelihood of new damages in already damaged areas,
(2) allowing for recovery of resources in damaged areas, and
(3) reducing the likelihood of future damages in pristine areas.

Limiting access to some currently scarred areas could displace existing users and re-allocate impacts to areas that are currently not scarred or show limited scarring. Re-allocation of benthic impacts during seasonal area closures has been observed in marine commercial fisheries (e.g. Dinmore *et al.* 2003). To prevent damages in pristine areas, consideration could be given to management measures in areas identified using the model-based approach we employed. Proactive protection of pristine areas with a high likelihood of scarring is a preferred conservation strategy that may also assist in protecting areas that are heavily scarred, but could not be mapped because of poor image quality.

The model-based approach applied here could be used to formulate protection strategies for other marine resources dependent on seagrass such as manatees in other high-use coastal areas. In addition, this approach should be considered in developing management plans in remote marine habitats with little motorised recreational activity. For example, Shark Bay, Australia, is a location where seagrass beds and large populations of marine megafauna, such as dugongs (*Dugong dugon*), exist and have the potential to be affected by boats. Results of models detailing the probability of boat-induced damages could be used in planning before increases in coastal development and boat traffic to prevent impacts on important marine resources.

Development and implementation of some management strategies designed to protect seagrass beds may be initially expensive; however, the costs associated with augmenting protection of these areas may be warranted. Intact seagrass beds provide high annual contributions to ecosystem values (Costanza *et al.* 1997). A recent benefit–cost analysis suggested that the overall cost of additional law enforcement is far outweighed by the benefit of protecting seagrass beds, which were valued at US\$140 752 ha^{-1} (Engeman *et al.* 2008). Finally, active restoration of damaged seagrass beds, if required, can also be quite costly.

Marine managers facing benthic damages associated with boating activities will need to consider multiple factors to help avoid and mitigate impacts. In Western Australia, Hastings *et al.* (1995) found that substantial seagrass damage associated with boat moorings could be best mitigated when both boat mooring technology and factors affecting the physical environment were considered. Similarly, we conclude that efforts should consider a variety of preventative management options, including robust enforcement programs, mandatory education programs and boating permits, improved aids to navigation, pole and troll and slow-speed zones, limiting motorised watercraft access by watercraft characteristics and area-specific access limits. We recommend a traditional, collaborative adaptive-management approach that includes extensive participation by local stakeholders. Consensus on desired conditions and establishment of strong management objectives would be critical to success (Susskind *et al.* 2012). Adaptive management and monitoring will allow marine managers to assess the effectiveness of various strategies and take future action to balance resource protection with human use, by increasing or relaxing restrictions as needed to achieve desired conditions.

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