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Damage and recovery assessment of vessel grounding injuries on coral reef habitats by use of georeferenced landscape video mosaics

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Abstract

Vessel groundings are a major source of disturbance to coral reefs worldwide. Documenting the extent of damage caused by groundings is a crucial first step in the reef restoration process. Here, we describe the application of a novel survey methodology, landscape video mosaics, to assessment of the damage caused by vessel groundings. Video mosaics, created by merging thousands of video frames, combine quantitative and qualitative aspects of damage assessment and provide a georeferenced, landscape, high-resolution, spatially accurate permanent record of an injury. The scar in a Florida reef impacted by a 49-foot vessel, imaged in 2005 and 2006, covered an area of 150 m^2 (total imaged area was >600 m^2). The impacted coral community showed limited signs of coral recovery more than 3 years after the initial impact; the cover of corals was still significantly higher in the undamaged areas compared to the scar. However, seagrass colonization of the scar was observed. Finally, no evidence of further physical impacts was documented even when four hurricanes passed near the grounding site in 2005. The video mosaics developed in this study proved to be ideal tools to survey the grounding scars. Mosaics provide a means to collect information on the size of the damage area and the status and trends of the impacted biological communities and provide a permanent visual record of the damage, thereby expanding the quality and diversity of information that can be collected during field surveys.

The physical damage caused by vessel groundings can be a source of significant disturbance and mortality to shallow coral reefs and hardbottom habitats. In Southeast Florida, where commercial and recreational boating and shipping activities are intense, vessel groundings and propeller and anchor damage are, unfortunately, a common occurrence. In the Florida Keys alone, more than 600 boat groundings are reported each year (Shutler et al. 2006), and this number can be considerably higher if "orphan" or unreported groundings are included. Groundings of large vessels (i.e., >75 ft in length; Symons et al. 2006) can easily damage thousands of square meters of the benthos (Schmahl et al. 2006). Impacts of smaller vessels on coral reefs, however, which often go unreported, can represent a cumulatively larger source of coral mortality. Lutz (2006) reported that 57.1% of shallow patch reefs sampled in the Florida Keys (n = 49) showed evidence of boating impacts such as bottom paint and scars on coral tissue, overturned corals, and fragmented or crushed coral heads.

Physical damage to benthic organisms and habitats can be caused directly by the impact of vessels' hulls, keels, propellers, and anchors or indirectly through the movement of dislodged coral colonies and the shifting of sediments and rubble created during the initial impact (Precht 2006). In addition, significant collateral damage can be caused during the removal and salvage activities that follow the initial grounding (Bruckner and Bruckner 2006). Damage to coral reefs can range from superficial, where only the living surfaces of corals are damaged (Fig. 1A), to structural, where the geomorphic reef matrix is fractured and exposed (Fig. 1B).

The active rehabilitation and restoration of damaged reef habitats in the US relies largely on the ability of authorities with jurisdiction over the resources to prosecute the parties

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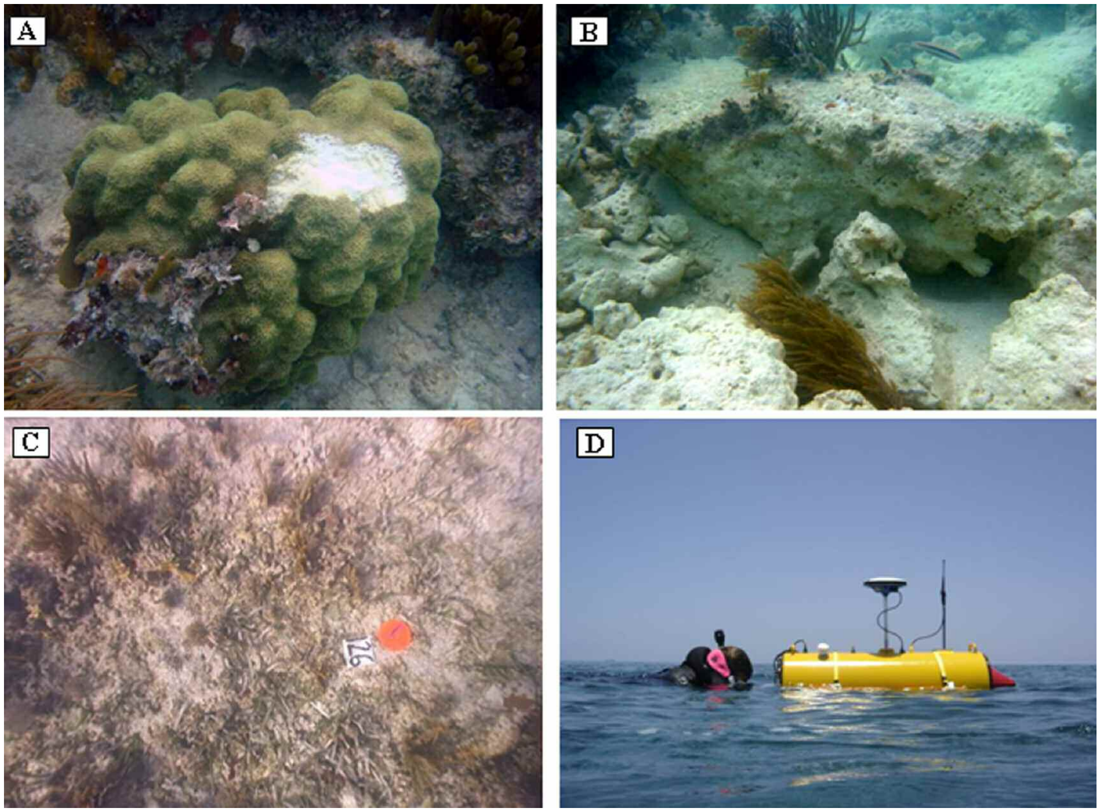

Fig. 1. (A), Superficial damage to a coral colony caused by a ship grounding. (B), Severe reef framework damage caused by a large-vessel grounding. (C), Numbered tiles and painted disks used as ground control points (GPCs) for mosaic creation. (D), Diver version of the Shallow Water Positioning System (SWaPS) used to determine the location of GCPs. The unit integrates a GPS unit and a video camera to provide geotagged images of the bottom.

responsible for the damage and retain monetary recoveries that can be used directly for restoration (Precht and Robbart 2006; Shutler et al. 2006). To determine the proper amount of restoration required, a two-stage Natural Resource Damage Assessment (NRDA) is conducted to determine: (1) the "primary" actions needed to return the habitat to its original baseline structure and function and (2) the "compensatory" actions needed to compensate the public for the loss of resources and services until primary restoration is completed (Symons et al. 2006). Central to the NRDA process is the accurate and comprehensive quantification of the damage caused by a vessel on a benthic community. In this study, we describe the application of a novel methodology, landscape video mosaics, that is ideally suited for the quantification of damage caused by vessel groundings on coral reefs as well as subsequent recovery patterns. This methodology can, with limited time in the field, satisfy the crucial initial damage assessment needs that are required for the subsequent recovery of funds form responsible parties as well as establish a visual baseline of the damage against which future recovery can be ascertained.

Accurately documenting patterns of physical damage (and subsequent recovery patterns) to benthic habitats can be especially challenging when the spatial extent of injuries exceeds tens of square meters. These large injuries are often too difficult to measure in situ by divers and too small or costly to be quantified effectively using aerial and satellite remote sensing tools. Moreover, in cases where immediate action is required to initiate recovery efforts and avoid secondary damage to the resources, damage assessment needs to be conducted quickly. Landscape mosaics capture data at a scale between diver observations and aerial imagery, thereby providing an ideal approach to assess grounding injuries because (1) the images are recorded close to the seabed (<2 m from the bottom), thus capturing detailed visual information; (2) the resulting mosaics cover large areas of the bottom at scales commensurate with the damage caused by large-vessel groundings; and (3) the imagery needed to document patterns can be collected quickly with an underwater video camera and, optionally, a surface GPS. Using this mosaic-based (or image-based) methodology, the dimensions of the injury caused by the 49-foot cabin cruiser *Evening Star* in December 2002 in the waters of Biscayne National Park, Florida, as well as the condition of the affected benthic community, were documented in 2005.

In addition to providing a method for measuring the extent of injuries, landscape mosaics create a spatially accurate map of the distribution and condition of benthic organisms so that patterns of recovery (or further damage) can be more easily assessed than by diver-based methods alone. Repeat mosaics taken over time at the same location can be used to measure changes to a study site without requiring extensive tagging of individual organisms. Gleason et al. (2007) exploited this advantage of mosaics to measure hurricane damage to *Acropora palmata* populations in the Florida Keys, and Gintert et al. (2009) showed how video mosaics can be used to document the impacts of bleaching on coral colonies in the Bahamas. In the present study, a second mosaic of the same grounding scar was constructed in 2006 to assess patterns of community succession and further damage caused by the passage of four hurricanes (Dennis, Katrina, Rita, and Wilma) during the summer of 2005 (Manzello et al. 2007).

The ability to measure distances and benthic cover over time with just an underwater video camera and, optionally (or ideally), a surface GPS receiver makes mosaics an appealing tool for assessing damage and monitoring recovery of vessel grounding scars. As underwater landscape mosaics have not been used previously for this purpose, the overall objective of this effort is to test the utility of mosaics for the application of assessing grounding scars. Specific goals are (1) to show that landscape mosaics are capable of imaging large areas of the seabed efficiently; (2) to document an extension to the established mosaic method (Lirman et al. 2007) to take advantage of GPS input; and (3) to use the video mosaics to document status and trends of coral communities at a Florida reef-grounding site.

Materials and procedures

Data acquisition—On December 5, 2002, the 49-foot vessel *Evening Star* ran aground on a hardbottom community dominated by stony and soft corals within the waters of Biscayne National Park, Florida (25°23.332′ N, 80°09.874′ W, 3 m of depth). On May 23, 2005, and again on July 19, 2006, video data of the damaged and surrounding areas was collected using a Sony TRV900 DV camcorder placed in an underwater housing following the methods described by Lirman et al. (2007). The camera operator swam a lawnmower's pattern of side-by-side strips followed by a similar pattern rotated 90 degrees. A bubble level taped to the back of the camera housing helped the diver keep the camera pointed in a nominally nadir angle. A digital depth gauge was used by the camera operator to keep a consistent depth during the surveys. The time required for a single diver to collect the video used for mosaic creation was <1 h in both years.

During the 2006 survey, positional (GPS) information was obtained for the outline of the injury as well as 25 ground control points (GCPs) along the periphery of the scar using the diver platform of the Shallow Water Positioning System (SWaPS) (Fig. 1D). SWaPS consists of an integrated GPS and video system that collects video frames that are individually geotagged. A static GPS base station is established in the vicinity of SWaPS operations to track the detectable GPS satellites in synchrony with the mobile GPS receiver located in the SWaPS platform. Both receivers record the GPS L1 and L2 carrier phases and code ranges every second during operations. Both data files are postprocessed using the KINPOS program as described in Mader (1996). The position of the base station is accurately determined using OPUS, a GPS processing service created by the National Geodetic Survey (http://www.ngs.noaa.gov/OPUS). The SWaPS methodology has been previously used to document the position of objects underwater with submeter accuracy (Lirman et al. 2008). The GPS tracks recorded by the diver were used to demark the perimeter of the scar, and the area of the scar was then computed from the polygon delimited by the scar perimeter using linear distances between GCPs. Positions of the 25 GCPs, identified using numbered ceramic tiles and painted disks easily visible in the video (Fig. 1C), were captured by the SWaPS platform and used for mosaic creation. The deployment of the tiles used to establish the position of the GCPs as well as the SWaPS survey took a single operator <1 h.

Mosaic creation—Three mosaics were created in total. One mosaic each from 2005 and 2006 used the algorithm described in detail by Gracias et al. (2003), Negahdaripour and Madjidi (2003), and Lirman et al. (2007), which is called in this study the "image-only method." A third mosaic was created from the same raw video data acquired in 2006, but incorporating the SWaPS ground control points into the image registration algorithm. The differences between the image-only and the image-plus-GPC methods are summarized in Fig. 2 and outlined below. The two mosaics created with the image-only method were used to assess the status and trends of the benthic community between 2005 and 2006. The two mosaics created from the 2006 data were used to assess the spatial accuracy of the mosaics.

Under the image-only method, the video is processed to estimate the image-to-image motion between pairs of sequential images. This information is used to recreate the camera trajectory. Subsequently, the estimated camera trajectory is refined by estimating motion between nonsequential but overlapping images. To create the final mosaic, contributions from all of the individual, registered frames are blended into a single image (Fig. 2). The image-only method, as described in Lirman et al. (2007), was used here with two improvements. First, the video was preprocessed to remove patterns of strong light intensity on the seabed caused by wave refraction by use of the method detailed by Gracias et al. (2008). Second, an improved blending method was used to create the final mosaic (Gracias et al. 2009). The mosaic creation method presented here assumes the imaged area is essentially flat. The robust image matching technique, however, is able to deal with departures from this assumption, up to the case where the average camera altitude is approximately twice the depth of variations of the sea-floor topography. Variations in altitude and pitch and roll are handled by the image-matching algorithm as changes in scale or planar-perspective projection.

The image-plus-GCP method differs from the image-only method in the global optimization step (Fig. 2). Under the

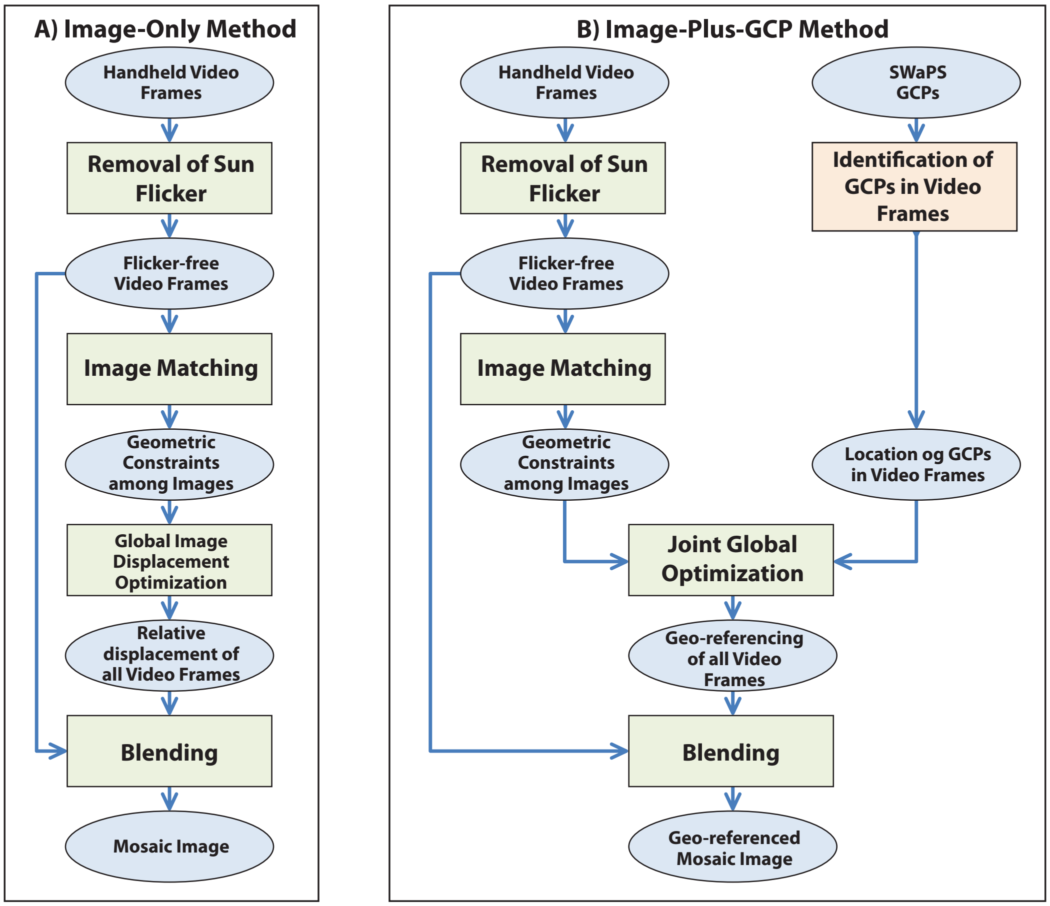

Fig. 2. Flow charts illustrating the data (ellipses) and the processing steps (rectangles) for the image-only method (A) and the image-plus-GCP method (B) of mosaic creation. Fully automated processing steps are in light green. The only step requiring user intervention is in light red (identification of ground control points in video frames). The primary difference between the algorithms is in the cost function minimized in the global optimization step.

image-only method, the cost function that is minimized uses only the image-to-image registration points (Gracias et al. 2003). In contrast, under the image-plus-GCP method, the cost function to be minimized uses terms for both the image-to-image registration points and the image-to-GPS registration points (Ferrer et al. 2007). In both the image-only and image-plus-GCP algorithms, the image registration process estimates the 3D position and orientation of the camera for each image, thus accommodating for changes in altitude and pitch and roll. In addition, the image-plus-GCP algorithm georeferences the mosaic to a world coordinate system (Universal Transverse Mercator Zone 17N, in this case). Therefore, after the blending step, the mosaics created with GPS input are directly exportable to GIS software or Google Earth (Geotiff® and KMZ formats).

The use of mosaics to survey the damage caused by groundings shifts the bulk of time needed to complete a diver-based classic damage assessment from the field to the lab. The time required to collect both the video (<1 h) and the GCPs (<1 h) in the field was minimal and easily achieved with one pair of divers. The processing time for the completion of the landscape mosaics ranged from 5 to 10 days. It is important to note, however, that most of the processing steps are automated and therefore require only minimal operator input, so the actual operator time required was only a few hours for each mosaic. More importantly, significant improvements to the mosaic algorithms have been made over the past 3 years, and total processing times for mosaics similar to those presented here are now 1–2 days. The processing time is roughly divided into the following portions: sunflickering removal (33% of the time [Gracias et al. 2008]), global matching (64%), optimization (1%), and blending (2%). For the 2006 mosaic, documenting the position of the GCPs from the geotagged video took approximately 3 h.

Spatial accuracy of mosaics—To provide an independent method to evaluate the accuracy of the GPS locations for the GCPs obtained with SWaPS, as well as a way to assess the spatial accuracy of the video mosaics, the distance between adjacent GCPs was measured by divers using flexible underwater tapes. The distances measured by divers were compared to the same distances obtained independently from the GPS data as well as from the mosaics (Lirman et al. 2007). The accuracy of the distance measurements extracted from the GPS information and mosaics was ascertained by calculating absolute error (AE): AE = |Diver measurements – GPS or mosaic measurements| (Harvey et al. 2000; Lirman et al. 2007). To assess the benefit of incorporating the locations of GCPs obtained with the SWaPS system into the mosaic creation algorithm, distances were extracted from both of the 2006 mosaics, one constructed with the image-only method and the other constructed with the image-plus-GCP method. For the former case, the scale of the mosaic was set by deploying objects of known sizes (PVC quadrats and meter sticks) and measuring their sizes in the final mosaic. A Kruskal-Wallis nonparametric test with the distance assessment method as main factor was used to compare the AE values among assessment methodologies.

Status and trends of the benthic community—The mosaics created in this study were analyzed to assess the percent cover of benthic organisms in both the grounding scar and adjacent, undamaged areas as well as the patterns of permanence and removal of stony corals between 2005 and 2006. All information on the percent cover of the dominant benthic taxa (i.e., stony corals, soft corals, sponges, seagrass) was measured using the point-intercept method within replicate 1 × 1 m sections of the mosaics (Lirman et al. 2007). For this assessment, a set of random points were superimposed onto each mosaic using the image analysis software CPCe (Kohler and Gill 2006). The random points were used as the central locations of simulated 1 × 1 m quadrats used as sampling units. Once the quadrats had been positioned within each mosaic, a set of 25 quadrats within the grounding scar and 25 quadrats from the adjacent, undamaged areas were selected (the first 25 random points were selected for each habitat type). Each individual quadrat was then analyzed by superimposing 25 random points within its boundary using CPCe (Kohler and Gill 2006). The identity of the organism or bottom type immediately under each point was determined, and the percent cover of each category was calculated as the proportion of the points occupied by a given taxon over the total number of points (i.e., 25 points per quadrat) as described by Lirman et al. (2007). The percent cover data were analyzed in a two-way ANOVA with time (2005, 2006) and habitat type (scar, undamaged area) as factors. Finally, a subset of organisms (corals, sponges) visible in the 2005 mosaic were identified and relocated in the 2006 mosaic to determine permanence or removal/mortality between surveys. Because mosaics of the same area collected over time are easily referenced to each other, it is possible to determine the location of organisms or features in different surveys without the need to deploy markers. Thus, removal of organisms can be easily determined by locating their initial position in a prior survey.

Assessment

Landscape mosaics of the grounding area—The 2005 and 2006 mosaics were created from 2149 and 2207 video frames, respectively (Fig. 3). The minimum final ground resolution was 5 mm/pixel. The area of the bottom imaged by the mosaics was 291 and 637 m^2, respectively. From the 2006 mosaic, which was large enough to completely image the grounding scar, the injury was documented to be 45 m in length and ranged in width from 3 to 5 m. The total area of the injury was 150 m^2, determined by visually delineating the boundaries of the scar directly from the 2006 mosaic created with the image-plus-GPC method. The area computed by swimming the SWaPS platform along the boundary of the scar and measuring the polygon delineated by the GPS locations captured in the video was 148 m^2.

The mean distance between GCPs estimated by divers was 4.6 m, the maximum distance between GCPs was 6.5 m, and the minimum distance was 3.2 m (n = 23 distances measured between GCPs). The mean AE between diver and GPS measurements of the GCPs was 0.22 m (SD 0.12), whereas the AE between diver and 2006 mosaic (image-only method) measurements of the GCPs was 0.71 m (0.9). The AE between diver and 2006 mosaic (image-plus-GCP method) was reduced to 0.25 m (0.14), or 5% of the mean distance between GCPs. Significant differences in the mean AE values among the methods used were documented (Kruskal-Wallis test, $P < 0.05$), with the diver-mosaic (image-only) comparison having significantly higher AE values than those of diver-GPS and diver-mosaic (image-plus-GCP), which were not significantly different from each other.

Status and trends of the benthic community—In the area of overlap between the 2005 and 2006 mosaics, 69 coral colonies were identified in 2005. Of those, 62 (90%) were relocated in the 2006 mosaic, showing that limited physical damage was experienced by this site due to the 2005 hurricanes (or any other potential source of physical damage like swells or additional groundings). Seven colonies were removed or died completely between surveys (10%). Two surviving colonies, both within the scar, appeared to have become dislodged and moved from their original location between surveys.

Three years after the initial vessel impact, the benthic communities in damaged and undamaged areas were still significantly different in the percent cover of the dominant taxa (Tables 1 and 2). The cover of stony corals and soft corals was significantly higher in the undamaged areas, whereas no significant differences were detected in the cover of sponges between habitats. No significant differences in the cover of corals and sponges were documented between 2005 and 2006. The most striking feature of the interannual comparison was the evident encroachment of seagrass (*Thalassia testudinum*) into the scar from the surrounding, unaffected habitat (Fig. 4). The cover of seagrass within the scar increased significantly between 2005 (3.7%, SD 4.4%) and 2006 (8.2%, SD 8.5%).

Discussion

Video mosaics—Documenting the extent of damage caused by physical disturbance is one of the main challenges of post-damage surveys in coral reef habitats but a crucial first step in

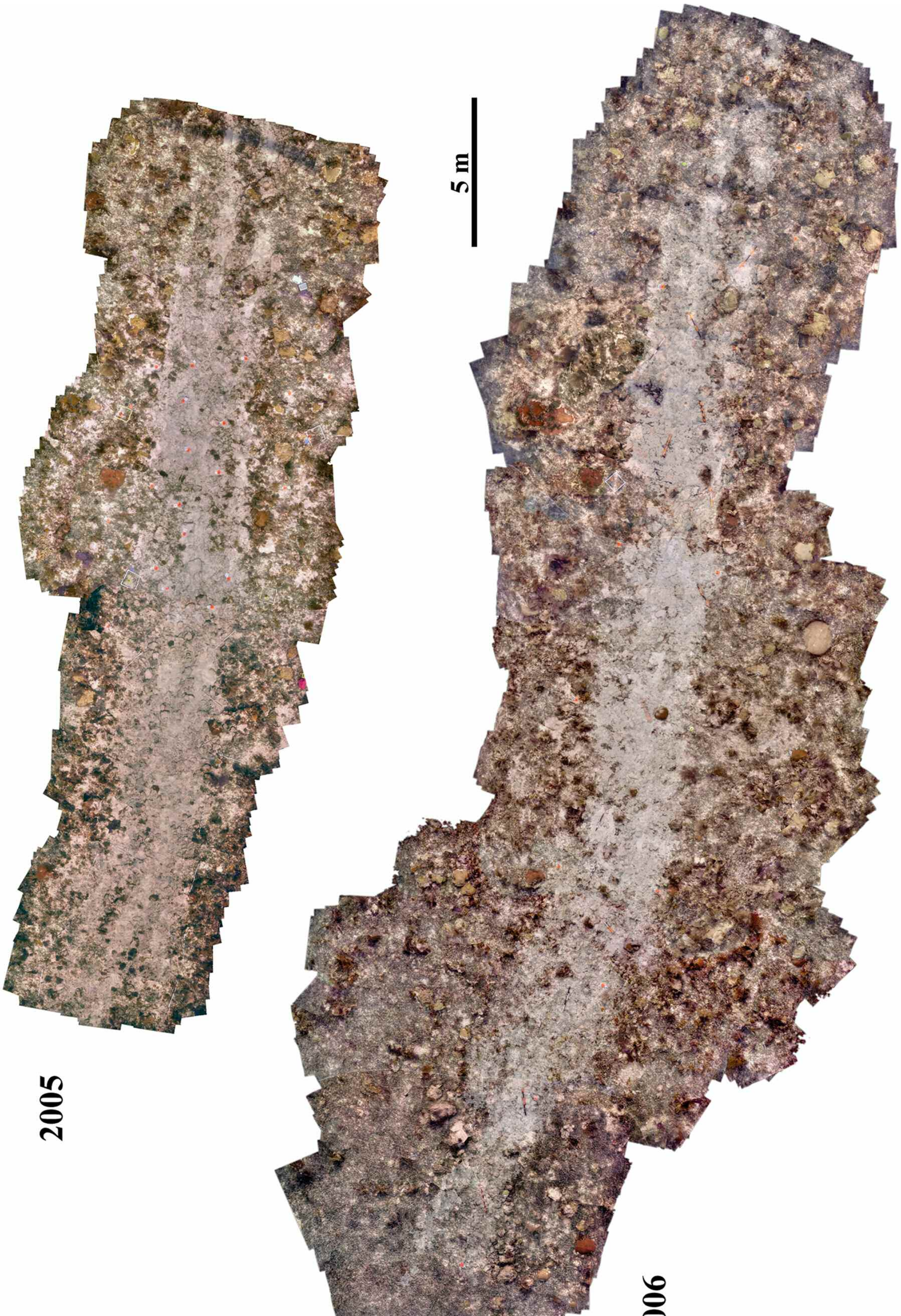

Fig. 3. Landscape video mosaics of a vessel grounding scar on a shallow coral reef habitat (3 m) in Florida in 2005 and 2006.

Table 1. Mean (SD) of the main component of the benthic communities within and outside the grounding scar surveyed in 2005 and 2006.

Year	Position	Stony corals	Soft corals	Sponges	Seagrass	Macroalgae/rubble
2005	Scar	1.7 (3.2)	1.9 (4.0)	1.0 (2.5)	3.7 (4.4)	91.7 (12.6)
2005	Outside	8.2 (8.3)	13.1 (11.7)	1.6 (3.2)	16.0 (12.3)	61.1 (18.7)
2006	Scar	1.5 (2.8)	3.3 (3.1)	1.7 (2.3)	8.2 (8.5)	85.3 (10.7)
2006	Outside	7.7 (6.7)	12.5 (8.5)	1.0 (2.2)	29.7 (18.0)	49.0 (15.6)

Values were obtained from 25 replicate 1-m^2 simulated quadrats.

Table 2. Results from a two-factor ANOVA with year and location as factors.

	Year	Position	Interaction
Stony corals	NS	*	NS
Soft corals	NS	*	NS
Sponges	NS	NS	NS
Seagrass	*	*	NS

Cover data were arcsin-transformed before analysis. NS, no significant differences in mean cover; *, significant differences in cover ($P < 0.01$).

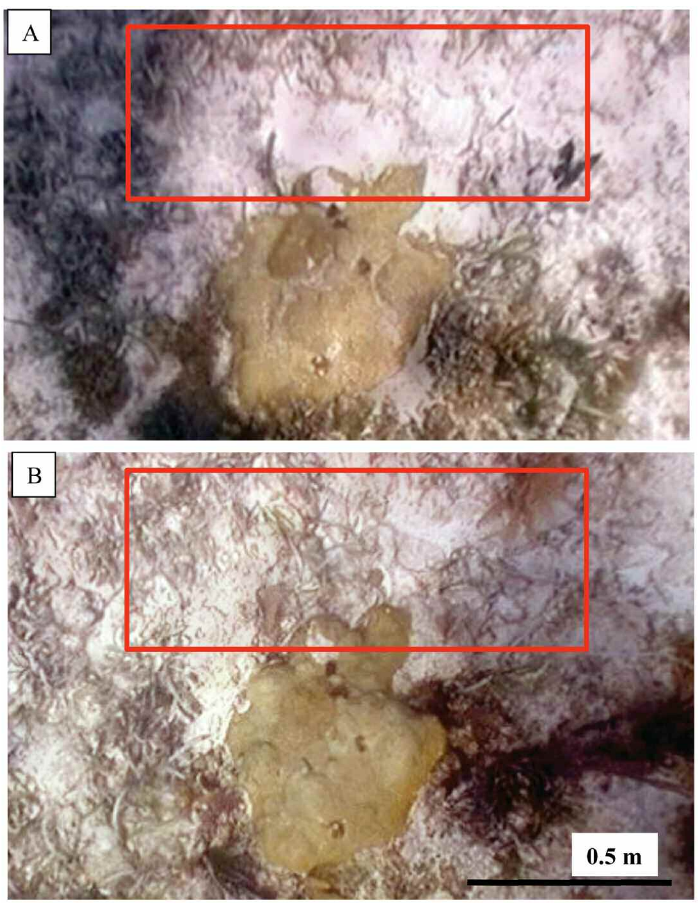

Fig. 4. Evidence of seagrass encroachment and growth within the grounding scar surveyed in 2005 (A) and 2006 (B).

the reef restoration process (Precht 2006). In the case of vessel groundings, the effective and accurate assessment of the extent of the damage caused is a required step in the Natural Resource Damage Assessment and Habitat Equivalency Analysis (HEA) processes commonly undertaken in the US to determine the amount of compensatory restoration required (Milon and Dodge 2001; Shutler et al. 2006). The application of video mosaics described in this study thus provides a novel methodology to accomplish this required first step in the coral reef restoration process in a timely, accurate, and cost-efficient manner. The largest cost savings result from a shift of the bulk of the data collection and processing time from the field to the lab. Field activities are often expensive (boats, divers), are influenced by weather conditions, and require highly trained field personnel. By being able to collected all the required data in a couple of hours by divers who only need to know how to position markers underwater and operate a video camera, field costs can be reduced considerably.

The time period immediately following the initial reef injury is crucial for both the damage assessment and the early rehabilitation processes (i.e., triage). A delayed response may result in an inaccurate damage assessment and the further loss of surviving coral colonies due to secondary damage caused by loose rubble and sediments. Accordingly, an assessment method that can be implemented rapidly and efficiently (<2 h of survey time in the field with just a pair of divers), and that maximizes the variety of damage indicators that can be collected with low cost and reduced field time, is highly desirable in these situations. A thorough assessment of the extent of damage caused by vessel groundings often combines a quantitative aspect (i.e., estimating the areal extent of the scar or injury, counting the number of injured coral colonies) as well as a more qualitative aspect, where visual documentation of significant features of the injury and affected corals are commonly captured using video or photographs (Symons et al. 2006). Video mosaics combine both quantitative and qualitative aspects of damage assessment and provide a georeferenced, high-resolution, spatially accurate, landscape view of an injury that can be recorded rapidly in the field with just an underwater video camera and can serve as a permanent record for future analyses. From the mosaics, accurate measurements of injury extent can be extracted, and a visual record of the damaged coral colonies is recorded simultaneously.

The use of landscape mosaics for the assessment of ship groundings can provide significant time and data benefits over traditional damage assessment surveys. Although small (10 m^2) injuries can be easily surveyed by divers in <1 day, large injuries can take teams of divers up to a week or more for an adequate assessment using conventional methods (Hudson and Diaz 1988), which still do not provide a permanent visual record of the damage. Large grounding scars are commonly measured in situ by divers using flexible tapes following the "fishbone" method described by Hudson and Goodwin (2001). In addition, the boundaries of the damaged areas or the positions of objects of interest (e.g., injured corals) are surveyed using surface-deployed GPS units positioned over specific locations, and the extent of the damage is later calculated from the polygon delineated by the GPS locations.

Landscape mosaics offer an alternative to previous methods that rely heavily in extended underwater time to document damage patterns to benthic resources. The ability to document visual and spatial information over large damaged areas (>150 m^2) in approximately 1 h of dive time (plus less than an hour if GCPs are needed) using a single diver reduces field time and costs. The automated mosaic algorithms used here can create landscape images of large (>600 m^2) areas in <24 h of computer processing time with minimal analyst input. By georeferencing the resulting mosaic images, small-scale changes in injury size and changes in the biological communities are easily quantified in the lab, whereas traditional diver-based methods require extensive underwater measuring and tagging of the impacted areas for damage and recovery analyses. Although some large vessel groundings can clearly exceed the dimensions of the mosaics presented here (e.g., Marshall et al. 2002; Schmahl et al. 2006), most injuries can be imaged using the mosaic algorithm presented in this study. Extending the landscape mosaic approach to even larger areas is a subject of ongoing research.

Previous landscape mosaics used in status and damage assessments (Gleason et al. 2007; Lirman et al. 2007; Gintert et al. 2009) were built with data collected by use of solely a video camera in an underwater housing and without the aid of a positioning system (i.e., using the image-only method). This was useful because GPS signals are strongly attenuated underwater and therefore are not generally available for mapping the locations of underwater objects. Other underwater navigation aids, such as acoustic positioning systems or Doppler velocity logs, are commonly used in place of GPS underwater, but these systems can add great expense to the survey package. In this study, the incorporation of GPS information into the mosaic processing (the image-plus-GPC method) significantly reduced the error between diver and mosaic measurements by using the GPS position of known points within the mosaic to assist the image registration process. Although the use of surface-based GPS to establish positions underwater becomes increasingly inaccurate as depth increases, most grounding sites are shallow, suggesting that using the image-plus-GCP approach to creating mosaics for grounding assessments is technically feasible. Finally, whereas the use of a surface-based GPS platform proved to be an accurate way of estimating the surface area damaged by the grounding, the combination of GPS and video mosaics provides assessment capabilities that far exceed those of just the GPS unit.

One of the most commonly used methods of reef restoration is the transplantation of coral colonies onto damaged and restored habitats or restoration structures (e.g., Clark and Edwards 1995; Epstein et al. 2003). Moreover, the survivorship and growth of transplanted colonies is often used as a measure of restoration success (Rinkevich 2005). Following the survivorship and growth of a large number of coral colonies can be time-consuming effort and requires that each colony be individually tagged (Lirman and Fong 2007). By providing a georeferenced map of the bottom (or restoration structure), video mosaics can be used to track the fate of individual damaged or transplanted colonies without the need of extensive tagging. Moreover, growth and partial mortality patterns can be extracted directly from the mosaics, limiting the time that trained divers need to spend collecting this information underwater. The value of mosaics for before-and-after studies was evidenced in studies by Gleason et al. (2007), where the damage caused by hurricanes on a shallow reef community was assessed directly from mosaics, and Gintert et al. (2009), where the impacts of coral bleaching were evaluated on coral colonies of the Bahamas. In both examples, as in this study, the condition of a large number of coral colonies was assessed over time without the need to deploy individual tags.

Florida grounding scar—The coral populations within the grounding scar surveyed in 2005 and 2006 showed limited signs of recovery. Coral cover within the scar remained significantly depressed compared with adjacent, unaffected areas 3–4 years after the injury. Although some corals were observed within the scars, their large size indicates that these colonies either survived the initial impact or were moved into the scar through wave action or during storms. In habitats or regions where coral recruitment is high, the recovery of coral communities can be rapid (Lirman and Miller 2003). However, when the availability of sexual propagules is low and/or when the settlement substrate is not adequate, the recovery of severely damaged coral communities can be a long process. The colonization of sediment and rubble fields by seagrass and macroalgae can be an important first step in the recovery process of damaged communities, as it stabilizes the loose rubble and provides a more stable settlement substrate for corals and other reef organisms. Between 2005 and 2006, a significant increase in the cover of seagrass was recorded within the grounding scar surveyed in Florida, suggesting a potentially positive step in the slow recovery process. The positive impact of seagrass colonization of grounding scars and rubble fields is the stabilization of the loose rubble through the binding action of their rhizomes. Binding of loose rubble has been identified as a necessary precursor to reef recovery and expansion (Rasser and Riegl 2002). In the absence of rubble stabilization, uncemented pieces can become projectiles during storms and compound the initial damage. In addition, the recruitment of corals and other organisms can be impaired by the rolling action of unconsolidated rubble.

The 2005 hurricane season was unusually active for Florida, with four hurricanes (Dennis, Katrina, Rita, and Wilma) affecting the region (Manzello et al. 2007). Considering the damage that was observed on a shallow reef just 40 km away from this grounding (Gleason et al. 2007), it was hypothesized that the impacts of the storms would also be detectable within the area affected by the vessel grounding, especially considering that a large field of unconsolidated coral rubble still remains in place within the scar at this unrestored site. However, no hurricane impacts were documented in the affected area, highlighting the variable nature of hurricane damage over relatively small spatial scales (Lirman and Fong 1997).

Comments and recommendations

Providing a rapid and accurate assessment of the damage caused by vessel groundings on coral reef habitats is a crucial first step in the reef restoration process. Accurate assessments of reef damage are needed for the recovery of monetary fines from responsible parties, the drafting of reef restoration plans, and the assessment of restoration success. In this study, we describe the application of a novel underwater survey technology, landscape video mosaics, to the mapping and monitoring of vessel grounding scars on coral reefs. This new application of underwater mosaics covered a larger area (>600 m^2) than previous surveys with this technology and demonstrated the potential to incorporate external navigation into the mosaic processing, thereby enhancing the spatial accuracy of the resulting landscape map. The video mosaics provided a means to accurately and efficiently collect information on the size of the damage area as well as the status and trends of the impacted biological communities, thereby expanding the quality and diversity of information that can be collected during field surveys. The damaged portion of the reef surveyed in Florida covered an area of 150 m^2, and the impacted coral reef community showed limited convergence to the undisturbed community in the same habitat more than 3 years after the initial impact.

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