# High Resolution Landscape Mosaics for Coral Reef Mapping and Monitoring

**What is a landscape mosaic?** Individual underwater images taken close to the seabed (~1-2m) have high resolution and minimal water column attenuation, but cover only a small area. A landscape mosaic is a composite of many underwater images. The mosaics have the clarity and resolution of individual pictures but afford a "landscape view" of the seabed (Fig 1).

The U.S. Strategic Environmental Research and Development Program (SERDP) has supported a) the development of software tools for generating underwater landscape mosaics without relying on external navigation and b) the evaluation of these mosaics for coral reef mapping and monitoring. We are seeking to identify potential applications and partners.

**Data Acquisition Requirements:** Mosaics are made in one of two modes: "Standard mode" uses video data only; "Enhanced mode" uses still images acquired synchronously with the video. Both need:

- Near-nadir view video 1-2 m from seabed.
- High (~80%) overlap between swaths.

Enhanced mode additionally requires:

- Still camera synchronized with video.

### Mosaic Characteristics:

- Area covered: ~ 400 $m^2$ (~2000 frames)
- Spatial resolution (pixel size):
  - enhanced mode, sub-mm;
  - standard mode, ~ 3 mm.
- Spatial accuracy: +/-5 cm (1 standard deviation)

**Highly automated mosaic production** requires about 4 man-hours and 24-36 hours computer time with current desktop processors.

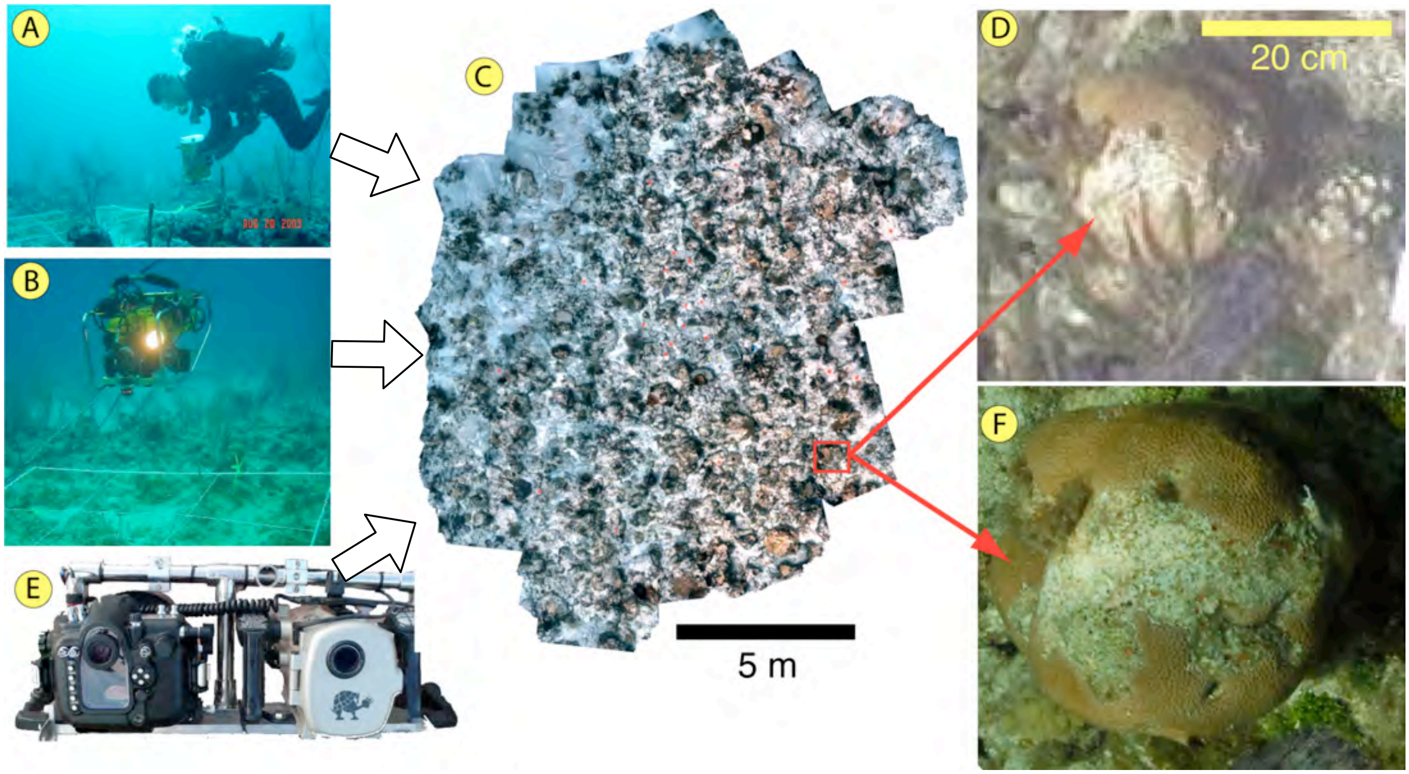


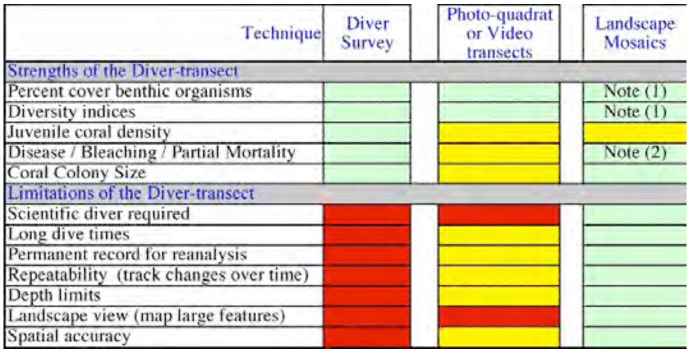
**Figure 1:** Mosaic overview: Video images acquired by a diver (A) or other platform such as an ROV (B) are automatically stitched together to form a landscape mosaic (C) covering a large area (about 200 $m^2$ in this case). "Standard mode" (i.e. video only) produces mosaics with mm-scale resolution (D). In "enhanced mode", still imagery is acquired simultaneously with the video (E) to achieve sub-mm resolution (F).

## Key Benefits:

- Landscape view: Mosaics provide a landscape view of coral reefs that has previously been unobtainable. This enables new measures of reef health, such as documenting spatial relationships of disease patterns, or the effects of hurricane damage and ship groundings.
- Spatial accuracy: High spatial accuracy, combined with a landscape view, enables accurate size and distance measurements to be taken directly from the mosaic. Mosaics can be georeferenced and integrated with other data sets using Geographic Information Systems (GIS)
- Colony monitoring without tagging: Mosaics are efficient tools to track patterns of change over time. Mosaics collected in repeat surveys can be referenced to one another with only four permanent markers, allowing monitoring of individual coral colonies without the need for extensive tagging.

**Compared with traditional techniques:** Mosaics retain key strengths of a diver-based approach, while overcoming the limitations of diver-based or photo-quadrat / video transect methods (Table 1).

## Table 1: Comparison of monitoring techniques.



| Technique | Diver Survey | Photo-quadrat or Video transects | Landscape Mosaics |
|---|---|---|---|
| Strengths of the Diver-transect | | | |
| Percent cover benthic organisms | 🟩 | 🟩 | 🟩 Note (1) |
| Diversity indices | 🟩 | 🟩 | 🟩 Note (1) |
| Juvenile coral density | 🟩 | 🟨 | 🟨 |
| Disease / Bleaching / Partial Mortality | 🟩 | 🟨 | 🟩 Note (2) |
| Coral Colony Size | 🟩 | 🟨 | 🟩 |
| Limitations of the Diver-transect | | | |
| Scientific diver required | 🟥 | 🟥 | 🟩 |
| Long dive times | 🟥 | 🟨 | 🟩 |
| Permanent record for reanalysis | 🟥 | 🟨 | 🟩 |
| Repeatability (track changes over time) | 🟥 | 🟨 | 🟩 |
| Depth limits | 🟥 | 🟨 | 🟩 |
| Landscape view (map large features) | 🟥 | 🟥 | 🟩 |
| Spatial accuracy | 🟥 | 🟨 | 🟩 |

Green indicates full capability, yellow partial capability, and red poor capability. Note (1): Enhanced mode required for species-level IDs, but identification of major functional groups (e.g., corals, sponges, algae) is done with standard mode. Note (2): Enhanced mode required.

**Sample mosaics are available upon request!**

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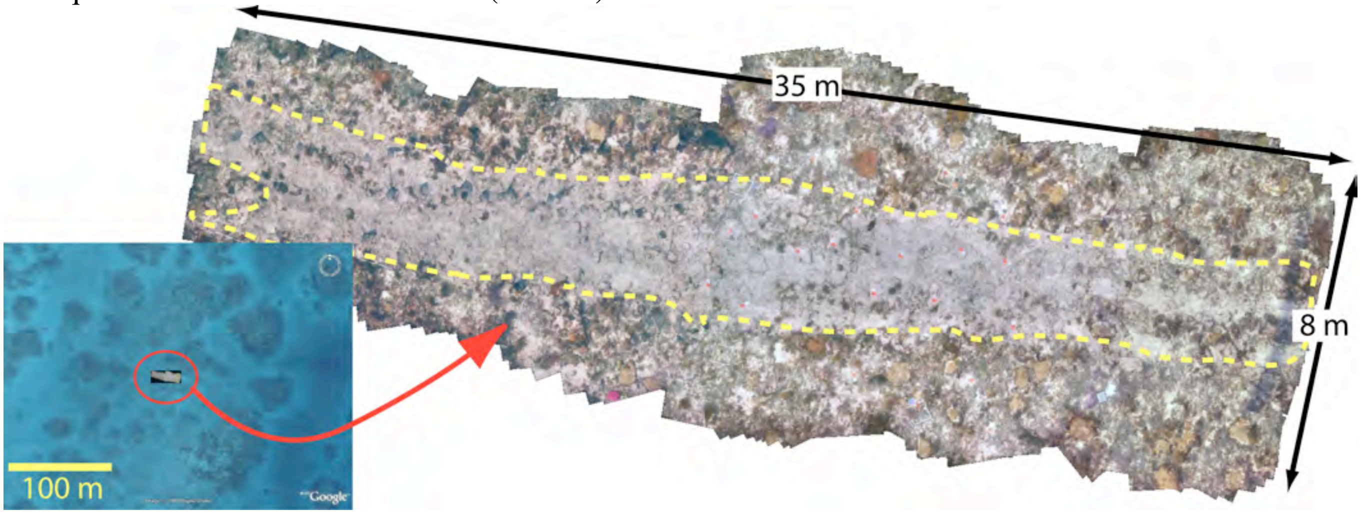

**Figure 2:** Mosaic of a scar created by a ship grounding on a shallow reef, Florida Keys (depth = 3 m). The dashed line marks the extent of damage. The inset shows this mosaic inserted into Google Earth, illustrating the potential to incorporate mosaics in GIS systems. Groundings are large and cumbersome to survey solely by divers.. An image conveys more information about the extent of the damage than measurements of the overall dimensions, especially when viewed by non-technical personnel (e.g. juries).

## References:

Lirman, D., N. R. Gracias, B. E. Gintert, A. C. R. Gleason, R. P. Reid, S. Negahdaripour and P. Kramer (2007). Development and application of a video-mosaic survey technology to document the status of coral reef communities. *Environmental Monitoring and Assessment* **1-3**: 59-73.

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ORIGINAL ARTICLE

# Development and application of a video-mosaic survey technology to document the status of coral reef communities

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**Abstract** The recent decline in the condition of coral reef communities worldwide has fueled the need to develop innovative assessment tools to document coral abundance and distribution rapidly and effectively. While most monitoring programs rely primarily on data collected *in situ* by trained divers, digital photographs and video are used increasingly to extract ecological indicators, provide a permanent visual record of reef condition, and reduce the time that divers spend underwater.

In this study, we describe the development and application of a video-based reef survey methodology based on an algorithm for image registration and the estimation of image motion and camera trajectory. This technology was used to construct two-dimensional, spatially accurate, high-resolution mosaics of the reef benthos at a scale of up to 400 $m^2$. The mosaics were analyzed to estimate the size and percent cover of reef organisms and these ecological indicators of reef condition were compared to similar measurements collected by divers to evaluate the potential of the mosaics as monitoring tools.

The ecological indicators collected by trained divers compared favorably with those measured directly from the video mosaics. Five out of the eight categories chosen (hard corals, octocorals, *Palythoa*, algal turf, and sand) showed no significant differences in percent cover based on survey method. Moreover, no significant differences based on survey method were found in the size of coral colonies. Lastly, the capability to extract the same reef location from mosaics collected at different times proved to be an important tool for documenting change in coral abundance as the removal of even small colonies ($<10$ cm in diameter) was easily documented.

The two-dimensional video mosaics constructed in this study can provide repeatable, accurate measurements on the reef-plot scale that can complement measurements on the colony-scale made by divers and surveys conducted at regional scales using remote sensing tools.

**Keywords** Benthic surveys · Image motion · Reef condition · ROV · Video mosaics · Video surveys

## 1 Introduction

The recent worldwide decline in coral reef health and extent has fueled a myriad of local and regional efforts

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aimed at collecting comprehensive monitoring data that can be used to evaluate the present condition of reef communities as well as to provide a baseline against which future changes can be accurately gauged (Gardner *et al*., 2003; Kramer, 2003; Wilkinson, 2004). While sampling design and survey approaches differ among monitoring programs, the use of plot (e.g., quadrats) and line-based (e.g., line intercept) methods to estimate the percent cover of benthic organisms prevail as important components of these efforts (Hodgson, 1999; Kramer and Lang, 2003). Coral cover has historically been the predominant indicator of reef condition but recent studies have also highlighted the importance of the size-structure of coral populations as a powerful but often underused status indicator (Bak and Meesters, 1998, 1999). In response to these studies, plot and line-based methods are now commonly supplemented by colony-based methods that document the size and condition of individual coral colonies (Lang, 2003).

The rapid patterns of reef decline have also prompted the design of innovative assessment tools to document coral abundance, distribution, and condition rapidly and effectively (Solan *et al*., 2003; Fisher *et al*., 2005). With the development of better and more affordable photography and videography techniques and equipment, many programs routinely complement diver-based measurements with digital images of the bottom that are later analyzed using image analysis software (Riegl *et al*., 2001; Porter *et al*., 2002). These digital tools improve survey efficiency by: (1) reducing the time that divers need to spend underwater by shifting data capture away from the field and into the lab; and (2) providing a permanent visual record of reef condition. The use of digital video provides the added benefit of capturing a large number of digital frames in a limited amount of time.

Digital photographs and video frames provide two-dimensional images of the bottom that can be analyzed with the same methods commonly used by divers to estimate percent cover *in situ*. These methods include: (1) the point intercept method where a number of points are randomly placed over each image and the identity of the benthic organisms immediately under each point is determined; and (2) the area estimation method where the boundary of each organism is delineated. In both cases, the proportion of the total number of points or total reef area occupied by each organism is used to measure percent cover. While these methods provide an effective estimate of the areal coverage of benthic organisms, they provide only limited size-estimation capabilities because sizes can be measured only for organisms that fall completely within an image. This limitation is especially manifested in reef habitats with large corals and high topographical relief where individual colonies are rarely captured wholly within frames or video transects.

The goals of the present study are to: (1) describe the development and application of a novel, video-based reef survey methodology that provides a powerful and efficient alternative to existing photography and video-based approaches; and (2) evaluate whether the video mosaic method could provide the type of ecological information related to coral reef condition commonly obtained by trained divers *in situ*. This technique, based on a recently developed algorithm for image registration, is used to construct spatially accurate mosaics of the reef benthos that can be analyzed to estimate not only the percent cover of organisms but also their size and spatial distribution and arrangement patterns. This flexible mosaicing algorithm allows the technique to be used in a variety of applications from low cost surveys with handheld underwater video cameras to mapping deep reefs with remotely operated vehicles (ROV). A reef site in the Florida Keys, U.S., was surveyed using these two platforms and the community attributes obtained by analyzing the video mosaics are compared to similar indicators collected by trained divers to provide a direct comparison between methods.

## 2 Materials and methods

### 2.1 Video mosaic creation

### *2.1.1 Video acquisition*

The field activities for this study were conducted at Brooke's Reef (25°40.508′N, 80°5.908′W, depth = 7–10 m), a patch reef located in the northernmost section of the Florida Reef Tract, just offshore of Key Biscayne, Florida. A square plot (3 m × 3 m) was established at this site using aluminum pipes cemented to the bottom to provide a permanent reference location for video surveys. Three video mosaics of the same reef area were created using different survey platforms (Table 1). For the first mosaic (June, 2004), video footage was acquired by a diver using a Sony TRV900 DV camcorder placed in an underwater

**Table 1** Description of the three different mosaics constructed in this study based on digital video collected at a reef in the northern Florida reef tract (depth = 7–10 m)

| Survey | Date | Survey platform (Camera resolution) | Altitude | Area covered | Ground resolution |
|---|---|---|---|---|---|
| 1 | June 04 | Diver (720 × 530 pixels) | 2 m | 53 $m^2$ | 3.0 mm/pixel |
| 2 | April 05 | ROV (1024 × 768 pixels) | 2.5 m | 400 $m^2$ | 2.5–3.0 mm/pixel |
| 3 | April 05 | ROV (1024 × 768 pixels) | 1.5 m | 45 $m^2$ | 1.4 mm/pixel |

camera housing. This first survey is included to illustrate that the mosaicing algorithm can produce geometrically accurate mosaics from a standard, low-cost, handheld camera. For the second and third mosaics (April, 2005), video was collected using a Flea digital camera mounted on a Phantom XTL remotely operated vehicle (ROV) (Xu, 2000) representing high and low altitude data sets from which ecological indices were assessed. The cameras were internally calibrated to reduce image distortion from the lens and housing (Bouguet, 2002). The frame resolution is 720 × 530 pixels for the handheld camcorder and 1024 × 768 pixels for the Flea camera. On all occasions, the camera followed a lawnmower's pattern of side-by-side strips, complemented by the same pattern rotated 90° to ensure full coverage of the area and high superposition among the strips.

### *2.1.2 Mosaic algorithm*

The mosaic-creation algorithm used in this study stems from previous work on underwater video mosaicing by Gracias and Santos-Victor (2000, 2001). The method comprises four major stages. The first stage consists of the sequential estimation of the image motion, using a subset of the captured images. The set of resulting consecutive homographies (i.e., coordinate mapping between two image projections of the same 3D plane) is cascaded to infer the approximate trajectory of the camera. The trajectory information is then used to predict the areas of image overlap from non-consecutive images (i.e., neighboring video strips). To reduce the algorithmic complexity and memory requirements, a set of key frames are selected based on an image superposition criterion (typically 65–80%). Only such key frames are used in the following optimization steps.

In the second stage, a global alignment is performed where the overall camera trajectory is refined by executing the following two steps iteratively: (1) point correspondences are established between non-adjacent pairs of images that present enough overlap; and (2) the trajectory is updated by searching for the set of homographies that minimizes the overall sum of distances in the point matches.

In the third stage, high registration accuracy is obtained by re-estimating the camera trajectory using a general parameterization for the homographies. This parameterization has six degrees of freedom (DOF) for the pose and is capable of modeling the effects of general camera rotation and translation. The essential building block of this step consists of the registration of pairs of images done as follows: (1) a set of point features corresponding to textured areas are extracted from one of the images using the Harris corner detector method (Harris and Stephens, 1988); and (2) for each feature (defined as a small square image patch centered at the detected corner location), a prospective match is found in the other image using normalized cross-correlation. We assume that prior information exists on the expected image motion (typically in the form of a homography). This information is used to: (1) establish the location of the correlation window center; and (2) define the required warping of the image feature so that the search over the other image becomes essentially a translation (2D) search. This allows for the use of area-correlation for heavily rotated or slanted images. Finally, a robust estimation technique is used to remove outliers using a Least Median of Squares criterion based on a planar motion model.

The final stage of the mosaicing process consists of blending the images (i.e., choosing representative pixels from the spatially registered images to render the mosaic image). The mosaic is created by choosing the contributing pixels that are closest to the center of their frames. The image rendering method used in this study compares favorably to other traditional rendering methods, such as the average or the median, by: (1) preserving the texture of the benthic objects; (2) reducing artifacts due to registration misalignments of 3D structure; and (3) allowing for an efficient implementation in terms of memory requirements and execution speed. However, in the presence of strong illumination changes or strong 3D content, the present version of our method can create visible seams along the boundaries of the images. The visibility of these seams may be reduced by employing more computationally intensive rendering methods, such as optimal seam finding (Uyttendaele *et al.*, 2001; Agarwala *et al.*, 2004) and gradient domain blending (Levin *et al.*, 2004). A fast, memory-efficient method for optimal seam finding is currently being developed to address the processing of large underwater image sets with variable light conditions as included in this study.

### *2.1.3 Spatial accuracy*

To quantify the geometric accuracy of the mosaics, a geometric distortion analysis was performed using ground-truth data consisting of a set of points of known positions that are easily located on the mosaic images. The accuracy analysis consists of two steps. In the first step, 2D positions were measured by divers taking distance measurements to the closest cm between markers placed on the bottom relative to four reference stakes using flexible underwater tapes. For this study, the area of interest is assumed to be approximately flat, so the geometric analysis is carried out in 2D. Given the fact that it is difficult to measure XY locations underwater accurately, the creation of the ground-truth data had to be done indirectly using a network of distance measurements between points (Holt, 2000). A set of ground-truth points was created within the test area by placing 24 markers (painted CDs) on the bottom with masonry nails and attaching four control stakes permanently with underwater cement (Fig. 1). The distances between each marker and the four control stakes, as well as the distances among the control stakes, were measured by divers using flexible tapes.

Given a set of distance measurements, we want to estimate the 2D locations of all points with respect to a common metric reference frame. Let $\tilde{d}_{ij}$ be the measured distance between points $i$ and $j$. The observed noisy measurement relates to the ideal noise-free distance $\tilde{d}_{ij}$ as: $\tilde{d}_{ij} = d_{ij} + \varepsilon$, where $\varepsilon$ is an additive noise term. Each point is represented by its 2D coordinates: $P_i = (x_i, y_i)$. The observations relate to the sought parameters as:

$$\tilde{d}_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} + \varepsilon$$

Using a Least-Squares criteria, the problem can be formulated as finding the set of $(\hat{x}_i, \hat{y}_i)$ such that:

$$(\hat{x}_i, \hat{y}_i) = \arg\min_{(x_i, y_i)} \sum_{i,j} \left(\tilde{d}_{ij} - \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}\right)^2$$

To establish a reference frame for the coordinates, additional constraints need to be imposed. These can be defined as: $x_1 = y_1 = y_2 = 0$, which sets the origin at point 1 and the world X axis along the line between points 1 and 2. The coordinates of the ground-truth points were estimated using a standard non-linear least squares algorithm (Press, 1988).

In the second step of the spatial accuracy analysis, comparisons were made between distance measurements taken directly from the mosaics and the ground-truth distance measurements taken by divers in an operation known as mosaic "referencing". The computation of this step can be done by using a set of points of known world coordinates that can be located on the mosaic. The most general model for mapping the world plane into an image plane requires the knowledge of at least four points whose world coordinates are known. However, this mapping can be computed using a larger set of point correspondences, resulting in a higher-precision referencing. In this study, all 24 markers were used for referencing the mosaics.

For each ground-truth point of metric coordinates $(x_i, y_i)$ and mosaic image coordinates $(u_i, v_i)$ we consider the difference residue defined as:

$$\begin{bmatrix} r_{x_i} \\ r_{y_i} \end{bmatrix} = \begin{bmatrix} \frac{h_1 u_i + h_2 v_i + h_3}{h_7 u_i + h_8 v_i + 1} \\ \frac{h_4 u_i + h_5 v_i + h_6}{h_7 u_i + h_8 v_i + 1} \end{bmatrix} - \begin{bmatrix} x_i \\ y_i \end{bmatrix}$$

where $\vec{h} = [h_1 \ldots h_8]^T$ are the parameters of the world-to-mosaic projective mapping. This mapping is computed using standard least squares as:

$$\hat{\vec{h}} = \underset{\vec{h}}{\operatorname{argmin}} \sum_i \left(r_{x_i}^2 + r_{y_i}^2\right)$$

Two criteria were used to assess the geometric distortion: (1) the standard deviation of all residues $(r_{x_1}, r_{y_1}, \ldots, r_{x_N}, r_{y_N})$; and (2) the maximum distance error: $d_{\max} = \max_i \sqrt{(r_{x_i}^2 + r_{y_i}^2)}$. These indicators are useful for two main reasons: (1) they provide nominal

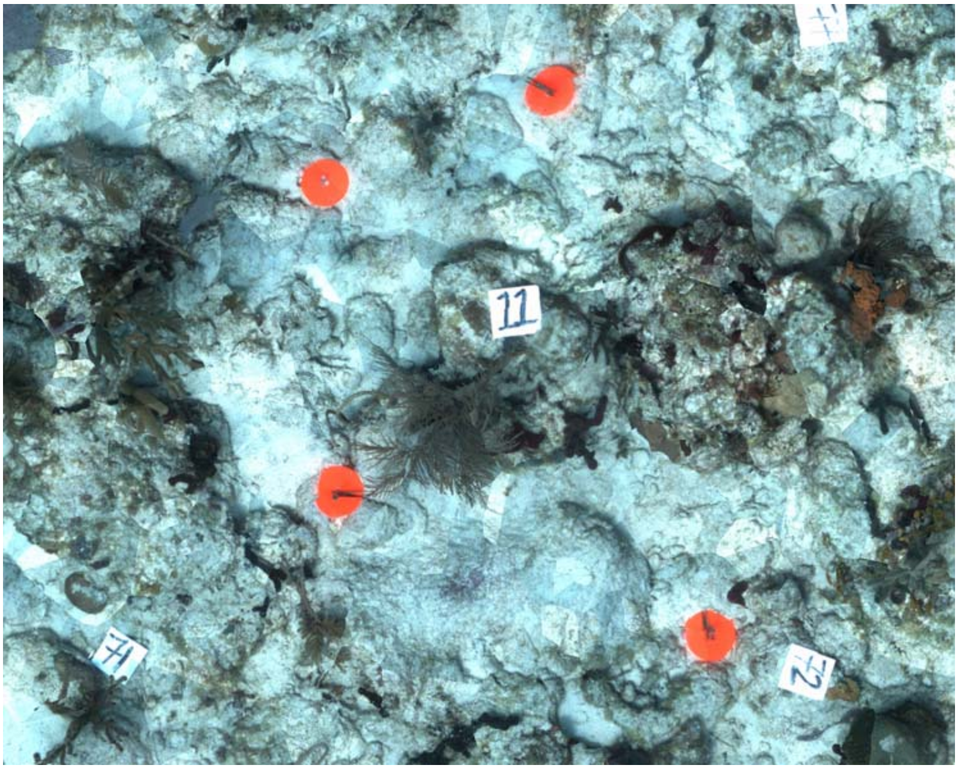

**Fig. 1** Sample image from the second mosaic showing the placement of the ground-truth markers (painted CDs) used for measuring spatial accuracy. The numbered tiles show the location of coral colonies for which size measurements were obtained by divers

error bounds to metric distance measurements made over the mosaic; and (2) they can be used as quality indexes to compare mosaics created under different environmental conditions, such as varying relief, depth, illumination, and turbidity.

### *2.1.4 Sub-sampling mosaic images: Tile extraction and change detection*

Referencing a mosaic allows for any area of the image to be delimited in metric coordinates.

Using the parameter vector $\vec{h}$, the metric coordinates of image point $(u_i, v_i)$ are given by:

$$\begin{bmatrix} x_i \\ y_i \end{bmatrix} = \begin{bmatrix} \frac{h_1 u_i + h_2 v_i + h_3}{h_7 u_i + h_8 v_i + 1} \\ \frac{h_4 u_i + h_5 v_i + h_6}{h_7 u_i + h_8 v_i + 1} \end{bmatrix}$$

Using the location of control stakes as a reference, a sample grid can be established so that sub-sections or “tiles” of known size can be surveyed (Fig. 2). Also, if mosaics share a reference frame defined by the same four control stakes, the same locations can be retrieved from all images if desired. The capability to extract the same reef locations from mosaics collected at different times was tested here as a mechanism to document patterns of change in the abundance and spatial distribution of reef organisms. In this study, tiles covering areas of $0.25\,\mathrm{m}^2$ were extracted from the mosaics to evaluate the percent cover of benthic organisms using the point intercept-method. The tiles extracted from the first mosaic were compared to the same tiles extracted from the third mosaic to evaluate changes in coral abundance from 2004–2005.

## 2.2 Benthic characterization

### *2.2.1 Diver surveys*

The benthic coverage of the different components of the coral reef community was quantified using the point-intercept method. This method was chosen because: (1) it is the method used by EPA’s Coral Reef Monitoring Program (CRMP) which surveys >40 permanent reef sites throughout the Florida Keys National Marine

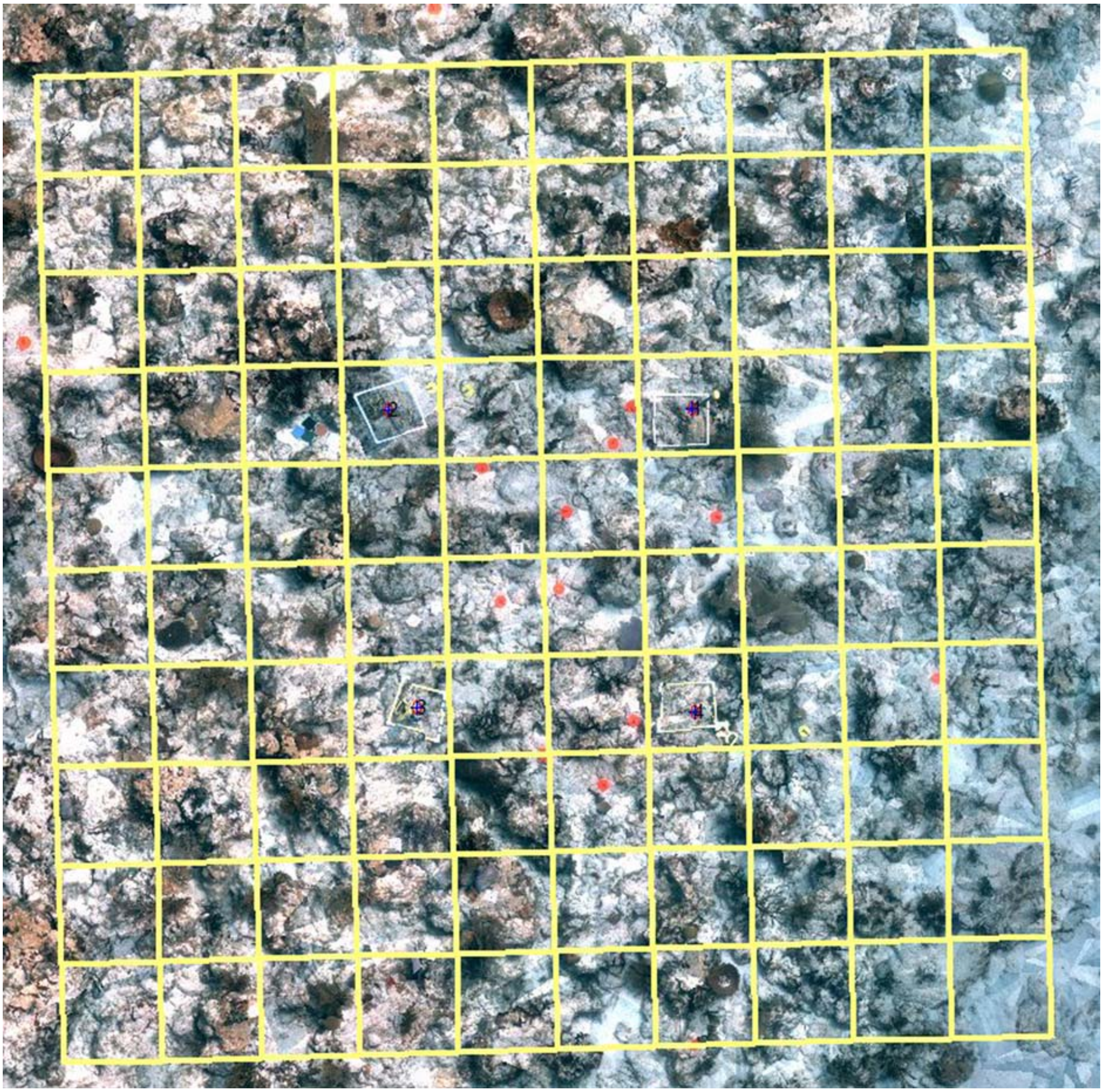

**Fig. 2** Example of a sampling grid constructed to extract subsections or tiles from video mosaics. The grid is referenced using four numbered control stakes. If the same four reference points are used from multiple mosaics, the same locations can be extracted to assess change patterns in the abundance of benthic organisms over time. In this mosaic, the white PVC quadrats are placed over each of the control stakes

Sanctuary (Porter *et al*., 2002); and (2) it can be applied during *in situ* visual surveys as well as to analyze photographs and video mosaics.

The point-intercept method consists of deploying PVC quadrats (0.25 $m^2$) subdivided with elastic rope. In each quadrat, survey points are identified by marking a subset of the rope intersections with colored plastic ties. In the field, the quadrats are placed on the bottom haphazardly and the identity of each benthic organism lying directly under the labeled points is recorded. In this project, eight main benthic categories were identified: stony corals, octocorals, sponges, the zoanthid *Palythoa*, macroalgae (>1 cm in canopy height), crustose coralline algae, algal turfs (<1 cm in canopy height), and sand. A preliminary analysis of the minimum number of quadrats as well as the number of points per quadrat needed to characterize the benthic community was conducted following methods outlined by Brown *et al*. (2004). Based on this analysis, 25 quadrats (covering approximately 25% of the reef area surveyed) and 25 points per quadrat were analyzed.

The number of points occupied by each category was used to determine their percent cover within quadrats and these values were averaged among quadrats to determine a mean value for each category. In addition to these measurements, the size (maximum diameter and height) of coral colonies within the survey area was quantified by divers using a flexible tape.

### *2.2.2 Video mosaics*

To quantify the cover of benthic categories from video mosaics, each mosaic was sub-divided into $0.25\,\mathrm{m}^2$ sub-sections or "tiles" (i.e., the same dimensions as the quadrats used by divers in the field) and a subset of mosaic tiles was extracted at random from the complete set to simulate the random placement of individual quadrats by divers in the field. The images were analyzed using the CPCe program developed by the National Coral Reef Institute (http://www.nova.edu/ocean/cpce/index.html). This application superimposes a user-determined number of points over a digital image. Once the points are placed, the user can identify the benthic category under each point just as it is done in the field. The program creates, as an output, a file that summarizes the information for each image and calculates the percent cover of each category by quadrat and by site.

The size (i.e., maximum diameter) of the coral colonies measured by divers (identified by a numbered tile visible in each mosaic) was estimated using the image analysis software Image J developed by the US National Institutes of Health with the scale provided by the pixel-size of each mosaic.

### *2.2.3 Comparison of diver surveys to video mosaics*

To evaluate the performance of our video mosaics as assessment tools, indicators of reef condition measured by divers were compared directly to the same indicators obtained from mosaics created with video sequences collected at the same time. The indicators measured by a single diver (D. Lirman) were used as the standard against which all other measurements were compared.

The percent cover of the eight main benthic categories was compared among survey methods (i.e., diver surveys, high-altitude mosaic, low-altitude mosaic) using a Kruskal-Wallis test. As an additional measurement of coral cover, the boundaries of all stony corals found within the area imaged by the low-altitude mosaic were digitized and analyzed using the "particle analysis" feature in the ImageJ software that calculates the total area of polygon features within an area of interest. Finally, the abundance of juvenile corals ($<4$ cm in diameter) measured by divers within benthic quadrats was compared to the abundance of juvenile corals measured from the mosaic tiles.

To determine the accuracy of diver surveys and video mosaics to estimate coral colony size, the differences between the values obtained by Lirman and those obtained by a second diver (B. Gintert), or directly from the video mosaics were measured. Accuracy of the size measurements was ascertained by calculating two measurements of error as described by Harvey *et al*. (2000):

$$\begin{aligned}&\text{Absolute Error} = \text{AE} = (|\text{Diver 1} - \text{Diver 2}|)\\&\text{and}\quad (|\text{Diver 1} - \text{Mosaic}|)\end{aligned}$$

$$\begin{aligned}&\text{Relative Absolute Error}\\&= \text{RAE} = [(|\text{Diver 1} - \text{Diver 2}|)/\text{Diver 1}]\\&\text{and}\quad [(|\text{Diver 1} - \text{Mosaic}|)/\text{Diver 1}]\end{aligned}$$

To compare the size data collected by divers and mosaics, an ANOVA with two factors, survey method and coral size category, was performed using the AE values.

## 3 Results

### 3.1 Video mosaics

The first video mosaic (Fig. 3) was created from 365 key-frames selected using a criterion of 75% overlap between consecutive images. For the second mosaic (Fig. 4), 496 key frames were selected out of the complete set of 5061 images, using 72% overlap. The registration parameters for the non key-frames were obtained by linear adjustment of the sequential matching, constrained by the registration parameters of the two

**Fig. 3** Video mosaic constructed with video collected from a hand-held digital camcorder in June 2004 at Brooke's Reef in the Florida Reef Tract (depth 7–10 m). The video was collected at a distance of 2 m from the bottom. The painted CDs show the location of ground-truthing points

closest key-frames. For the third mosaic (Fig. 5), 872 key frames were selected from a set of 3439 images with a 75% overlap criterion. The colors on all mosaics were adjusted by manually selecting both a white and a black reference and linearly interpolating the red, green, and blue intensities. The algorithms were coded in Matlab 6.2, and the overall processing took between 6–12 h per mosaic using a 3.0 GHz PC.

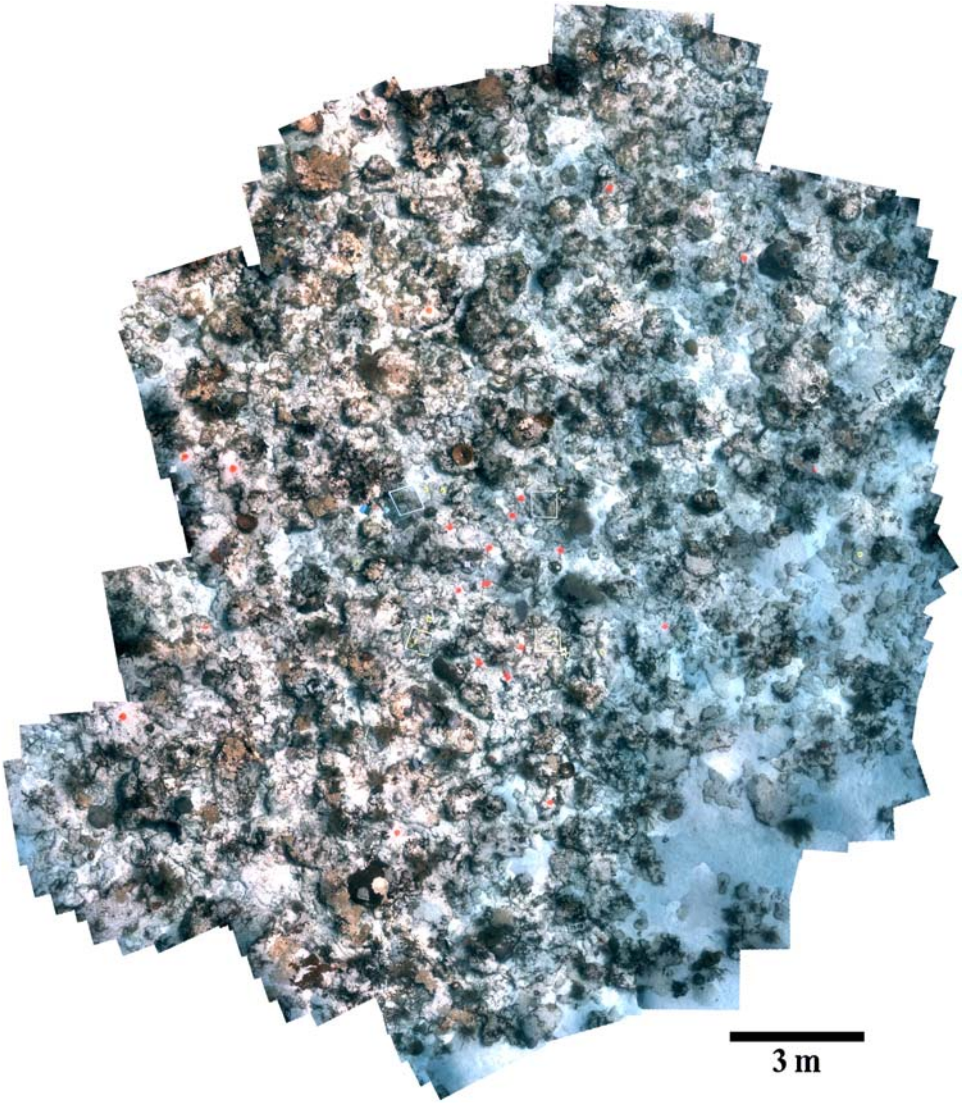

**Fig. 4** Video mosaic constructed with video collected from a high resolution camera from an ROV platform in April 2005 at Brooke's Reef. The video was collected at a distance of 2.5 m from the bottom

### 3.2 Spatial accuracy of video mosaics

The algorithm used in this study produced three mosaics with high spatial accuracy. The distortion indicators showed an improvement in spatial accuracy (i.e., decreases in the standard deviations of the residues and maximum distance errors) going from video collected by a diver holding a digital camcorder (first mosaic) to video collected by a high-resolution camera mounted on the ROV (second mosaic). However, distortion indicators did not improve with increased image resolution as the distance to the bottom was decreased in the third mosaic. Standard deviations of the residues were 5.1, 3.9, and 5.5 cm, while maximum distance errors were 12.9, 10.7, and 13.5 cm for the first, second, and third mosaics respectively.

### 3.3 Comparison of diver surveys to video mosaics

Five out of the eight categories chosen (hard corals, octocorals, *Palythoa*, turf, and sand) showed no significant differences in percent cover based on survey method (Table 2, $p > 0.05$). The remaining three categories, corresponding to functional forms of reef

**Table 2** Mean cover (±S.E.M.) of the different benthic categories surveyed by divers and measured from video mosaics from a reef site in the northern Florida Reef Tract (depth = 7–10 m). Divers surveyed twenty-five 0.25 $m^2$ quadrats. For comparison, a subset of 25 quadrats (0.25 $m^2$) were sampled at random form the video mosaics collected at 2 different resolutions. High-resolution mosaics were collected at a distance of 1.5 m to the bottom (2.5–3.0 mm/pixel). Low-resolution mosaics were collected at a at a distance of 2.5 m to the bottom (1.4 mm/pixel). CCA = Crustose Coralline Algae. *p* values from a Kruskal-Wallis test

| Benthic categories | Diver | Mosaic – high resolution | Mosaic – low resolution | *p* |
|---|---|---|---|---|
| Stony Corals | 1.4 (0.5) | 2.0 (0.7) | 1.8 (1.0) | 0.6 |
| Octocorals | 7.5 (2.6) | 6.2 (1.6) | 4.7 (1.6) | 0.6 |
| Macroalgae | 38.1 (3.4) | 31.7 (3.0) | 21.2 (3.1) | <0.01 |
| CCA | 1.1 (0.4) | 0.3 (0.2) | 0 | 0.02 |
| Sponges | 3.4 (1.2) | 12.9 (1.9) | 13.6 (1.9) | <0.01 |
| *Palyhtoa* | 4.2 (2.6) | 1.2 (0.5) | 2.7 (1.7) | 0.3 |
| Sand | 5.8 (2.0) | 9.2 (2.0) | 7.5 (1.7) | 0.6 |
| Turf | 38.9 (2.9) | 36.5 (3.0) | 41.6 (3.9) | 0.3 |

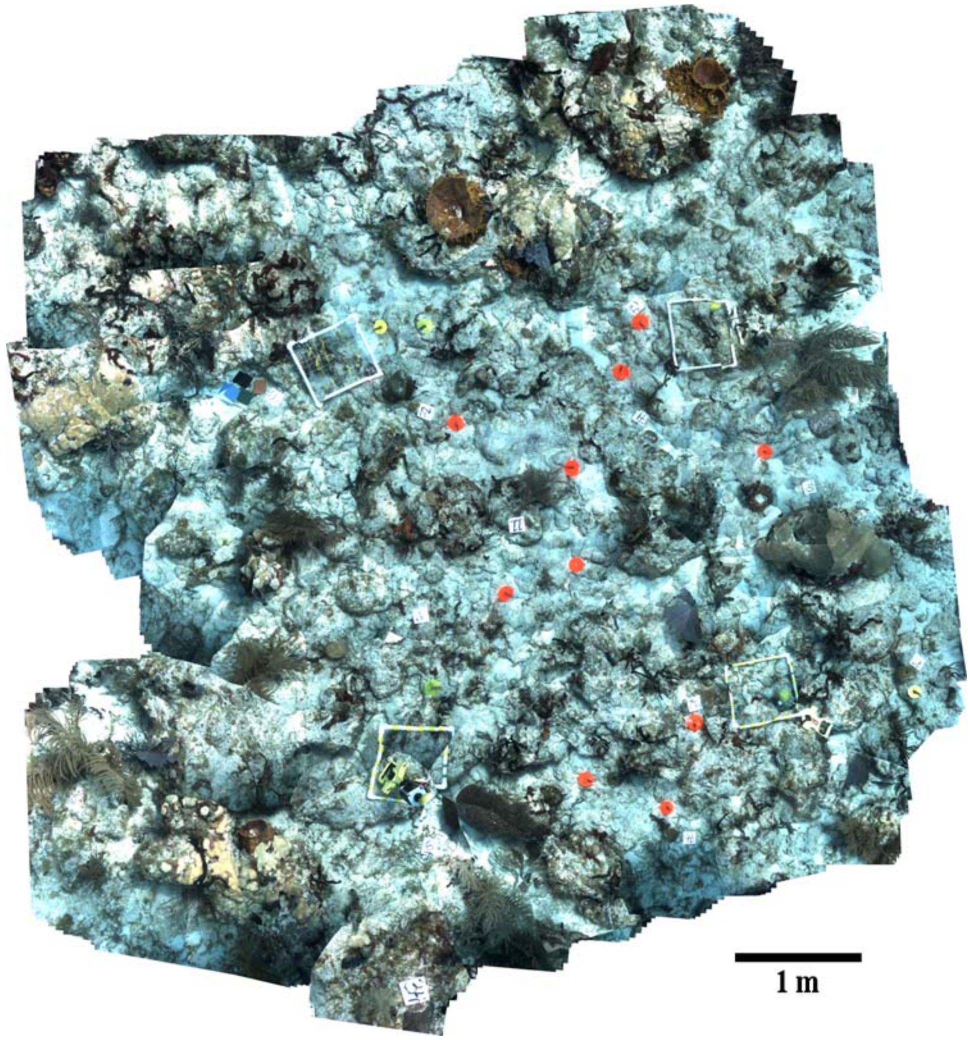

**Fig. 5** Video mosaic constructed with video collected from a high resolution camera from an ROV platform in April 2005 at Brooke's Reef. The video was collected at a distance of 1.5 m from the bottom

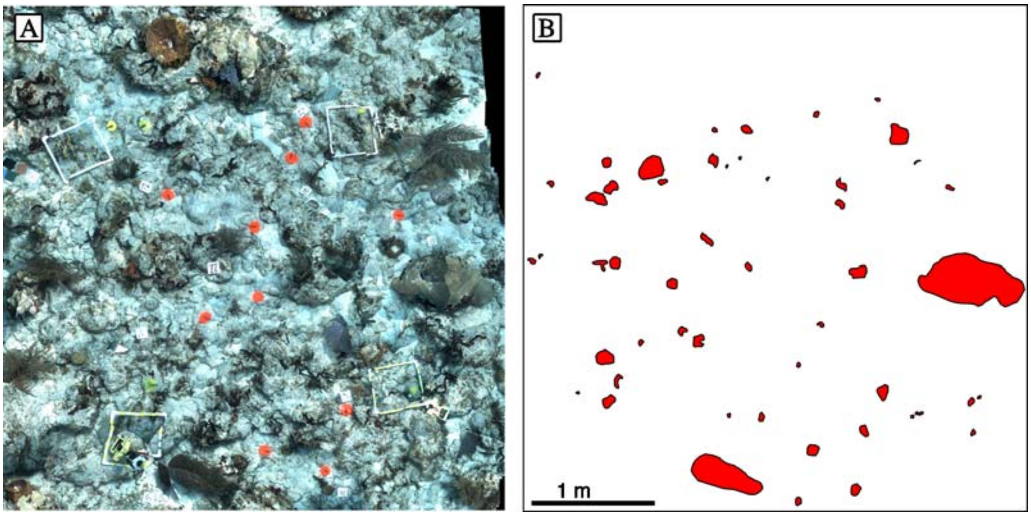

**Fig. 6** Abundance and spatial distribution of stony corals obtained from a high-resolution (1.4 mm/pixel) video mosaic (A). The boundaries of each coral colony (B) were digitized and the benthic coverage of stony corals was measured using the ImageJ software. The coral cover obtained by this method (2.8%) was within the 95% confidence intervals of the values obtained by divers and from video mosaics using the point-count method

macroalgae (erect macroalgae and crustose coralline algae) and sponges did show significant differences among survey methodologies ($p < 0.05$). However, when macroalgae categories are grouped together into a single macroalgae group, no significant differences were found among survey methodologies ($p > 0.05$).

The coral cover value obtained by digitizing the boundaries of all of the coral colonies within the area imaged by the high-resolution mosaic (2.8%) was within the 95% confidence intervals of the values obtained by divers and from video mosaics using the point-count method (Table 2; Fig. 6).

Lastly, while the mean abundance of juvenile corals (<4 cm in diameter) documented by divers during visual surveys were 1.1 and 1.4 juveniles $\mathrm{m}^{-2}$, no juvenile corals were detected from the mosaics.

When the accuracy of the two methods was compared using the AE, significant differences were found among the size categories, with AE increasing with colony size and height (ANOVA, $p < 0.01$) (Table 3). However, no significant differences were documented based on survey method (ANOVA, $p > 0.05$).

### 3.4 Change detection

The removal of coral colonies or other benthic organisms and changes in the composition of the substrate can be easily discerned by looking at the same section of the reef (Fig. 7). Using this method, the mortality or removal of four coral colonies (out of 50 colonies) was documented between 2004–2005 (mosaics 1 and 3) from an area of approximately 16 $\mathrm{m}^2$ (Fig. 6).

## 4 Discussion

The use of digital imagery in benthic monitoring has increased dramatically in the last decade and video surveys are now routinely conducted as complements to diver-based measurements (Carleton and Done, 1995; Ninio *et al*., 2003; Page *et al*., 2003). Moreover, several large-scale monitoring programs are now based almost exclusively on the analysis of video imagery. One such example is the Coral Reef Monitoring Program of the Florida Reef Tract where permanent belt transects are surveyed annually and video frames are sub-sampled to obtained estimates of coral cover and condition (Porter *et al*., 2002). The methodology presented here provides an important improvement over this technique by constructing referenced, spatially accurate landscape images of the benthos at a scale of up to 400 $\mathrm{m}^2$ from which spatial distribution patterns and size measurements can be extracted.

**Table 3** Comparison of coral size measurements between: (1) two divers measuring the same colonies; and (2) between diver measurements and measurements of the same colonies obtained directly from the video mosaics. $AE_1$ = absolute error = (|Diver 1 − Diver 2|), $RAE_1$ = relative absolute error = [(|Diver 1 − Diver 2|)/Diver 1]. $AE_2$ = absolute error = (|Diver 1 − Mosaic|), $RAE_2$ = relative absoluteerror = [(|Diver 1 − Mosaic|)/Diver 1]. Measurements taken by Diver 1 (Lirman) were considered here as the standard against which all other measurements were compared. Values reported are means (±S.D.)

| | Diver-Diver comparison$_1$ | | | Diver-Mosaic comparison$_2$ | | |
|---|---|---|---|---|---|---|
| Coral sizes (cm) | $AE_1$ | $RAE_1$ | N | $AE_2$ | $RAE_2$ | N |
| <10 | 0.7 (0.3) | 8.9 | 9 | 1.6 (0.4) | 21.0 | 22 |
| 10–20 | 1.9 (0.7) | 10.6 | 15 | 2.5 (0.4) | 16.5 | 45 |
| >20–30 | 4.8 (1.2) | 17.7 | 7 | 3.4 (0.8) | 14.2 | 19 |
| >30–80 | 5.4 (2.7) | 11.1 | 7 | 5.6 (1.4) | 13.1 | 20 |

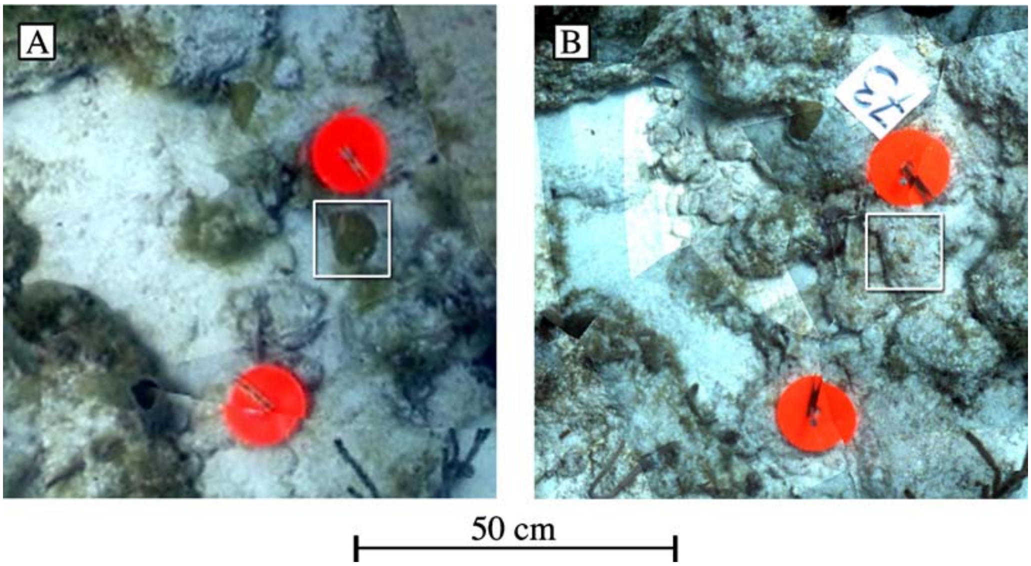

**Fig. 7** Referenced mosaic sub-sections or tiles used to assess patterns of change in the abundance and distribution of benthic organisms between 2004 (A) and 2005 (B). The box highlights the removal or mortality of a small (<10 cm in diameter) coral colony between surveys

The ecological indicators collected by trained divers *in situ* compared favorably with those measured directly from the video mosaics. Percent cover of the dominant benthic organisms on reefs of the Florida Reef Tract was characterized well from the video mosaics compared to diver-based measurements. Estimates of bottom cover of hard corals, octocorals, sponges, the encrusting zoanthid *Palythoa*, and sand were statistically similar to values collected *in situ* by trained divers, while significant differences were found between the percent cover of the three dominant macroalgal groups estimated by the different methods. This pattern is a direct consequence of the increased difficulty in assigning points to these categories with decreasing image resolution. Not surprisingly, the categories that are consistent among methods are those that are the easiest to identify in the field and from photographs due to their shape, color, and clear boundaries. In contrast, those categories that have ill-defined boundaries and subdued coloration showed the highest variability among methods. Lastly, a major limitation of video-mosaic surveys is the ability to detect and identify juvenile corals (<4 cm in diameter). These small corals are often found on cryptic habitats and can only be seen in visual surveys where the observer can shift the angle of view. Future improvements in camera resolution will enhance the detection capabilities of this technique and facilitate the classification of additional benthic categories and smaller organisms.

The capability of identifying individual coral colonies and measuring their size directly from each mosaic is one of the most important benefits of this novel technique. While the accuracy of the mosaic measurements relative to the diver-based measurements was influenced by colony size, these patterns result from the difficulty that divers commonly encounter while trying to measure coral colonies in the field. Colony boundaries are easily distinguished in small ($<20$ cm) colonies that commonly exhibit circular shapes, but larger colonies with irregular shapes pose a challenge for divers trying to delimit live tissue boundaries. Future improvements in the 3D representation of benthic mosaics are expected to substantially improve the accuracy of this technique with respect to the measurement of larger colonies with more complex topographies (Negahdaripour and Madjidi, 2003; Nicosevici *et al*., 2005).

Previous research on the design of field programs aimed at documenting patterns of change in benthic resources over time has highlighted the increased statistical power gained by surveying precise specific locations repeatedly compared to the survey of random locations (Van de Meer, 1997; Ryan and Heyward, 2003). The demarcation of permanent plots on hard benthic substrate is commonly achieved by attaching pipes or nails on the bottom, and the number of markers needed to mark multiple colonies, quadrats, or transects at a given site can be quite large. Video mosaics provide an alternative to these labor-intensive methods. By placing a limited number of permanent markers to provide a reference frame within each video mosaic (only four permanent markers were used in this study to accurately survey an area of 400 $\mathrm{m}^2$), the technique described in this study can reduce significantly the bottom-time needed to collect ecological information in the field. Moreover, by providing the ability to survey specific sub-plots repeatedly within a larger area of the benthos, video mosaics provide increased statistical power to detect small changes in abundance, cover, and size of benthic organisms. However, a trade-off exists between within-site precision and the ability to survey large areas, making the video mosaic technique an ideal method to survey areas $<500\,\mathrm{m}^2$ but impractical for documenting changes in the extent and condition of benthic resources at larger spatial scales. It is expected that further improvements in the mosaicing algorithms combined with the use of improved positioning modalities (e.g., acoustic transponder networks) will make this technique practical at larger scales in the near future.

Another major benefit of the algorithm described here is the ability to provide landscape-level views and analytical capabilities of benthic data collected by remotely operated platforms (i.e., AUVs, ROVs). This technique can provide unique opportunities to study the spatial arrangement, condition, and sizes of benthic organisms at locations not easily accessible to scientific divers, thus providing a crucial set of tools for the study of deep benthic communities where diver bottom-times are restricted.

The analysis of mosaics constructed over two spatial dimensions has highlighted several advantages over strip mosaics constructed along a single spatial dimension. For example, the sizes of coral colonies were accurately measured from two-dimensional mosaics, even though they are typically hard to acquire from one-dimensional mosaics where only the smallest coral colonies are completely imaged along a single transect. Moreover, two-dimensional imagery from repeated surveys was accurately referenced to assist with change-detection, unlike linear transects that are exceedingly difficult to duplicate precisely over time. Two-dimensional video mosaics can provide useful tools to assess the impacts of physical sources of disturbance to shallow reefs such as boat groundings, which can cause significant localized damage to reef resources (Lirman and Miller, 2003). The spatial extent of features such as vessel grounding scars that are often too small to map using airborne or satellite-based remote sensing tools and too large to be mapped efficiently by divers, could be measured accurately from a two-dimensional video mosaic.

The ability to extract accurate distance measurements from the mosaics was evidenced by the low values calculated for the distortion indicators. Moreover, the spatial accuracy of the video mosaics presented here was similar or lower than the measurement uncertainty of diver measurements, which typically exhibits a standard deviation of 5 cm (Holt, 2000). While an improvement in camera resolution resulted in a reduction in spatial distortion, the higher distortion of the low-altitude mosaic highlighted a present limitation of the mosaic algorithm. The sources that contribute to spatial distortions in mosaics include: (1) departures from the model assumption of a flat environment; (2) amount of superposition among strips during the acquisition; (3) limited visibility underwater; (4) limited resolution of the imaging sensors; and (5) limited accuracy of the image matching algorithm. The higher distortion recorded for the third mosaic, collected closest to the bottom, can be likely attributed to the fact that the scene's surface planarity assumptions were clearly violated at the low altitude at which the video sequence was collected and indicates that further testing is needed to determine the minimum distance to the bottom for which the 2D mosaicing algorithm can produce useful results.

In conclusion, two-dimensional video mosaics could be widely adopted as a component of reef monitoring and damage assessment programs. The flexible mosaicing algorithm developed for this study allows this technique to be used in a variety of applications from low cost surveys with handheld video cameras to mapping of deep reefs with ROV-based platforms. Two-dimensional video mosaics can fill an information gap for scientists and resource managers by providing repeatable, accurate measurements on the reef-plot scale that can complement measurements on the colony-scale made by divers as well as surveys conducted over regional scales from remote sensing platforms.

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SHORT COMMUNICATION

# Documenting hurricane impacts on coral reefs using two-dimensional video-mosaic technology

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**Keywords**
*Acropora palmata*; Florida; hurricane damage; reef framework damage; video-mosaics.

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## Abstract

Four hurricanes impacted the reefs of Florida in 2005. In this study, we evaluate the combined impacts of hurricanes Dennis, Katrina, Rita, and Wilma on a population of *Acropora palmata* using a newly developed video-mosaic methodology that provides a high-resolution, spatially accurate landscape view of the reef benthos. Storm damage to *A. palmata* was surprisingly limited; only 2 out of 19 colonies were removed from the study plot at Molasses Reef. The net tissue losses for those colonies that remained were only 10% and mean diameter of colonies decreased slightly from 88.4 to 79.6 cm. In contrast, the damage to the reef framework was more severe, and a large section (6 m in diameter) was dislodged, overturned, and transported to the bottom of the reef spur. The data presented here show that two-dimensional video-mosaic technology is well-suited to assess the impacts of physical disturbance on coral reefs and can be used to complement existing survey methodologies.

## Problem

During the summer of 2005, an unprecedented sequence of four hurricanes impacted the reefs of the Florida Keys. Damage patterns to coral reefs are commonly influenced by the strength, path, and duration of each storm event (Harmelin-Vivien 1994; Lirman & Fong 1997; Lirman 2000). In the case of sequential storms, damage patterns can be also determined by storm frequency and prior disturbance history (Witman 1992). When the time required for live coral fragments to re-attach to the bottom and for loose rubble to stabilize exceeds the interval between storms, physical impacts can be compounded as loose pieces of coral rubble are mobilized by subsequent storms (Lirman & Fong 1997). The impacts of storms on coral colonies are often influenced by colony morphology, and the branching morphology of corals like *Acropora* spp. makes them especially susceptible to physical disturbance (Woodley *et al.* 1981). In fact, hurricane damage and coral diseases have been identified as the main source of mortality to acroporids in the Caribbean region, where this taxon has undergone such a drastic decline in abundance that the U.S. NOAA Fisheries Service has proposed listing *Acropora palmata* and *A. cervicornis* as 'threatened' species under the U.S. Endangered Species Act (Bruckner 2002; Oliver 2005; Precht *et al.* 2005).

The cumulative effects of the 2005 storms on one of the last remaining populations of *A. palmata* in the northern Florida Reef Tract were assessed with a newly developed survey methodology that is used to construct spatially accurate, high-resolution landscape mosaics of the reef benthos. Video-mosaics provide a complement to

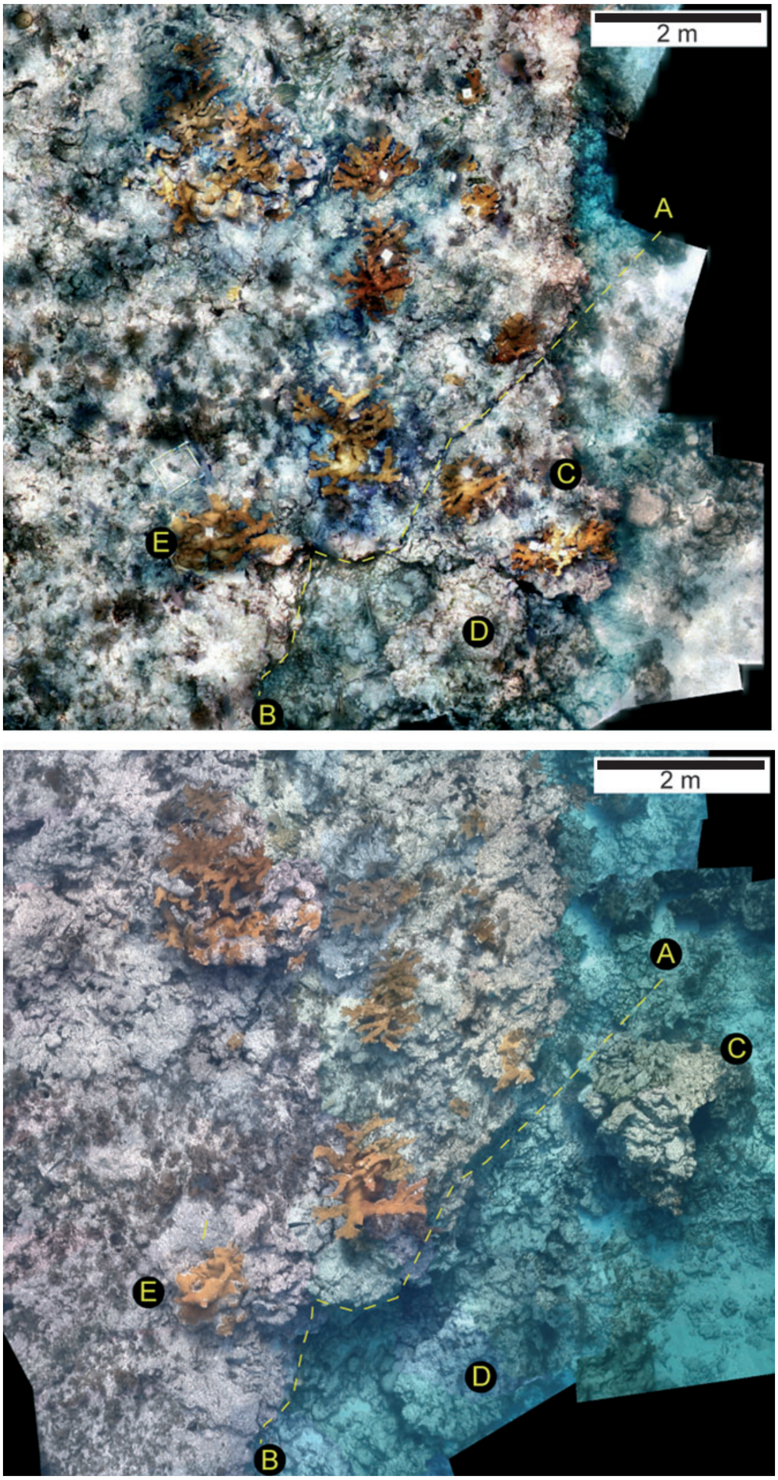

**Fig. 1.** Two-dimensional video-mosaics from a study plot at Molasses Reef in the Florida Reef Tract (depth 3.5–4.5 m). (Top) Mosaic from May 2005 was constructed prior to the start of the 2005 hurricane season. (Bottom) Mosaic from February 2006 following the passage of four hurricanes. The yellow line A–B shows where the reef framework was dislodged during hurricane Rita causing sections of the reef marked C and D to collapse. The section labeled C also appears in Fig. 2A. The *Acropora palmata* colonies located on section C are shown in Fig. 2B. Close-ups of the *A. palmata* colony labeled E appear in Fig. 2C and D.

standard diver-based survey methods, which require a high level of training and extended time underwater. Moreover, two-dimensional mosaics cover larger areas than one-dimensional 'strip' mosaics (Jaap *et al.* 2003) thereby allowing new types of analyses such as measuring the sizes of coral colonies and visualizing large features on the reef (Lirman *et al.* 2006).

## Material and Methods

In this study, we used video-mosaic technology to document hurricane impacts on a population of the branching coral *A. palmata* at Molasses Reef (25° 0.609 N, 80° 22.397 W, depth = 3.5–4.5 m). Mosaics of the study plot (approximately 10 m × 10 m) were constructed from underwater video collected at 2 m from the bottom using a Sony TRV900 DV camcorder. The mosaicing algorithm is described in detail by Gracias *et al.* (2003), Negahdaripour & Madjidi (2003), and Lirman *et al.* (2006). Briefly, the method has four steps: (1) acquire the video in a series of parallel, overlapping swaths covering the study area; (2) estimate the image-to-image motion between pairs of sequential images to calculate an estimate of the camera trajectory; (3) refine the estimated camera trajectory by estimating motion between non-sequential but overlapping images; and (4) produce a single image by blending contributions from the individual frames. The mosaics constructed for this study have a ground resolution of 1–2 mm per pixel and coral colonies or fragments >5 cm in diameter are easily identified within each image.

Video data were collected before the passage of the hurricanes at Molasses Reef in May 2005 and again in February 2006 after hurricanes Dennis (dates of influence over the Florida Keys = July 9–10, 2005, peak wind gusts at Molasses Reef (C-MAN station) = 90 km $h^{-1}$), Katrina (August 25–26, 2005, 116 km $h^{-1}$), Rita (September 19–20, 2005, 100 km $h^{-1}$), and Wilma (October 24–25, 2005, 147 km $h^{-1}$). The video required to build the mosaics of the study plot was collected in <30 min, and production of the mosaics required approximately 10 h using a standard personal computer.

Landscape video-mosaics such as the ones produced in this study have high spatial accuracy (standard deviations of the residues = 4–5.5 cm, maximum distance error <14 cm) and thereby provide the capability to measure distances and sizes directly from the images once a scale has been established (Lirman *et al.* 2006). The scale in these mosaics is provided by PVC segments and ceramic tiles scattered throughout the images. The size of the *A. palmata* colonies found within each mosaic was measured as: (1) the maximum colony diameter (to the closest cm); and (2) the projected surface area of live tissue. The image-analysis software ImageJ was used to calculate these metrics.

## Results and Discussion

The direct physical damage caused by hurricanes and tropical storms can vary significantly across scales, ranging from minimal to severe (Harmelin-Vivien 1994). Whereas changes in coral cover, abundance, and condition can be easily discerned from traditional before-and-after surveys, changes to the structure of reefs are harder to quantify. The video mosaics created in this study provide a unique view of the reef benthos that facilitates the

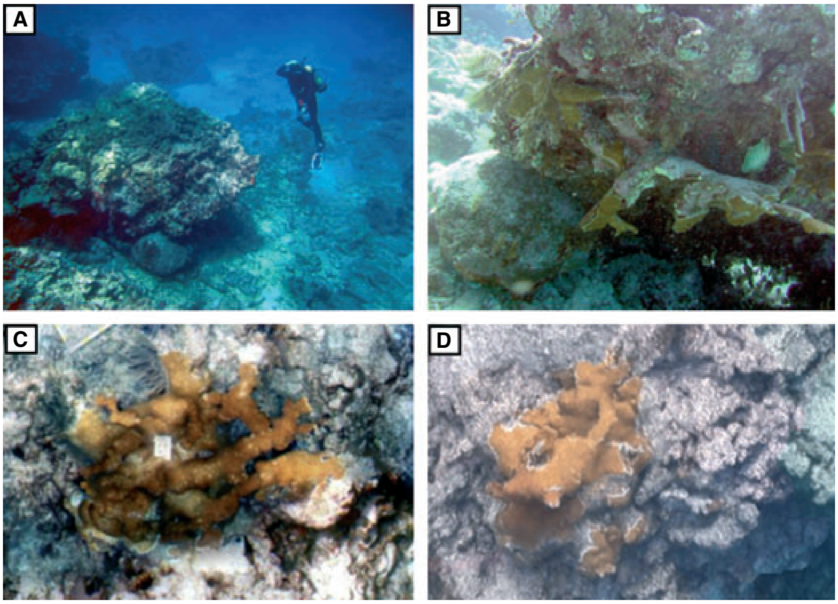

**Fig. 2.** A: Photograph of the reef section (labeled C in Fig. 1) that was dislodged during Hurricane Rita. B: Photograph of two *A. palmata* colonies attached to the dislodged reef section shown in A. These colonies ended up facing the sediments and died shortly after the storm. C: May 2005 and D: February 2006 photographs of an *A. palmata* colony (labeled E in Fig. 1) that experienced fragmentation and tissue losses due to the 2005 hurricanes.

documentation of colony-level impacts as well as large-scale structural changes to the reef framework.

If only coral cover and colony-based information such as abundance and size-structure had been collected prior to the onset of the 2005 hurricane season, the damage report for the *A. palmata* population at Molasses Reef after the passage of four major storms would have revealed, unexpectedly, only limited damage considering the intensity and frequency of the 2005 hurricanes. A total of 19 *A. palmata* colonies were identified from the video mosaic from May 2005, prior to the onset of the 2005 hurricane season, and 17 of these colonies remained, in the same location, in the study plot in February 2006 (Fig. 1). The two colonies that were removed from the plot were located on one of the sections of the reef framework that was dislodged during Hurricane Rita (Fig. 2A). These two colonies remained attached to the dislodged reef section but ended up in contact with bottom sediments and died shortly after this storm (Fig. 2B). The tissue on these large colonies (110 and 155 cm in maximum diameter) represented 14% of the total live *Acropora* tissue on the plot prior to the storms. For those colonies that remained, the net tissue losses between surveys were only 10%. Fifty-two percent of colonies lost live tissue, the maximum tissue loss for an individual colony was 46%. The mean diameter of colonies decreased slightly from 88.4 cm (SD ±70.1) to 79.6 (±63.3) cm. Tissue losses were mainly attributed to the removal of branches (Fig. 2C and D).

An increase in the abundance of colonies through fragment formation and reattachment after storms has been documented previously for *A. palmata* in Florida (Fong & Lirman 1995) but was not observed within the study plot at Molasses Reef. Fragment reattachment requires a minimum amount of time (Lirman 2000) and the succession of storms during the summer of 2005 may have impeded this process.

Considering the limited impacts documented for coral colonies at Molasses Reef, one of the most remarkable impacts of the 2005 hurricanes was the damage caused to the reef framework. Within the study plot, a large section of the reef (surface area = 12.7 $m^2$, diameter = 6 m) was dislodged and deposited on the sand at the bottom of the reef spur (Figs 1 and 2A). The shift in orientation of these sections resulted in the smothering and burial of coral colonies and the exposure of reef framework that may be further weakened by the future activities of bioeroders (Glynn 1988). The precise documentation of such large-scale modifications to the structure of the reef was only possible because of the landscape view provided by the video-mosaics.

The methods used to assess damage and recovery patterns of reef communities commonly entail the construction of underwater maps of the benthos based on diver-collected distance measurements and drawings, and the deployment of survey markers and permanent tags for coral colonies within plots. Assessing the impacts of severe physical disturbance on coral reefs can be especially challenging when large-scale modifications to the reef structure and the removal of both coral colonies and survey markers take place, as is commonly seen not only after storms but also after ship groundings (Hudson & Diaz 1988; Jaap 2000). The data presented in this study show that landscape video-mosaics provide the tools needed to accurately assess reef damage and recovery patterns and provide a significant addition to the existing survey techniques.

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