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SEAGRASS LOSS IN BELIZE: STUDIES OF TURTLEGRASS (*THALASSIA TESTUDINUM*) HABITAT USING REMOTE SENSING AND GROUND-TRUTH DATA

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Abstract: Spatial and temporal change in turtlegrass (*Thalassia testudinum*) habitat of the South Water Caye Marine Reserve (SWCMR) in Belize were analyzed using satellite images backed up with ground-truth data. We had two primary objectives. First, we wanted to determine areal expanse of seagrass across a large area (~12 km by 3 km) of the SWCMR, and address its change over time. We used paired satellite images taken during 2001 and 2005 to determine coverage by seagrass and measure temporal variables. These analyses recorded an overall seagrass loss of 1.8% (52.3 ha) during the 4 yr period. Secondly, we wanted to determine whether seagrass gains or losses were consistent across the study area. Replicate sampling was used as a statistical basis and confirmed a significant loss of seagrass across the region. It also helped identify two regions of significant seagrass loss; one 600 ha area lost 12.4% of its seagrass; another 240 ha area lost nearly 40%. These components helped us assess seagrass habitat in an area perceived as critical to Belize fisheries, and provided the scale and statistical rigor necessary to adequately assess a broad region of study. The salient results from our study were not the magnitude of seagrass loss *per se*, but the loss in seagrass habitat from an area that is thought to be relatively pristine. Seagrass-habitat loss in this region of the Caribbean Sea may be evidence that even near-pristine areas can be impacted by anthropogenic factors. Determining the causes of habitat loss may help prevent loss of productivity, habitat, and livelihood for the associated human and nonhuman communities.

Introduction

Seagrass ecosystems are among the most productive on earth, and their ecological and economic importance is becoming obvious as they diminish worldwide. Seagrass habitats are vital primary producers that improve water quality, promote sedimentation, recycle nutrients, and provide structure that serves as refuge and nursery ground for fisheries species (e.g., Moriarty and O'Donohue 1994, Hall et al. 1999, Short and Wyllie-Echeverria 2000, Gillanders et al. 2003, Green and Short 2003, Corlett and Jones 2005). The interest in seagrass is global, as is the research effort to assess changes in seagrass habitat. Many studies centered around areas of long-term loss of seagrass (e.g., Short and Short 2003, Duarte et al. 2008), while others documented regions of seagrass recovery (e.g., Virnstein et al. 2007).

Turtlegrass (*Thalassia testudinum*) is a common seagrass species in waters of the tropical western Atlantic from Venezuela to eastern Florida and the Bahamas (den Hartog 1970), and is one of many species adversely affected by natural and anthropogenic factors. Researchers contend that protecting seagrass habitat may prevent loss of commercial fisheries, improve water quality, and help maintain healthy interrelated communities (Ward 1998).

The purpose of this study was to discern the stability of the turtlegrass-dominated seagrass community in the South Water Caye Marine Reserve (SWCMR) of Belize by using satellite imagery. This reserve is generally perceived to be pristine, far from the coastal influences that adversely affect most other seagrass communities, and an area of interest to Belize fisheries and tourism. We had two primary objectives. First, we wanted to determine areal expanse of seagrass, and address its change over time by analyzing satellite images taken 4 years apart. Secondly, we wanted to determine whether seagrass gains or losses were consistent across the study area, and used ground truthing to confirm our observations by visiting sites of concern identified by satellite images. The multiple components of our study helped assess seagrass habitat in an area perceived as critical to Belize fisheries, and provided the scale and statistical rigor necessary to adequately assess a broad region of study.

Methods

Study Area

The study area was in the South Water Caye Marine Reserve, Belize (Central America), along Belize's Caribbean coast, about 14 km from the mainland. It is part of the Belize barrier reef ecosystem, which was designated as a UNESCO (United Nations Educational, Scientific, and Cultural Organization) World Heritage Site in 1996. The biological communities, physical oceanography, geology, and history of the area were summarized by Rützler and Macintyre (1982).

The area of habitat classification for this study (16° 54' to 16° 46' N; 88° 04' to 88° 07' W) was a ~3 km wide area

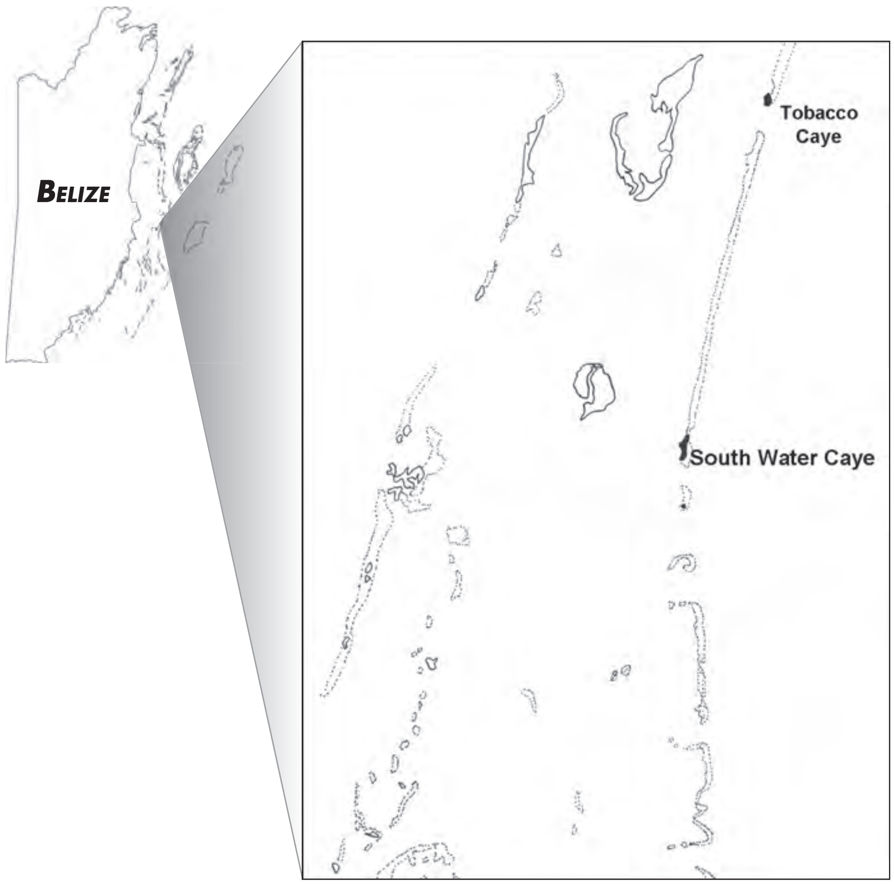

Figure 1. *Map of the study area in Belize with details of the islands (solid lines) and reefs (dotted lines) in the South Water Caye Marine Reserve (16° 54′ to 16° 46′ N; 88° 04′ to 88° 07′ W). Two major channels open into the lagoon. Tobacco Channel is just south of Tobacco Caye (shaded black); South Water Channel is just south of South Water Caye (shaded black).*

from Tobacco Caye southward beyond Curlew Caye (12 km), extending from the western-most region of back reef (2.5 m depth) to the lagoon (3-7 m depth) (Figure 1). We used a region of similar depth so we could attain consistent spectral contrast for classifying the seagrass (as per Andréfouët et al. 2003). There were no strong tropical cyclones through the area during this study period that destroyed or buried seagrass, nor did our divers observe any effects from previous storms, such as they observed elsewhere in the Caribbean.

Satellite Images

We used paired satellite images to determine change in areal coverage of the region by seagrass. In order to assess both total change in habitat and determine the region most affected by change, we analyzed seagrass habitats of the study area on two scales of distribution. Our broad-scale analyses included a large region of the SWCMR as an entity. Our medium-scale analyses included replicate samples (4 ha each) to address questions on a smaller scale (tens of meters). The replicates provided a means of statistical assessment of habitat change.

The images used in this study were acquired by the University of Mississippi Geoinformatics Center (Oxford, Mississippi), and consisted of an IKONOS image of 12 September 2001, and a Quickbird image taken on 10 April 2005. Both images covered the areas of study with minimal cloud cover (< 0.1% in the IKONOS image; 4% in the Quickbird image). As necessitated by differences in cloud cover, a masking technique was used to render the images comparable (see below). The two images were of high-spatial resolution (IKONOS = 1 m; Quickbird = 0.61 m) and consisted of 4 spectral bands of the same wavelengths; these similarities allowed for maximum analysis and comparison. The band widths for both images were 0.45-0.90 μm for the panchromatic band, 0.45-0.52 μm for band 1, 0.52-0.60 μm for band 2, 0.63-0.69 μm for band 3, and 0.76-0.90 μm for band 4. The QuickBird image had a significant presence of sun-glint reflection due to the angle of the sun (time of day) when the scene was collected. A process was used to remove the sun glint from the QuickBird image (see below).

Several pre-processing techniques were necessary to begin classifying and analyzing the satellite images. First, the panchromatic bands and the multispectral bands were combined to produce the pan-sharpened, multispectral imagery. Image rectification was performed in order to geometrically correct both the 2001 and 2005 images. Ground control points of known location in all areas of the images were used to correct the images, with most of them being geo-referenced points (piers, homes, and other unaltered structures). Nearest-neighbor resampling was used instead of cubic convolution resampling due to the degradation of textural information which occurs using cubic-convolution resampling (Andréfouët et al. 2003).

Removal of the sun-glint from the 2005 QuickBird image was required before further pre-processing steps could be initiated. Confused-resolution images result when light is reflected off of the crests and slopes of waves in the image (Hochberg et al. 2003). This reflection is known as sun glint, and may cause significant problems when classifying the image. The sun-glint-affected pixels in the NIR band are also present in the visible bands. In order to correct for the glint, a method detailed by Hedley et al. (2005) was used on the 2005 image. The steps for removal of the glint were completed by using ITT's ENVI 4.5, and the linear regression calculations were completed in Microsoft Excel (Hogrefe et al. 2008).

Both the IKONOS and QuickBird images were corrected and enhanced using common remote-sensing techniques such as georectification, land/cloud masking and image resampling, in addition to the aforementioned glint removal. The islands (present in both images) and shallows were de-selected from the images prior to classification of seagrass. The clouds in the 2001 image were on the margin of the study area; they were de-selected before classification. The presence of clouds in the 2005 image required that a cloud mask (delineated from the 2005 image) be applied to both images. This was done in order to generate classified images that represent the same area processed during the unsupervised classification.

The final step of preprocessing prior to the unsupervised classification was resampling the 2005 QuickBird image, with a 0.61 m pixel resolution, to match the lower 1.0 m pixel resolution of the 2001 IKONOS image. After resampling, both images had a pixel resolution of 1.0 m, which allowed for the unsupervised classification to be performed. These standard post-processing steps were completed using ERDAS Imagine 9.1.

An unsupervised classification was performed using Leica Geosystem's ERDAS Imagine 9.1. The classifications divided the images' digital numbers into 60 classes. The classification ran through 35 iterations up to 99% convergence. After classification of the two images, the 60 classes of each image were merged into 5 classes for preliminary assessment of the images. These 5 classes included several categories of seagrass density. An accuracy assessment was performed in order to draw an estimate of overall accuracy of the classifications. The method requires an error matrix (confusion matrix) to determine the accuracy of the classifications, in which classifications from the satellite images are compared with ground-truth data (Congalton and Green 1999). The preliminary accuracy assessment yielded values at about 90%; but those were below values necessary to support statistical analyses based on seagrass density. For further analyses the 60 classes were merged into 2 classes: one contained pixel values of all densities of seagrass combined; the other class contained pixel values that represented lack of seagrass (sand). Now the ground-truth data matched the classified images with high accuracy. From those data we totaled the number of pixels of each habitat to compare differences between the two images.

Ground Truthing

A field campaign was designed to collect ground-truth data to assess accuracy and spatial resolution of the images. We mapped the region with swim transects during March, May, and July 2001, May and June 2002, June 2003, and May and December 2004. We conducted surveys with glass-bottomed buckets, and made SCUBA observations during May and June 2005 for further rapid visual assessment (Mumby and Harborne 1998). After the 2001 surveys, a preliminary benthic map of seagrass habitat, distinguished by seagrass-density categories, was created. The map was based on ground truthing, an unsupervised classification using the ISODATA algorithm, and a 2001 satellite image (see below). We selected 162 points that were deemed references to check benthic coverage and image accuracy, and increased this number to 500 points with subsequent ground-truth surveys. Observations at the 162 points included estimates of seagrass density (dense, > 30 shoots/0.25 m^2; moderate, 5-29 shoots/0.25 m^2; sparse, < 5 shoots/0.25 m^2). The data taken at the additional points included only seagrass presence or absence. Each point was geo-referenced using a Garmin GPS 12CX with a positional accuracy of ± 1 m. After surveying each of the initial 162 points selected, the habitats of sand and seagrass in the area immediately surrounding the point (tens of meters) were also surveyed and recorded.

Ground truthing during preliminary work helped ascertain the adequacy of the region for study, and determine the distribution of seagrass and adjacent ocean-bottom habitats. We used numerous habitat categories during preliminary ground-truth data collection, including several seagrass-density categories, bare sand, sand with sparse algae (and no seagrass), and mixed-species habitats (turtlegrass, other seagrass species, algae, coral, and sponges). Some shallow areas of the region (< 2 m) supported algal mats and coral-rubble habitat with minimal seagrass. We found that those shallow regions, especially the back-reef areas (behind the reef crest) and coral-rubble habitats surrounding islands, had seagrass that was mixed with algae (usually *Ulva* spp.) and other seagrass species that increased potential for error in our classifications. Algal mats resemble seagrass in remotely sensed data, and might have obfuscated the analyses. We eliminated those shallow-water habitats, patch reefs, and recently dredged areas near South Water Caye from further classification. This preliminary work provided a study area (~ 12 km by 3 km) that was dominated by turtlegrass, with only minor presence (< 1% areal coverage) of other seagrass species or algae. Eliminating the shallow regions and patch reefs allowed us to reduce the habitat categories for further analyses to several categories of seagrass density and bare sand.

Replicate Sampling

We wanted to determine whether the change in seagrass coverage was consistent across the study area and provide a statistical basis for the study, so 40 ha replicates were used as subset samples. Twenty-four replicate sites, each about 4.0 ha (200 m by 200 m; 9.9 acres) in size, were chosen from the two images (48 sites total). The 24 replicates were at identical locations in each image, and were chosen at random (random-numbers generation by Excel). The choice of replicate size was made after checking the accuracy levels of classifying replicates between 1-25 ha, and finding a dip in

TABLE 1. *Data on seagrass characteristics and change in habitat. South Water Caye Marine Reserve, Belize.*

	Coverage by seagrass	Coverage by sand
2001 image		
Hectares	2352.3	430.5
Acres	5812.2	1063.6
%	84.5	15.5
2005 image		
Hectares	2300.0	480.1
Acres	5683.2	1186.4
%	82.7	17.3
Change in Habitat		
Hectares	-52.3	+49.6
Acres	-129.0	+122.8
%	-1.8	+1.8

accuracy level of replicate-sample sizes > 4 ha. The 4 ha replicates were placed on the image directly to the south of the randomly generated points. Classifying the 48 units (2 for each image) by numerous habitat categories during preliminary work allowed for a more accurate overall classification by heightening spectral differences in the areas of particular interest. Analysis of paired replicates from the two images allowed for precise quantification of changes, and provided detailed information on the geometry of habitat gain or loss that may not be obtained through the use of random (unmatched) replicates.

Results

The first objective was to determine areal expanse of seagrass, and address its change over time. For this we used a broad-scale analysis across the SWCMR, an area that supported 2,352.3 ha (5,812.2 acres) of seagrass during 2001 when the first image was taken (Table 1). Seagrass covered most (84.5%) of the seabed. Generally, some seagrass occurred across the entire study area, with the broadest areas of bare sand in the middle region, just north of the mangrove islands called Twin Cayes (Figure 2). Even those sandy regions had patches of seagrass scattered across them. North and south of the sandy region were extensive seagrass meadows, often represented as a mosaic of seagrass in varying densities.

Much of the study area had rounded patches of dense seagrass over a backdrop of more sparse seagrass habitat. The size of dense patches varied greatly, from < 10 m^2 to > 1 km^2 (near Tobacco Range; northern region). The backdrop of sparse seagrass also varied in spatial scale, usually grading from very sparse to moderate density seagrass habitat surrounding patches of bare sand. During 2001, the seagrass habitat of the region was measured at 53% dense seagrass, 18% moderate, and 29% sparse seagrass. Ground-truth data provided evidence that many regions were characterized by clear delineations between the various densities of seagrass, rather than the gradual-density increases that usually accompanied increasing depth.

Masking was required over 4% of the area to correct for cloud cover of the 2005 image. No masking was required for other features (e.g., patch reefs, back-reef areas), because those habitats were de-selected prior to classification. The

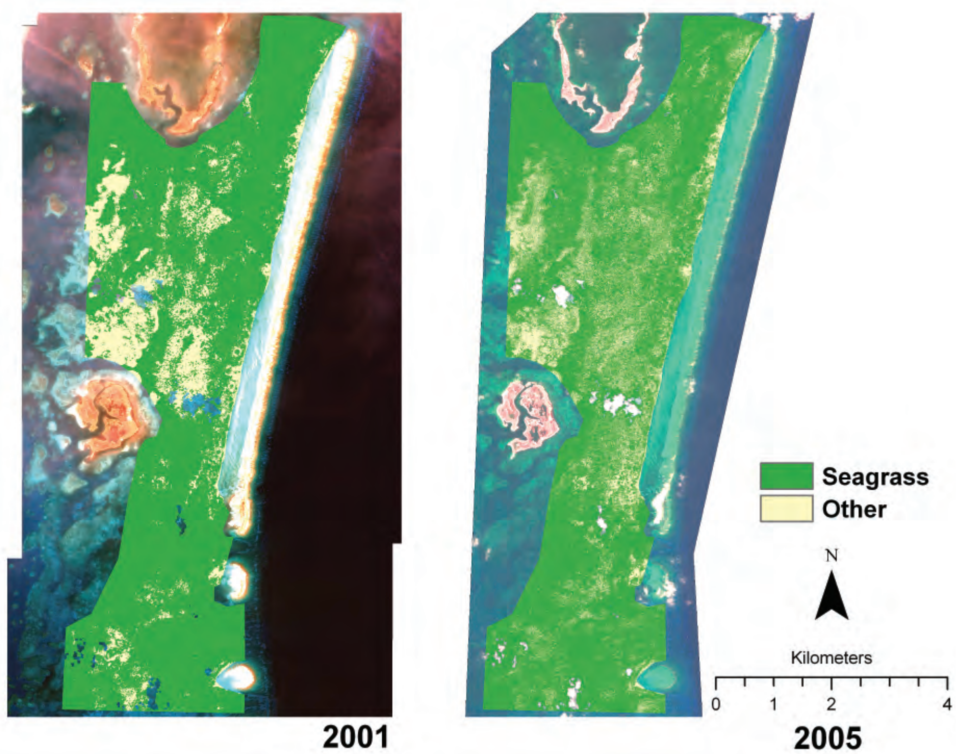

Figure 2. *Study area in the South Water Caye Marine Reserve, Belize. These two satellite images were taken during 2001 and 2005 to compare and contrast seagrass-habitat change. Seagrass (green) and sandy ocean floor (beige) are highlighted following classification techniques as areas of research focus. The land mass in the lower-middle of each image is Twin Cayes, a pair of mangrove islands. Tobacco Range, a circular loop of mangrove islands, occurs at the top of the image. The sandy areas of the 2005 image were muted by file decompression to jpeg (Joint Photographic Experts Group), so sand appears less distinctive than in the 2001 image.*

cloud mask rendered the images comparable in potential seagrass habitat, so that cloud-cover differences had no effect on our results.

The temporal component of the first objective required classification and quantification of seagrass in both images and comparisons of the results. All seagrass classified in the two images (all densities combined) was totaled to determine gain or loss overall. There was a loss of about 52.3 ha (129 acres) of seagrass from the study region, which represented a net decrease of 1.8% in seagrass habitat from 2001 to 2005 (Table 1). Dense seagrass decreased by 2.95%. Those data mean that overall there was a modest loss of seagrass across the region of study, from near Tobacco Caye to Curlew Caye. These analyses were corroborated by a corresponding increase in bare-sand seabed during 2005, and were verified through ground-truth data. A comparison of the two images, showing seagrass coverage, is provided in Figure 2.

The second objective, to determine whether seagrass gains or losses were consistent and significant across the study area, required sampling at randomly selected sites. We used 24 replicate samples (4 ha each) to assess potential medium-scale changes in seagrass coverage. The replicate samples confirmed a significant decrease in seagrass across the overall region of the SWCMR (1 way ANOVA; $p = 0.044$; df = 46).

Within the study area there were specific regions of significant seagrass loss. One 600 ha (1,483 acres) region in the middle of the study area, identified by replicates marked with stars in Figure 3, lost about 12.4% of its seagrass ($p = 0.017$; df = 18) during 4 years. A 240 ha region southeast of Twin Cayes, identified by dark circles (Figure 3), lost 40% of its seagrass ($p = 0.011$; df = 6). Although there were replicate samples with much seagrass gain, none of the regions that we analyzed with various spatial scales were statistically significant.

During preliminary work we analyzed the region by seagrass density. The accuracy assessments of those data were too low (89% for 2001; 90% for 2005) to warrant continued estimations of density as a measure of habitat loss, so we reduced the scope of detection to presence or absence of seagrass. This gave us a dataset with 500 observations of ground-truth data for each image, and only 3 errors in image classifications (all in the 2005 image) during an accuracy assessment. The reduced scope resulted in high accuracy-assessment values (> 99%).

The replicate samples provided high-resolution comparisons of various sites within the study area. Figure 4 is an example to indicate the flexibility and precision possible in assessing these remote-sensing data. There was 7.3% loss of seagrass at this location, as evidenced in red (middle image in Figure 4). We were able to analyze and quantify the entire study area in this manner.

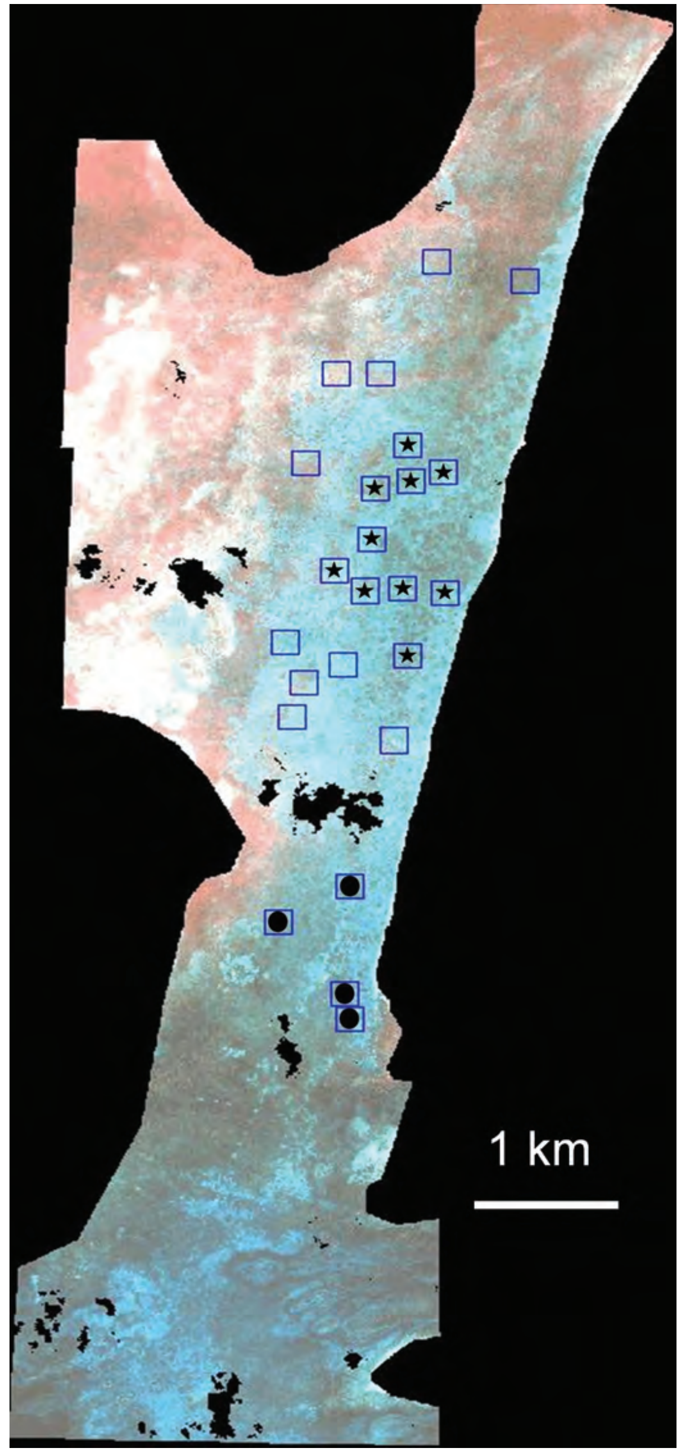

Figure 3. *Satellite image of the study area in the South Water Caye Marine Reserve, Belize. Replicates selected for statistical analyses are indicated by open squares. Replicates marked with black stars (12.4% seagrass loss) and circles (40% seagrass loss) are regions of significant change in seagrass. Clouds over the region appear as blackened areas with rough edges.*

Discussion

The decrease in seagrass across a broad-scale area of relatively pristine habitat in the South Water Caye Marine Reserve, and loss of 40% seagrass in some regions during a relatively short-duration study of 4 y, is reason for con-

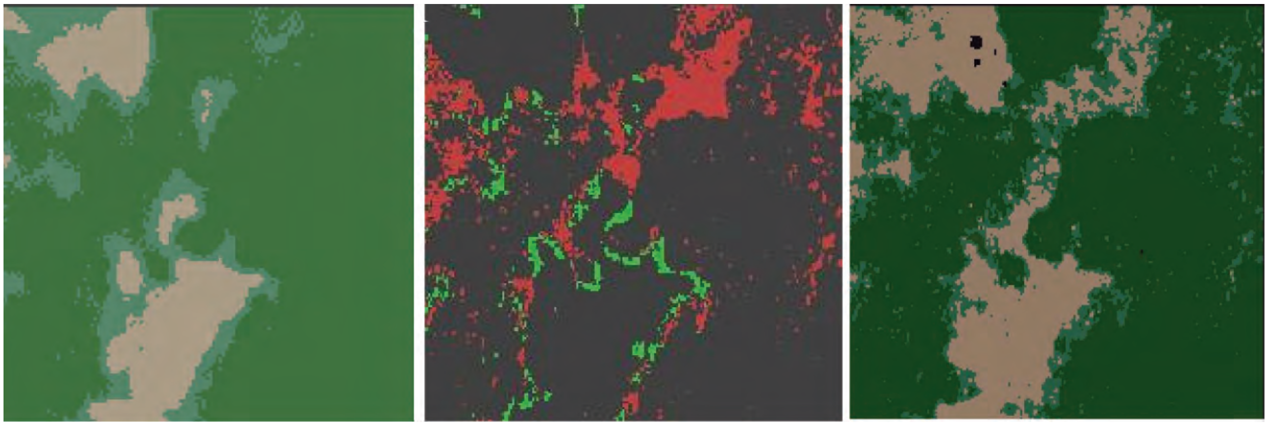

Figure 4. *One of the randomly selected areas showing an example of seagrass-habitat change. This image shows habitats classified into categories of dense seagrass (dark green), sparse seagrass (light green), and sand (beige) for 2001 (left) and 2005 (right). The middle image represents seagrass loss (red), gain (green), or no change (black) over the 4 y period. The coverage area shown is 200 m by 200 m.*

cern. These results, however, are not unique. Our results corroborate patterns of seagrass loss seen throughout many regions of the world (e.g., Short and Short 2003, Duarte et al. 2008).

SeagrassNet is a world-wide monitoring effort that includes some monitoring sites in Belize (Short et al. 2007). SeagrassNet sites were established along the coastal lagoon near Placencia (30 km SW of SWCMR) and Glover's Caye lagoon (35 km east of SWCMR). Short et al. (2006) reported a significant decrease in seagrass percent (46%) cover and shoot density (66%) near Placencia. They suggested that increased shoreline development was the likely cause. None of the study sites for SeagrassNet was placed in the SWCMR. Whereas other monitoring projects, such as SeagrassNet, used transect lines across the seagrass for data collections (Short et al. 2005), the satellite images we used provided data across an entire region. These remotely collected data had extensive flexibility for analysis, provided detailed information on several spatial scales, and allowed temporal comparisons of paired images in identical locations.

The use of remote sensing for seagrass studies is not new. Larkum and West (1990) used historical aerial photographs to find that 58% of the seagrass habitat in Botany Bay, NSW, Australia was lost over a 50 y period. Many other authors used remote sensing to monitor changes of seagrass (e.g., Ferguson and Korfmacher 1997, Hochberg et al. 2003, Duarte et al. 2008). The resolution of satellite imagery has increased greatly in recent years, which allows greater precision and accuracy than was available previously. Improved computers have allowed efficient handling of the huge datasets produced by these remote images. For instance, the original files for our 2005 image occupied 3 GB, which were too large for analysis by personal computers until recently.

The high accuracy assessments of our images can be attributed to the relatively high number of observations made in support of the classification data. This accuracy also benefitted from the simplicity of our habitat distinctions, once we merged the 60 classes into two contrasting habitats: seagrass versus sand. When we reduced the scope of detection to presence or absence of seagrass, and eliminated the shallow regions around the perimeter of the study area, we eliminated the errors almost entirely.

A change in seagrass habitat of 1.8% may not raise concern until one realizes that the value represents a habitat loss (seagrass to sand) across an area of 52.3 ha in 4 y, and likely an adverse effect on the organisms that inhabited that region. More salient to habitat concerns were the areas with rapid habitat loss identified in the replicate sampling, with significant regions of loss in excess of 12% and 40% (Figure 3). Seagrass that is replaced by sand means a 3 dimensional habitat was replaced by a more 2 dimensional habitat, with concurrent loss of refuges from predation, and degradation of the community (see Bolger et al. 2000).

Ground-truth observations of shrinking patch size confirmed the pattern of seagrass loss in the region, and was critical to interpreting the medium-scale patterns in seagrass change indicated by our replication study. Divers recorded that few of the seagrass patches in the region of 12% loss (Figure 3) had any rhizomes at all extending out into the sand from the established seagrass, indicating that expansion of patches was not occurring. These seagrass patches were very different in appearance from actively growing patches seen in northern portions of the SWCMR, where elongate rhizomes characterized the seabed, and long blades on the patch perimeter were typical. The short blade length that characterized patch perimeters of this area was further evidence that seagrass patches were shrinking in size. These blades appeared to be eroded by physical wearing or shortened by herbivore grazing.

The focus of this study was to determine whether seagrass habitat was being lost or gained, rather than address causes of change. But worldwide data and our preliminary analyses provided insight into possible factors that affected the region. The most common factors related to seagrass loss worldwide are increased nutrient loading and greater turbidity (Cambridge et al. 1986, Carlson et al. 1994, Duarte 1995, Frankovich and Fourqurean 1997, Heck et al. 2000). Preliminary research in the study area indicated that the proximity of the broad seagrass meadows to deep channels (connections to clear, open-ocean water) was correlated (Wally and Gaston 2004). Those data demonstrated an inverse relationship between habitat patch size (perhaps fragmentation) and channel proximity, suggesting that water-quality measures (e.g., nutrients and turbidity) were related to the habitat loss in the SWCMR. The northern region of SWCMR has a wide, deep channel (12 m) near Tobacco Caye; the southern region near South Water Caye has a similar channel (10 m deep) (Figure 1). Both channels provide access for ocean-water flux into the lagoon during rising tides. Indeed, the large area of seagrass loss indicated by our replicate sampling (Figure 3), behind a 9 km barrier of reef, occurred almost midway between the two channels. This pattern leads us to suggest that the lack of clear, ocean water influx may be a limiting factor to survival of seagrass in that region.

The most salient result of our study was not the magnitude of seagrass loss *per se*, but the loss in seagrass habitat from an area that was thought to be relatively pristine. Unlike many broad-scale and long-term studies, we detected the loss of seagrass over a short period, by quantifying changes across the study area with high-resolution images. This resolution allowed detection of medium-scale changes, and the ground truthing provided confirmation and evidence of their accuracy. Our evidence of seagrass decline should stimulate action from those dependent on the ecosystem for their own wellbeing. The SWCMR was established during 2005, in part to protect its habitats from further decline. Our data were presented to the Belize Ministry of Fisheries and Coastal Management during a 2006 conference, and elicited concern from their personnel for the future of the region. The health and productivity of the coral-reef ecosystem in Belize depends on the quality and quantity of seagrass habitats in the region, as it does for similar ecosystems worldwide. Seagrass-habitat loss in this region of the Caribbean Sea may be evidence that even near-pristine areas can be impacted by anthropogenic factors. Finding out what led to decline of these habitats may help prevent loss of productivity by the ecosystem, and loss of ecological services to their associated human and nonhuman communities.

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