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CORAL REEF PAPER
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MAPPING CHANGES IN SUBMERGED AQUATIC VEGETATION USING LANDSAT IMAGERY AND BENTHIC HABITAT DATA: CORAL REEF ECOSYSTEM MONITORING IN VIEQUES SOUND BETWEEN 1985 AND 2000

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ABSTRACT

Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) imagery for eastern Puerto Rico, collected January of 1985 and March of 2000, was used to perform a multi-temporal classification technique to identify and quantify the dynamics of submerged aquatic vegetation (seagrass and macroalgae) in a study area located in Vieques Sound, off the east coast of Puerto Rico. This change detection was validated using benthic habitat maps of the area created from 1999 aerial photography, and then contextually edited to map different types of change occurring within the study period, including recent sedimentation, changes in seagrass patchiness, and macroalgal cover. The results show that the distribution of seagrass meadows and macroalgae were expanding more than decreasing in the study area between 1985 and 2000. Submerged aquatic vegetation (SAV) growth was mainly occurring in deeper waters, whereas shallower seagrass meadows along the north shore of Vieques became increasingly patchy. This analysis demonstrates that the dynamic nature of seagrass meadows and macroalgae in the Vieques Sound can be assessed accurately and efficiently by satellite imagery. The ability to map and identify changes in extent of SAV is important coral reef ecosystem monitoring and targeting of vulnerable and affected areas for more specific research and further study.

While concern is growing about the state of the Caribbean shallow water (< 30 m) coral reef ecosystems, which are in serious decline (Gardner et al., 2003), projects to quantify the extent or condition of these ecosystems over time are limited by cost, accessibility, and magnitude of study area (Mumby et al., 1999; Andréfouët et al., 2001). Satellites are valuable for efficient and consistent data collection in marine environments, and can be used to determine water depth, map marine habitats, and changes in these ecosystems over time, delineate ecologically significant boundaries, and locate study sites which aid conservation planning and monitoring (Dustan et al., 2001; Liceaga-Correa and Euan-Avila, 2002).

Satellites and the Marine Environment.— In recent decades, a number of satellite sensors with similar spectral discrimination characteristics have been launched for visualizing landscapes on Earth, each with their respective benefits and disadvantages, resolutions, and associated costs and licensing for imagery. The moderate-resolution (30 m) Landsat Thematic Mapper and the newer Enhanced Thematic Mapper (ETM+) are useful for mapping benthic habitats while also providing the lowest-cost imagery with an open licensing agreement from an extensive database of imagery that has been continuously collected since 1982, thanks to the long-term acquisition plan (Green et al., 1996; Palandro et al., 2003). Landsat has been used to map coral reef habitats (three to seven classes) with classification accuracies similar to IKONOS (multi-spectral, 4 m resolution) and often greater accuracy than SPOT (multi-spectral, 20 m resolution) with up to 80% accuracy for coral and sand classes, (Ahmed et al, 1994; Mumby et al., 1998; Capolsini et al., 2003). Landsat has also been shown to be one of the most accurate and efficient data sources for the single goal of mapping seagrasses, due to its large coverage area, temporal and spectral resolution (Luczkovich et al., 1993, Lennon and Luck, 1989). Given its relatively continuous global coverage and a consistent archival data set dating back more than 20 yrs, it is possible to compare imagery from different dates for time change analysis (Andréfouët et al., 2001; Palandro et al., 2003). This is Landsat's most powerful asset, making it possible to assess change in coral ecosystems over long or short time frames.

Reef studies using satellite imagery have typically discerned several types of benthic cover in the shallow water marine environment in clear water conditions: corals and hard bottom, unconsolidated sediments such as sand and mud, and submerged aquatic vegetation (SAV) (Green et al., 2000; Roelfsema et al., 2002; Hochberg et al., 2003). These habitats all comprise the complex coral reef ecosystem.

Seagrasses and Macroalgae in the Coral Ecosystem.— This study focuses on SAV, which includes seagrasses and macroalgae, the primary producers that provide food to reef organisms. SAVs offer habitat and protection, act as nurseries for juvenile fish, and stabilize sediments and enhance water quality (Kenworthy et al., 1988; Nagelkerken et al., 2000; Kendall et al., 2004). Major changes in seagrass and macroalgae cover in benthic environments can be symptoms of biotic or anthropogenic factors influencing shallow water coral ecosystems. Biotic factors that limit seagrass growth and meadow size include herbivory, sediment input, wave erosion, and storm events (Williams, 1998), while anthropogenic seagrass loss can occur due to physical disturbance, light shading by boats, or changes in water quality due to pollution or erosion from land (Kendrick et al., 2002; Hertler et al., 2004). Alternatively, seagrasses may also colonize new areas of former meadows by either horizontal expansion or colonization (Gallegos et al., 1994; Orth et al., 1994) but this process can also be aided by extreme weather events (Williams, 1988).

Algal biomass is typically low on a healthy reef due to grazing by herbivores, while high biomass generally accompanies bleached or degraded reef systems, as corals and algae are often in competition for space (Lirman, 2001). Loss of coral cover can occur due to a variety of anthropogenic causes, including over-fishing of herbivores, sediment deposits and run-off, pollution, thermal stress, and nutrient enrichment, which are all catalysts for fleshy algae colonization onto reefs (Szmant, 2002). Thus, the landscape dynamics of SAV are important symptoms to monitor in the coral reef environment, as they reflect changes in ecology and water quality, which can ultimately affect the coral ecosystem as a whole.

The overall goal of this study was to assess the use of Landsat imagery to monitor SAV over time, and identify the potential to incorporate satellite imagery into a coral reef monitoring program to aid managers in targeting specific areas for conservation and management. Specifically, we used Landsat to quantify changes in the patterns and distribution of SAV between two points in time 15 yrs apart in a shallow tropical ecosystem around Vieques Island, Puerto Rico.

Methods

Study area.—This study was focused on an area of about 660 km^2 just southeast of Puerto Rico in Vieques Sound (Fig. 1). This site was selected for the availability of cloud-free satellite imagery, benthic habitat data, water clarity, optimal surface conditions (no waves or sea foam), and a varied benthic seascape.

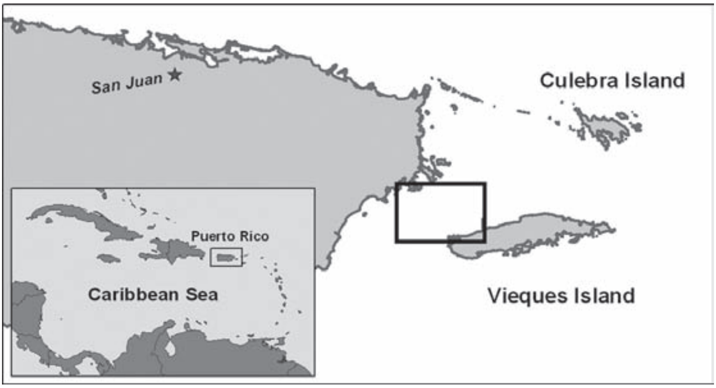

Figure 1. The study area (660 km^2) is located in Vieques Sound (also referred to as the Pasaje de Vieques), between Vieques and mainland Puerto Rico.

Image Processing.—Seasonal Landsat image pairs from January 21, 1985 and March 27, 2000 were processed for analysis of SAV change (Fig. 2). The two images were geo-positioned to each other with a horizontal position accuracy of < 50 m. The raw imagery was converted from Digital Numbers (DNs) to normalized reflectance (also called at-satellite reflectance, or albedo), which is a standardized, satellite-independent value (Green et al., 2000). The reflectance was then transformed into water reflectance (the signal < 10 cm above the water surface) by subtracting the near-infrared band to remove the effects of atmospheric factors (haze and aerosols), as well as waves on the spectral signal (Stumpf et al., 2003), which gives a surface reflectance comparable for images taken on different dates. The blue and green bands (1 and 2) of each water reflectance image were clipped to the study area and combined into one file for classification.

Water depth (m) was estimated for the entire study area as an auxiliary dataset, in order to study the effects of depth on SAV change. Depth was determined from water reflectance using a semi-automated process developed by Smith and Shapiro (2005), a non-linear log band ratio model previously described by Stumpf et al. (2003). Bathymetry estimates for seven different Landsat images (which includes the two used in this analysis) were combined by a median algorithm to produce a final estimated depth. The result is a continuous depth layer with an average accuracy of 90% in water < 20 m deep (Smith and Shapiro, 2005).

Change Detection.—Initial visual inspection identified specific areas of potential SAV gain or loss. Using PCI Geomatica version 8.2, an image differencing and thresholding technique on the blue and green water reflectance was used to label key areas of suspected submerged aquatic vegetation change. The March 21, 2000 image was subtracted from the January 21, 1985 image and pixels with a large increase or decrease in spectral reflectance (greater than the mean difference for the study area) between images were highlighted as change. A significant increase in the blue and green bands was labeled as a suspected change from SAV to bright sand (vegetation loss or sedimentation). Areas with decreases in spectral reflectance in both blue and green bands were highlighted as potential vegetation growth or colonization.

Because the image subtraction and threshold selection could be influenced by atmospheric or sensor differences, a classification algorithm was chosen to further delineate areas of potential SAV growth and loss. A K-means unsupervised classification was performed on the combined paired-date four-band image to produce 10 unique classes of pixels based on their similar spectral characteristics. Because the image contains data from two different time periods, the classification algorithm grouped pixels that were similar in one image, similar between years, as well as dissimilar between years, and was not affected by atmospheric or sensor differences that affect the entire study area. These clusters were then manually aggregated using the image differencing product as guidance to four unique classes: no data, no change (pixels were similar in both years), vegetation gain, and loss of vegetation (according to the image differencing results showing pixels that were significantly dissimilar between years). A

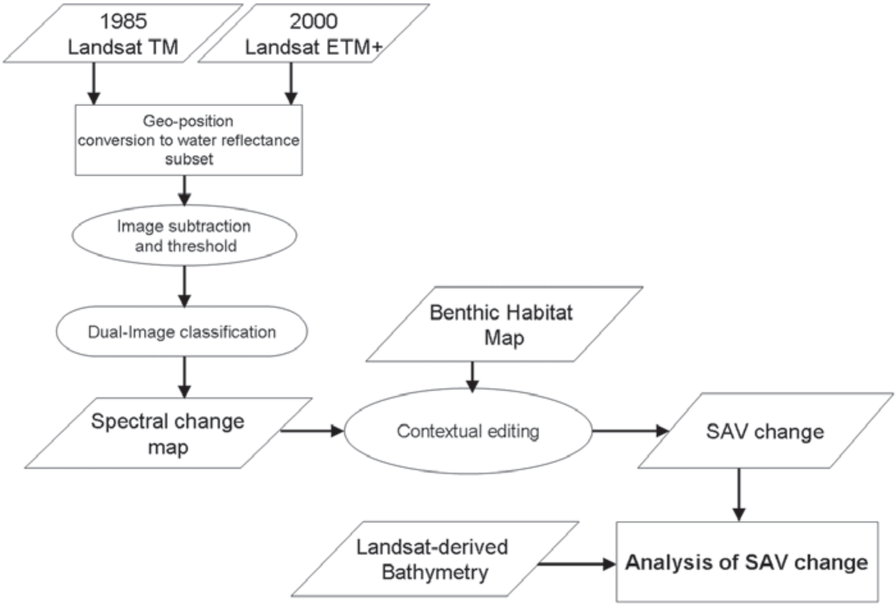

Figure 2. Cartographic model depicting the methodology for this analysis, starting with the processing of raw Landsat imagery and editing and evaluation of the change products.

median filter was run on the final binary images showing gains and losses in order to reduce noise, eliminate single pixels in any class, while preserving edges of the classes.

The benthic habitat map of Puerto Rico and the U.S. Virgin Islands (Kendall et al., 2001; Fig. 3) was used to validate the SAV change identified with Landsat. This dataset is the most accurate and complete benthic habitat map available for this area. It was created from classified aerial photography and has an overall accuracy of 93.6%, with Kappa = 0.90 (Kendall et al., 2001). The benthic habitat map was overlaid on the classified product to verify the type of change and to perform contextual, or spatial editing to differentiate similar spectral signatures of seagrass and algae by their location (Lubin et al., 2001). For example, if a "gain" pixel was located within a seagrass category, then it was classified as recent seagrass growth. This process estimates the accuracy of Landsat detected change while also quantifying the type of change and distribution of recent vegetation growth and loss within two levels of hierarchical habitat classes.

Finally, the differences in depth between both types of change observed were determined by a z-test between two random samples of 400 points for gain and loss. Using the Landsat-derived depth layer random samples for each change type were selected from both change types and statistically compared. Normality of the random samples was assessed and a z-test assuming unequal variances was performed to test the null hypothesis that both samples have similar means.

Results

Satellite-derived Change.—Visual inspection of enhanced raw (at-sea-surface) reflectance images show particular areas where changes in benthic cover occurred from 1985 to 2000 (Fig. 4). Given the water clarity in Vieques Sound and Landsat's ability to view the seafloor in water up to 30 m depth, one can see evidence of benthic change in the raw imagery. The different spectral properties of the differ-

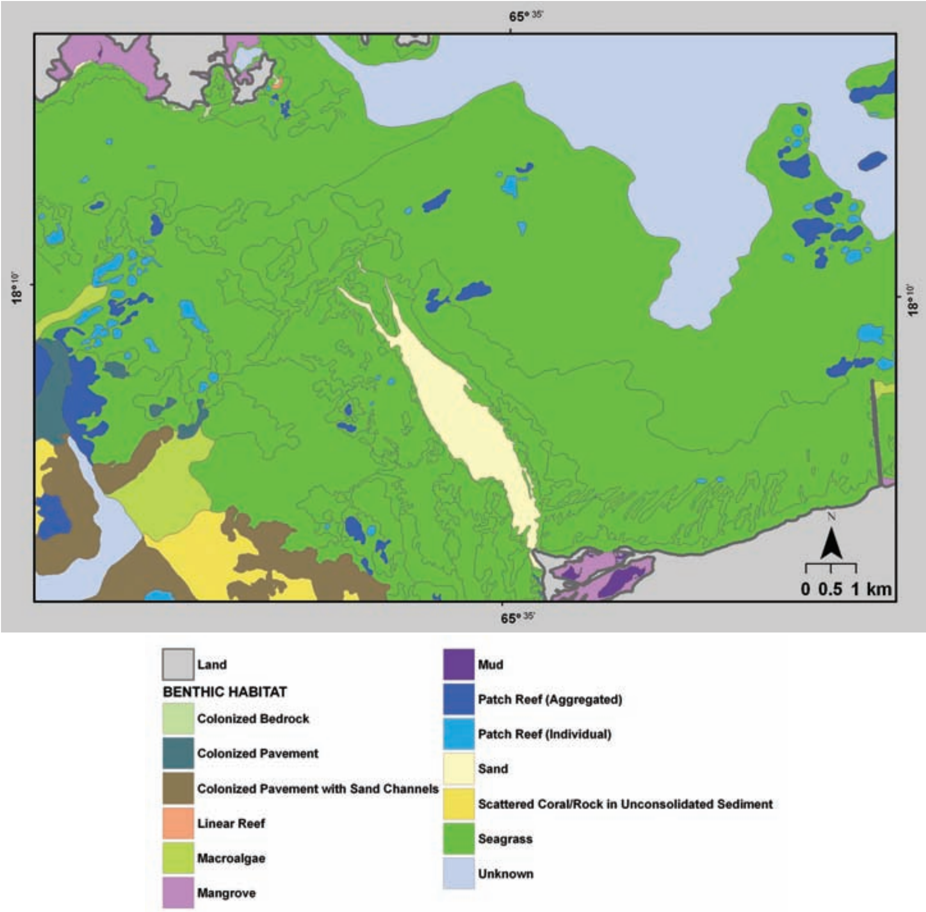

Figure 3. Benthic habitats of the study area are primarily mapped as seagrass, with aggregated and patch reefs, macroalgae, colonized pavement, and several areas of unknown habitat (Kendall et al., 2001).

ent benthic habitats, combined with knowledge of the study area make the boxed areas suspected sites of submerged vegetation change.

Analysis of SAV Change.—The changes in patterns of SAV identified from multi-temporal image show localized loss in areas near the north shore of Vieques and in a bright sandy area at the center of the study area (Fig. 5). New colonization, expansion of seagrass and algal communities mainly occurred west along the shore of mainland Puerto Rico, as well as in a large patch in the middle of the sound. Of the 27.7 km^2 of area classified as possible change, there was twice as much area identified as gain (18.6 km^2) than loss (9.15 km^2; Fig. 6).

Qualitative analysis of the overlaid NOAA benthic habitat map in geographic information system (GIS) revealed that, with a few exceptions, most of the areas classified as "new" growth fell within the vector boundaries of dense (70%–90%) and continuous seagrass. Likewise, a majority of the pixels classified as loss fell outside of the areas mapped as seagrass in 1999, though most were adjacent to mapped seagrass beds, indicating that these were most likely areas of receding seagrass meadows or seagrass patch density change. Pixel counts were conducted to quantify the areas

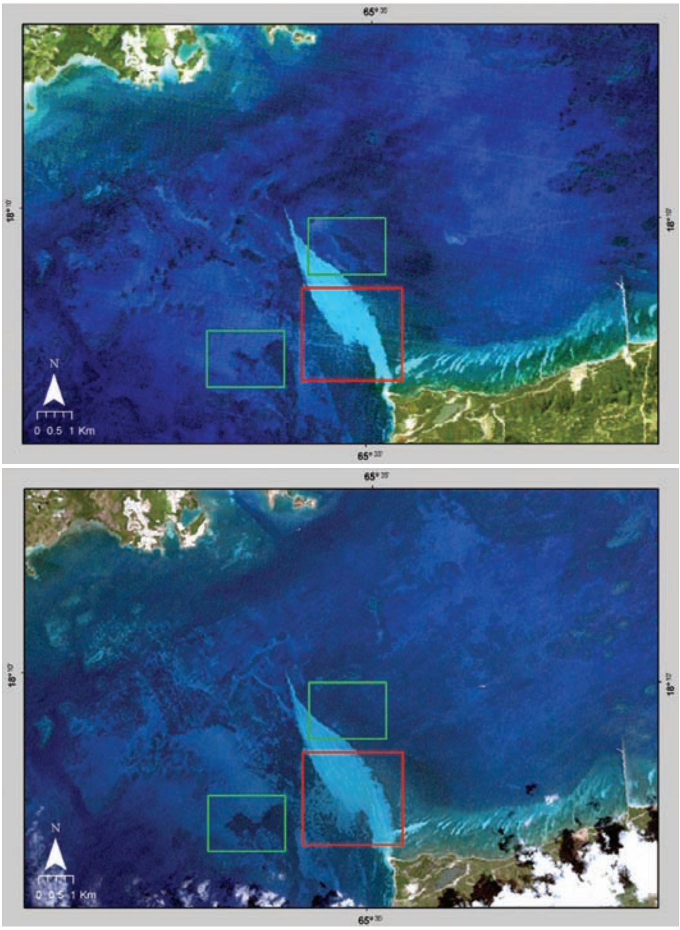

Figure 4. (A) Enhanced Landsat TM image of the Vieques Sound taken January 21, 1985. Light blue areas show sand, darker green and blue are seagrass and reef structures. Note the bottom cover pattern within the boxes. (B) Enhanced Landsat TM image taken March 27, 2000. The green boxes highlight the expansion of darker areas, which are potential seagrass/algae colonization. The red box encompasses areas that are brighter, likely a result of loss of submerged vegetation, or sedimentation in the water column.

classified as potential vegetation change within expected habitat classes at two hierarchical levels, testing the accuracy of Landsat at addressing change (Fig. 6).

Within the general or aggregated habitat classes, nearly 90% of pixels classified as new growth were within the SAV class of the NOAA benthic habitat map. The rest were evenly divided into coral reef habitats and the other delineations, which contain unknown and unclassified areas. The pixels classified as change that fell within coral and hard bottom habitats could represent fluctuations in macroalgae cover, as seagrasses tend to colonize soft sandy or muddy substrates (Hertler et al., 2004). About half of the area classified as vegetation loss was also within the submerged vegetation habitat classes (seagrasses and macroalgae), and it is likely that the identified change was a result of increased patchiness that occurred on a finer scale than the minimum mapping unit of the benthic habitat map (1 acre). This could mean that the multitemporal analysis is highlighting areas of vegetation loss that are changes from dense to sparse or patchy seagrass classes (termed "patchiness"; Fig. 7).

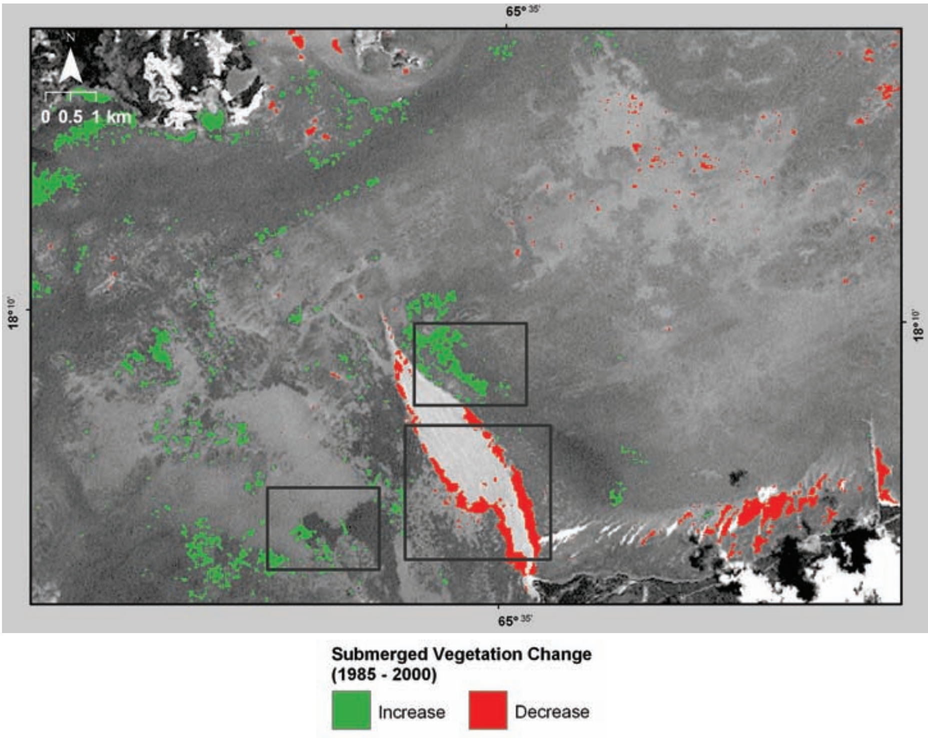

Figure 5. Seagrass dynamics in the Vieques Sound, determined from multi-temporal classification of Landsat imagery, showing areas of new vegetation loss (red) and growth (green) over time (1985–2000).

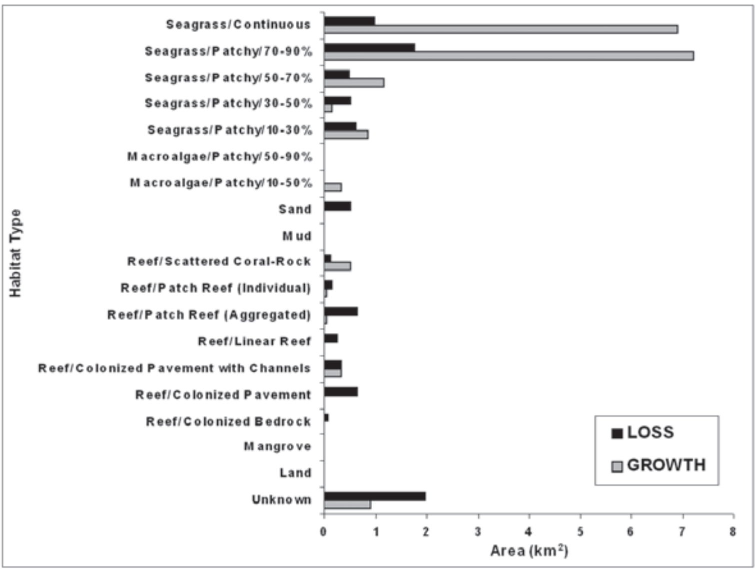

Figure 6. Area of Landsat satellite-observed SAV change within the detailed benthic habitat classes of Vieques Sound between 1985 and 2000.

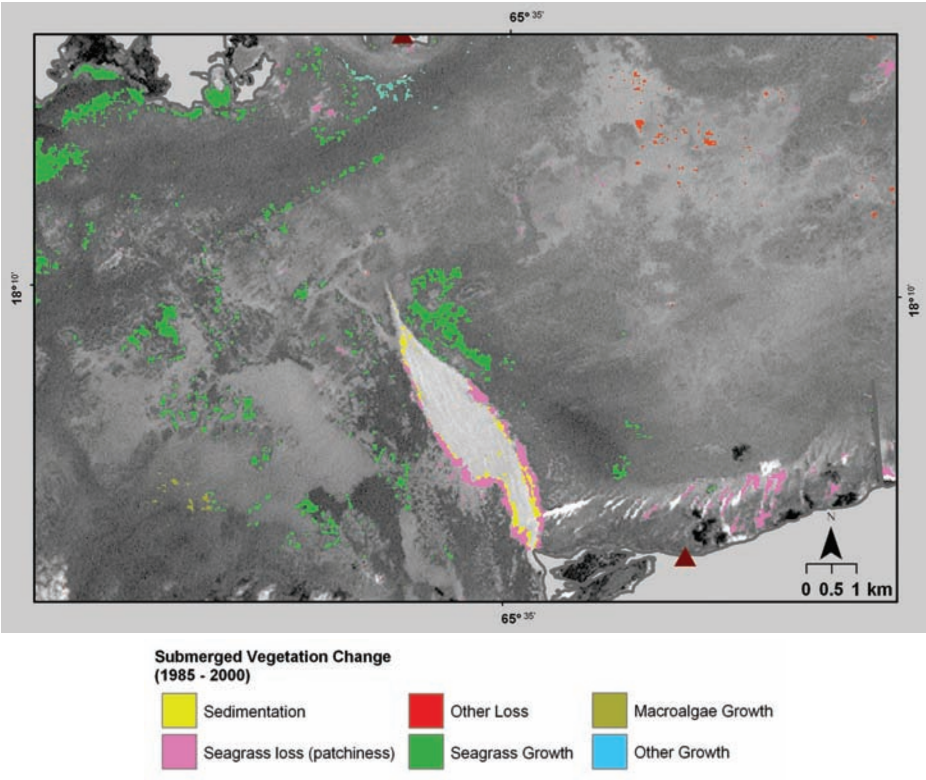

Figure 7. Landsat-observed change in SAV in Vieques Sound is further classified by contextual editing of the benthic habitat map. The location of the watershed outflow point was determined from terrain analysis, and is shown with a triangle.

A majority of the recent SAV growth (> 13 km^2) occurred within the dense (70%–90%) and continuous seagrass habitat categories close to the shores of Puerto Rico and in the western portion of the study area, which are changes in seagrass patch density within existing meadows. This mainly occurred close to the shores of Puerto Rico and in the western portion of the study area. There was very little new macroalgae growth, with < 0.35 km^2 of decreased satellite-detected greenness within macroalgae categories, in the southwest quadrant of the study area. Areas detected as SAV loss that were within sand classes in the habitat map were identified as recent sedimentation, and were localized in the large sandy patch in the central part of the study area. A few small areas of loss were mapped in the colonized pavement and patch reef habitats, which could be recent changes in macroalgae cover; however, these could not be verified due to lack of historical field data. These were grouped with SAV loss in unknown habitats ("other loss" in Fig. 7) and were mainly located in the northeast portion of the study area. Note that the nearly 5% of the mapped gain and 20% of loss (which is about 2 km^2) are within unknown, or unmapped habitats.

The z-test of the mean difference of depth between random samples of satellite-observed SAV gain and loss demonstrated that loss was significantly shallower than gain, indicating that SAV at shallower depths were likely to be more vulnerable to die-off or sedimentation than deeper vegetation (Table 1).

Table 1. Two sample z-test comparing mean depths of SAV loss and gain.

	gain depth (m)	loss depth (m)
Mean	8.29	4.89
Variance	10.53	24.82
Standard deviation	3.25	4.98
Observations (N)	400	400
P	<< 0.0001	

Discussion

Evaluation of the Remote Sensing Approach to SAV Monitoring.— We used a combination of Landsat imagery and classified aerial photography (NOAA benthic habitat maps) to locate and quantify changes in SAV in a coral reef ecosystem over a 15-yr time period in Vieques Sound. The Landsat sensor accurately located areas of recent seagrass colonization and smaller areas of macroalgae growth in a dynamic reef environment, a task which is essential for consistent habitat monitoring and moderate-scale reef studies. Auxiliary data sources were used to further assess and identify the type of changes being observed. In this case, in the absence of field data, the NOAA benthic habitat maps of Puerto Rico provided the information necessary to discern seagrass and macroalgae dynamics in Vieques Sound, and a Landsat-derived bathymetry was used to investigate the depth differences of SAV growth and loss (Fig. 8).

This analysis has demonstrated the efficacy of using moderate resolution satellite imagery for regional SAV mapping and change detection in shallow coral reef ecosystems. A Landsat–based change detection analysis however, should not provide

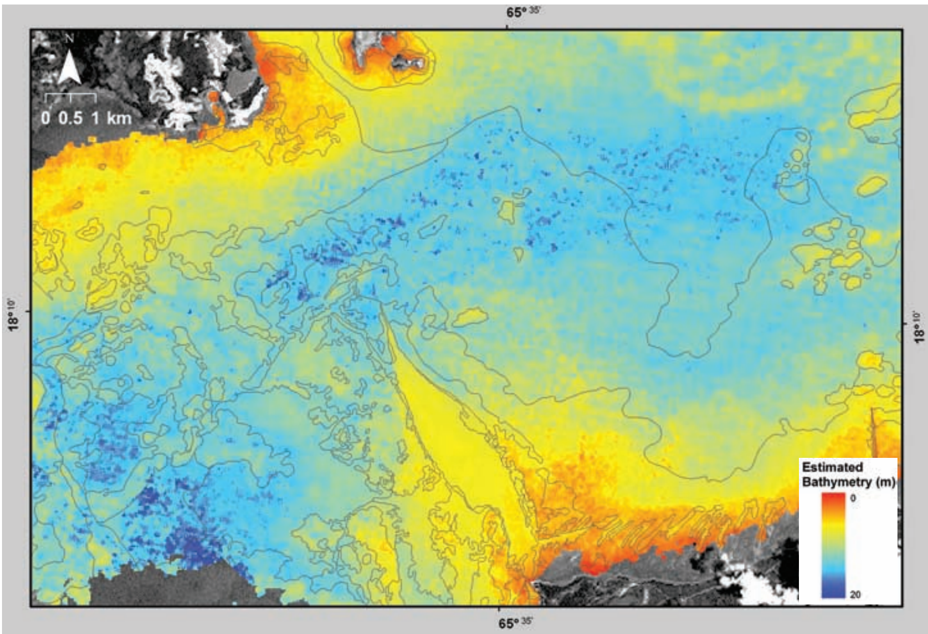

Figure 8. Landsat-derived bathymetry showing the range in depths (m) of the study area, along with the NOAA benthic habitat boundaries.

the final verdict on dynamics of coral ecosystem habitat quality; rather, this analysis is intended to identify the baseline trends and anomalies, or stratify ecosystems to focus on areas of particular concern for conservation or further verification from field data or higher resolution analyses. This process, using inexpensive moderate-resolution satellite imagery is useful for identifying areas of recent extensive growth or loss in seagrass and macroalgae, which can help to locate specific SAV habitats responding to positive or negative changes in water quality or harmful influences from land, and therefore require greater attention for conservation or protection. Additional higher resolution imagery (IKONOS, aerial photography), or field data could be collected for identified target locations, providing additional information for specific areas needing further monitoring (Kirkman, 1996; Palandro et el., 2003a; Kendall et al., 2004). In addition, it should be noted that the study area mainly comprises a seagrass ecosystem, and only a small area is mapped as macroalgae. Further studies in more coral and macroalgae-dominant seascapes are recommended to adequately test the ability of Landsat to detect moderate resolution phase shifts from coral cover to macroalgae.

Ecological Significance of Seagrass Growth in Vieques Sound.— The general trends observed in this study area are the overall expansion and colonization of seagrass at significantly deeper sites in the study area between 1985 and 2000 (Table 1). In addition, some smaller areas experienced increases in macroalgae cover. Decreases in seagrass density occurred within extensive meadows close to the north shore of Vieques, and localized areas of sedimentation were observed in the center of the study area. In other studies in the region, for example at La Parguera in southwest Puerto Rico, seagrasses nearshore have been in declining health and have consequently been receding, a process which has been linked at other locations to coastal development and erosion (Hertler et al., 2004). Indeed, a major outflow point from a Vieques watershed of 25 km^2 is close to the seagrass meadows that are becoming increasingly patchy. Since outflow points discharge land-based sources of sediment and pollution (WRI and NOAA, 2005), it is possible that the changes observed are due to decreases in water quality, and this area should be targeted for further investigation.

Vegetation loss in the center of the study area was evidently associated with sedimentation, as demonstrated by the significant change from dark reflectance in the earlier Landsat image to brighter reflectance, and identified as sand by recent mapping efforts. This only occurred at a few sites in the study area, primarily along the long wisp of sand featured at the center of the study area (in yellow, Fig. 7). Because of the shape of this sand feature, it is likely that currents deposited new sand to this area during the study period, which displaced local seagrasses or covered algal communities. Other significant areas of decreases in SAV were within seagrass communities, identified as changes in density, or increased patchiness (in pink, Fig. 7). A large area is also centered on the sandy wisp, and thus, likely to be related to currents and sediment deposition.

The trend of seagrass growth observed in this analysis is similar to the long-term seagrass expansion by seed dispersal that has been observed at varying rates in recent decades in the Buck Island Channel off of St. Croix in the U.S. Virgin Islands (Kendall et al., 2004). Similar to St. Croix, storms could contribute to patterns observed in Vieques Sound. Several hurricanes have passed near Vieques in recent decades,

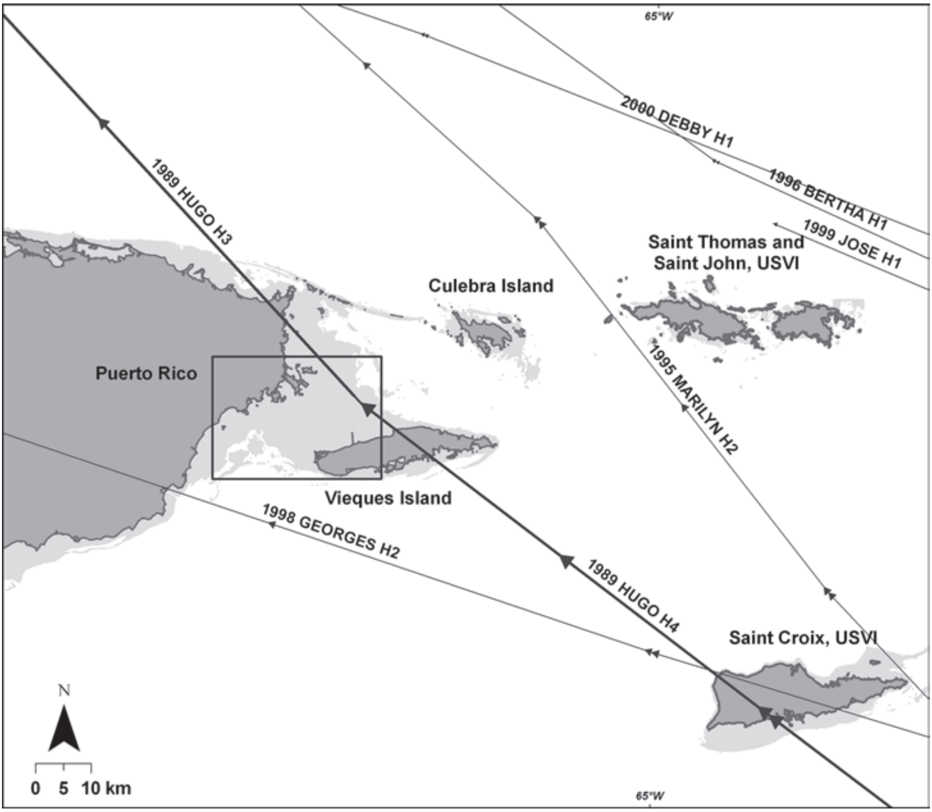

Figure 9. The path and intensity of hurricanes near the study area from 1979–2000. The year of the storm and the strength on the Saffir-Simpson scale (H1–H5) are indicated. Data source: NOAA Coastal Services Center.

including two category 2 storms, and the category four Hurricane Hugo that passed directly over the study area in 1989 (Fig. 9).

The seagrass meadows along the north shore of Vieques lie in shallower water and may be more vulnerable to strong storms compared to seagrasses in the center of the study area that do not appear to have been adversely affected. Portions of the meadows close to shore decreased in density between 1985 and 2000, though seagrass cover still dominated this area. The seagrass beds closer to the center of the sound may have been more insulated from storms due to greater depth or distance from land-based sources of pollution. Much of the mapped growth is in the middle of the sound and in deep bays near the east coast of Puerto Rico. This is consistent with the statistical depth analysis, which demonstrated that areas of SAV loss are significantly shallower than the areas of gain, suggesting that shallower vegetation may be more vulnerable to a combination of storm, coastal, and anthropogenic processes than deeper communities, which are more insulated by depth and located farther from shore. Management scenarios should thus focus on conservation of nearshore seagrasses on the north shore of Vieques and managing coastal erosion and land-based pollutants in this area.

While the general trend appears to be expanding seagrass, there are several areas of SAV loss, mainly in the center of the study area and along the north shore of Vieques. The areas of decreased patchiness close to shore may be indicative of land-related erosion or pollution. A terrain analysis of digital terrain completed by NOAA's Summit-to-Sea project has indicated a watershed outflow point in proximity to this area (Fig. 8, WRI and NOAA, 2005). This point is a source of discharge for storm run-off, which would include eroded sediment or pollutants that have accumulated on land. The location of this outflow point in proximity to the area of SAV loss is cause for concern regarding land-based sources of pollution and necessitates further investigation of the western watershed of Vieques, its outflow point, and the surrounding water quality.

The areas of macroalgae colonization and areas classified as "other growth" were located in the southwest portion of the study area in rather small, localized, and deeper sites. Since macroalgae often colonizes unhealthy or degraded corals, this relatively small area of new macroalgae can be a reassuring sign that the reef ecosystems in this deeper reef are not undergoing widespread decline and have remained generally intact during the study period.

In the absence of suitable field data, the NOAA benthic habitat maps were useful in determining the type of change that occurred and quantifying the distribution of vegetative change according to reef zones. Unfortunately, several large areas, which include 5% of all areas mapped as growth and 22% of mapped loss, remained unmapped or unknown, mainly a result of water quality and weather that limited the quality of data in certain reef areas (Kendall et al., 2001). This lack of information in these specific areas can greatly affect monitoring projects and scientific studies at the ecosystem scale that require consistent spatial data layers. This study points to the importance of up-to-date benthic habitat maps in order to effectively monitor entire reef ecosystems. There is an urgent need to "fill in" these benthic habitat maps with new data. Additional collections during better atmospheric and water conditions, in combination with additional field verification and data from other sources such as multi-beam or Light Detection and Ranging (LIDAR) instruments are necessary to provide additional data for interpreting benthic habitat in areas too deep or turbid to delineate habitats from space-borne platforms. The Landsat sensor, which provides a very affordable and continuous imagery source can thus be used not only to map and monitor reef and seagrass ecosystems at moderate scales, but to identify specific locales with poor water quality or other hindrances require additional data collection.

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