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Assessing the distribution of patch reef morphologies in the Lower Florida Keys, USA, using IKONOS satellite imagery

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Abstract. As live coral cover continues to decline in the Florida Keys, it becomes increasingly important not only to determine the location and abundance of live coral remaining, but also to understand why certain areas possess higher coral cover than others. At present, coral cover tends to be highest at shallow inshore patch reefs. Our study has two objectives: 1) to determine, to the full extent visible by satellite imagery, the number and characteristics of patch reefs that could be recognized using IKONOS imagery; and 2) to test the assumption that various morphological groups of patch reefs occupy distinct cross-shelf zones in the Lower Keys. Two previous survey efforts using aerial imagery and reported 420 and 750 patch reefs, respectively, from Big Pine to the Marquesas Keys. By performing a visual assessment on IKONOS satellite imagery, we were able to delineate 2,251 patch reefs for this region. These patch reefs vary in their overall morphology (i.e., shape) and are spatially distributed in several cross-shelf bands. Patch reef classes identified were Aggregate, Atom, Colony, Crescent and Dome. Aggregate patch reefs are very numerous, relatively small, and dominantly located either shallow-midshelf or offshore. Dome, Colony and Crescent patch reefs are larger in area and are most common in the shallow-midshelf or offshore zones. This study represents an important first step in understanding the factors that may be controlling the distribution and shape of patch reefs along the Florida Keys Reef Tract and, subsequently, relating this to living coral cover on modern reefs.

Key words: Florida Keys, patch reef, morphology, coral, remote sensing.

Introduction

Declines in overall live coral cover throughout the Florida Keys are well documented (Porter et al. 2002). The Florida Keys Coral Reef Evaluation and Monitoring Project (CREMP) has monitored 40 reef sites throughout the Keys since 1996. In 2005, coral cover on patch reefs averaged 14.6%, compared to 3.0% for the offshore bank reefs (Beaver et al. 2006). Coral cover has continued to decline on the offshore bank reefs so that live coral assemblages are now concentrated on shallow-water patch reefs. Thus, to adequately assess and protect remaining coral assemblages, it is essential to know the number, extent and spatial characteristics of the many patch reefs spread throughout the region.

The Florida Keys have historically been separated into three geographic regions: Upper, Middle and Lower Keys (Ogden et al. 1994). Previous efforts to determine the number of patch reefs in the Lower Keys utilized aerial survey methods. Marszalek et al. (1977) identified 420 reef structures from Big Pine to the Marquesas Keys. The Florida Marine Research Institute's Benthic Habitat Map of the Florida Keys estimated 750 patch reefs (inclusive of aggregate patch reefs) in the Lower Keys region (FMRI 2000).

Our study area encompasses a 523 km^2 region stretching from Big Pine Key in the northeast to Sand Key Reef in the southwest, and extends from the land to the outer reef system (depth≈20m) (Fig. 1). We used high spatial resolution, georeferenced IKONOS satellite imagery provided by the National Oceanic and Atmospheric Administration (NOAA) to find, categorize and map the size, shape and distribution of patch reefs. Initial observations indicated that patch reef distribution is non-random. Patch reefs appear to occur in distinct bands that parallel land, each with increasing distance from shore. There also appears to be segregation between patch reef morphologies (i.e., shape), with different types rarely sharing a given zone. The goals of this study were to 1) determine the number and characteristics of patch reefs that could be visually identified using IKONOS imagery and 2) test the assumption that various morphological groups of patch reefs occupy distinct cross-shelf zones in the Lower Keys.

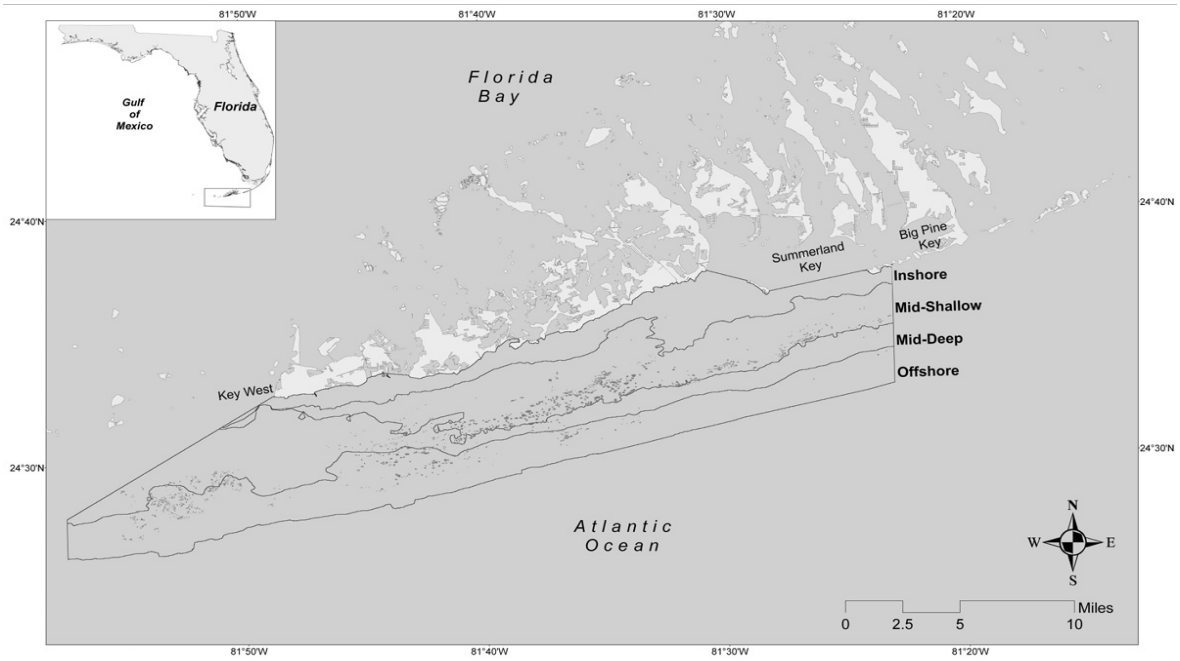

Figure 1: Lower Florida Keys study region displaying cross-shelf zones and patch reef distribution.

Methods

Data Source

Twenty-five IKONOS images acquired during 2006 and corresponding to the Lower Keys region were provided by NOAA. Of these, the four clearest images that provided complete coverage of the study region were selected for analysis, while the remaining 21 images were used to assist in later verification. IKONOS is a privately owned satellite (GeoEye) with a spatial resolution of 4 m that collects data in three visible wavelength bands (450 – 520 nm, 510 – 600 nm and 630 – 700 nm). The Lower Keys were segmented into four zones (Inshore, Mid-Shallow, Mid-Deep and Offshore) using digital bathymetry and clearly visible cross-shelf habitat breaks (Fig. 1). Digital bathymetry was compiled from three sources; NOAA Geophysical Data System (GEODAS), the Benthic Habitat map of the Florida Keys and an internal FWRI bathymetric dataset (Palandro et al. 2008).

Patch Reef Mapping/ Typology

The location of each patch reef was determined by visually examining each image. Cosmetic stretching was applied to the red, green, and blue bands (RGB) to enhance differences between suspected patch reefs and other benthic habitats. When a patch reef was found, it was marked as a point using ENVI 4.3 ® remote sensing software. The decision to classify a structure in the imagery as a patch reef was based on the appearance of a reef-like structure, surrounding benthic attributes (e.g., halo) and local knowledge.

The shape of each patch reef was delineated from the satellite imagery (Fig. 2) using all available overlapping imagery for a given area. The two to three clearest images (e.g. cloud-free, transparent water) were used to verify the presence of a patch reef. After the initial mapping of all visible patch reefs, the designation of each was further confirmed using ancillary datasets. These included satellite imagery, analog aerial imagery and interferometric acoustic data, as well as consulting with people familiar with the area. Final quality control measures for the dataset are still underway; therefore, for the purpose of this study, it is assumed that all reef structures identified in the imagery are in fact patch reefs.

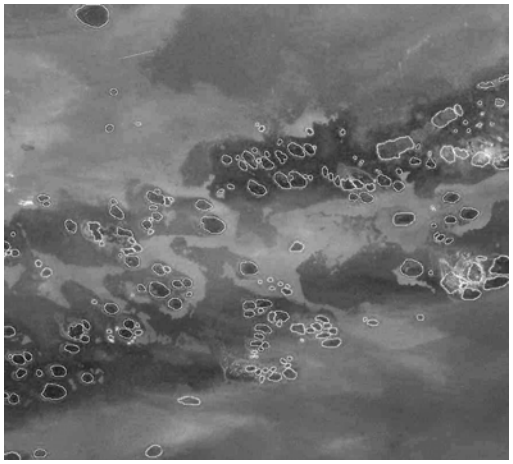

Figure 2: Examples of patch reefs delineated from IKONOS imagery. White versus gray outlines were used to differentiate between reefs during quality control analyses.

After determining the point location of each patch reef, a polygon was created of the entire reef area; the area contained within, and excluding, a visible sand halo. A sand halo is an area that generally fringes a patch reef and is created by grazing herbivores (Randall 1965, Ogden et al. 1973). The bright reflectance of the sand halo is in contrast to the darker return of the actual patch reef (contained within it) and provides a clear boundary for delineating only the reef area. The polygons that were created were exported to ArcGIS 9.3. Patch reef morphology in the Florida Keys has historically been divided into just two categories: dome and linear (Marszalek et al. 1977, Chiappone 1996). Patch reef morphology were classified here into a greater number of morphologies: Aggregate, Atom, Colony, Crescent and Dome (Fig. 3). Each of these morphologies can be considered a subset of the original 'dome' classification.

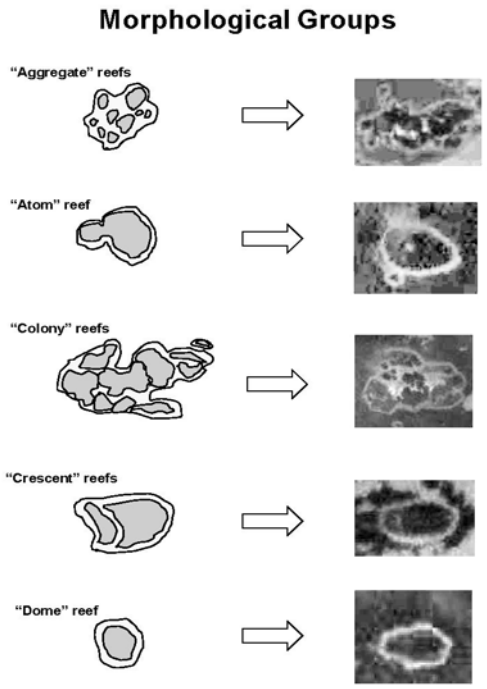

Figure 3: Categories of patch reefs identified.

Defining characteristics of each patch reef morphology are as follows:

Aggregate: a grouping of patch reefs of various sizes - generally three to ten in number – that share a common halo and exhibit complete separation between individual reefs.

Atom: a circular or elliptical-shaped patch reef containing a second patch reef within its sand halo. The secondary patch reef is always many times smaller in scale and is contained completely within the halo of the 'parent' reef, such that it appears in the process of budding off.

Colony: like Aggregate patch reefs, Colony reefs are found in close proximity to one another and share a common halo. Unlike Aggregate reefs they exhibit a 'conjoined' structure, for which a visible sand halo does not entirely separate individual reefs within the group.

Crescent: two patch reefs that share a single halo surrounding their exterior, and have complete separation in between via a sand channel. Crescent reefs always orient themselves in a northeast-southwest direction with the larger of the two reefs shaped like a 'bullet' with the smaller, 'boomerang-shaped' reef trailing in its wake.

Dome: the 'classic' dome patch reef; a single circular or ellipsoid reef with a single halo.

Patch Reef Metrics

Area and perimeter measurements (m^2 and m respectively) were obtained using XTools Pro for ArcGIS 9.3. The major axis of each patch reef was determined by placing a minimum area bounding rectangle around the delineated patch reef polygon. The major (long) axis of the rectangle then served as an estimate of the maximum diameter of the patch reef.

The complexity of each patch was defined by its perimeter to area ratio (P/A). Because this measure is sensitive to the size of the patch reef, a corrected perimeter to area ratio (PAC) was used that is not sensitive to changes in size of a patch of given shape. PAC index values range from 1.0 for a circle, 1.1 for a square, and can become infinitely large for long, narrow, and highly convoluted shapes (Baker and Cai 1992). PAC is defined as,

$$PAC = P / \sqrt{(4\pi \times A)},$$

where P is the perimeter of the individual patch reef polygon and A is the area contained within the sand halo. The PAC index was calculated for each polygon individually and then averaged across the morphological group.

The coastline of the Lower Keys was delineated as a polyline in ENVI and exported into ArcGIS. Distance from shore was derived as a linear measurement between the centroid of each patch reef polygon and the nearest point on the shore. The extreme south-western end of the shoreline defined by this study was Key West. Therefore, the shoreline value used for the patch reefs just inshore of Sand Key Reef would have been Key West. However, the distance from shore measurement for patch reefs west of Key West is greater than if the shoreline had been artificially extended westward toward the Marquesas. For our study, we used only the current land-sea boundary extending from the northern tip of Big Pine Key, to the western end of Key West, as our shoreline.

Table 1: Total number (N), Percent of Each Morphology by Number, Total Area (km^2), Percent of Each Morphology by Area, μ Area (m^2) and Area σ, μ PAC, μ Maximum Diameter (m) and Maximum Diameter σ (m), μ Distance to Shore (km) and Distance to Shore σ (km) for all patch reefs by morphology.

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	N	Percent of Total N	Total Area (km^2)	Percent of Total Area	μ Area (m^2)	Area σ	μ PAC	μ Max. Diam (m)	Max. Diam σ (m)	μ dist. to shore (km)	dist. to shore σ (km)
Aggregate	1185	52.6	1.914	32.4	1614	1802	1.269	48.5	28.2	7.394	2.661
Atom	100	4.4	0.372	6.3	3719	4675	1.283	70.8	51.1	5.437	1.002
Colony	184	8.2	0.944	15.9	5132	8467	1.357	87.2	73.7	5.126	1.134
Crescent	93	4.1	0.673	11.4	7336	6812	1.301	107.2	51.7	4.917	0.772
Dome	689	30.6	2.005	33.9	2909	3538	1.259	64.2	38.3	6.014	2.407
Total	**2251**		**5.908**								

Results

The total number of patch reefs detected in the Lower Keys region was 2,251. Of these, the Aggregate morphology was the most numerous (1185) and was located the farthest from shore, averaging 7.4 km. The largest area of patch reefs was in Dome reefs, because of their large individual size and abundance (689). Dome reefs, along with Aggregate, Colony and Crescent patch reefs were abundant in the Mid-Shallow region (Fig. 4). Aggregate and Dome reefs comprise most of the patch-reef area on the outer shelf. Aggregate reefs tended to be much smaller (on average 1614 m^2) than the Dome reefs (2909 m^2), but because of their large numbers (1185 Aggregate patch reefs or 52.6% of the total number), the Aggregate patch reefs nevertheless represented the second largest group in terms of overall area (1.914 km^2 of the total 5.908 km^2, or 32.4% of the total area)(Table 1).

The distribution of all types of patch reef morphologies was heavily concentrated in the mid-shallow and offshore regions. This can be seen on the map in Figure 1, and is detailed in Figure 4.

The PAC shape index of each individual reef further reflects reef morphology. The corrected perimeter to area ratio (PAC) can serve as a useful indicator of the complexity of the reef shape, with a high PAC ratio indicative of a complex or elongated shape and a low PAC ratio indicating a compact, circular shape.

The mean PAC did not indicate substantial shape differences. The Colony reef shapes were the most complex, with PAC averaging 1.36. The Dome reefs were the least complex, and have PAC values averaging 1.26 (Table 1). As a whole, the mean PAC values were very similar among all of the morphologies.

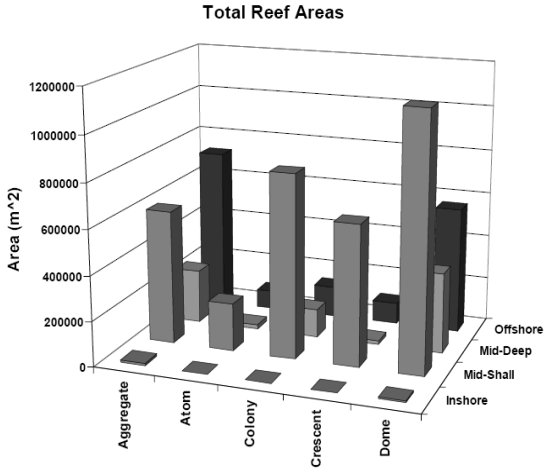

Figure 4: Total reef areas by class and distance from shore.

Discussion

The primary goal of this study was to identify and enumerate patch reef structures in the Lower Florida Keys Reef Tract using IKONOS satellite imagery. Using this method, 2,251 structures were identified. This is a substantial increase over previous estimates, more than six times Marzalek et al. (1977) and almost four times the FMRI (2000) estimates from aerial photography.

The qualitative characteristics that were initially observed in the patch reef dataset were not quantitatively demonstrated through the metrics we used. The patch reef data in Table 1 does not indicate that patch reefs have distinct morphologies and distributions in the Lower Keys, as was initially proposed. The summary data in Table 1 indicates that there exists high variability within morphological classes, and relatively small differences between them.

Future analyses will determine whether other metrics are more sensitive to – and can be used to quantitatively describe – the differences among patch reef morphologies

One inherent problem was that the reef parameters; area, perimeter, diameter, and the corrected perimeter to area ratio (PAC), were all affected by the 4 m pixel resolution of the original IKONOS imagery (i.e., polygons could not be delineated through the center of a pixel even if, in actuality, the edge of the reef may have). One possible way to better replicate the natural reef edge would be to use higher resolution (i.e. pan-sharpened or 1 m) imagery. This would alleviate this concern to a degree, however any delineation based on pixilated imagery would nevertheless result in a non-natural edge. A disadvantage of using higher resolution imagery is that it would greatly increase the amount of time spent analyzing the images.

A second possible limitation was that the patch reefs were subjectively classified by the observer and the data on a given reef were categorized under that class. Future multivariate statistical analyses will examine the reef-associated parameters independent of previously assigned classes.

Previous studies cited Florida Bay water and mobile calcareous sands as primary determinants of patch-reef growth, with patch-reef development focused on trough edges bordering Hawk Channel (Lidz et al. 2006). Key to our long-term analysis will be to determine how environmental and geological processes influence patch morphology and how this is manifested in the spatial distribution of patch reefs.

As live coral cover continues to decline, the importance of patch reefs in the Florida Keys will continue to increase. Under the working assumption that these patch reefs possess greater live coral cover than the offshore bank reefs, a comprehensive knowledge of their abundance, distribution, and controlling ecological parameters will be paramount.

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