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Quantification of two decades of shallow-water coral reef habitat decline in the Florida Keys National Marine Sanctuary using Landsat data (1984–2002)

David A. Palandro [a,*], Serge Andréfouët [b], Chuanmin Hu [a], Pamela Hallock [c], Frank E. Müller-Karger [a], Phillip Dustan [d], Michael K. Callahan [e], Christine Kranenburg [a], Carl R. Beaver [e,1]

[a] Institute for Marine Remote Sensing, College of Marine Science, University of South Florida, St. Petersburg, FL, USA
[b] UR Coreus - Institut de Recherche pour le Développement, Nouméa cedex, New Caledonia
[c] Reef Indicators Lab, College of Marine Science, University of South Florida, St. Petersburg, FL, USA
[d] Biology Department, College of Charleston, Charleston, SC, USA
[e] Fish and Wildlife Research Institute, Florida Fish and Wildlife Conservation Commission, 100 8th Ave. SE, St. Petersburg, FL 33701, USA

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ABSTRACT

The loss of coral reef habitats has been witnessed at a global scale including in the Florida Keys and the Caribbean. In addition to field surveys that can be spatially limited, remote sensing can provide a synoptic view of the changes occurring on coral reef habitats. Here, we utilize an 18-year time series of Landsat 5/TM and 7/ETM+ images to assess changes in eight coral reef sites in the Florida Keys National Marine Sanctuary, namely Carysfort Reef, Grecian Rocks, Molasses Reef, Conch Reef, Sombrero Reef, Looe Key Reef, Western Sambo and Sand Key Reef. Twenty-eight Landsat images (1984–2002) were used, with imagery gathered every 2 years during spring, and every 6 years during fall. The image dataset was georectified, calibrated to remote sensing reflectance and corrected for atmospheric and water-column effects. A Mahalanobis distance classification was trained for four habitat classes ('coral', 'sand', 'bare hardbottom' and 'covered hardbottom') using *in situ* ground-truthing data collected in 2003–2004 and using the spectral statistics from a 2002 image. The red band was considered useful only for benthic habitats in depths less than 6 m. Overall mean coral habitat loss for all sites classified by Landsat was 61% (3.4%/year), from a percentage habitat cover of 19% (1984) down to 7.6% (2002). The classification results for the eight different sites were critically reviewed. A detailed pixel by pixel examination of the spatial patterns across time suggests that the results range from ecologically plausible to unreliable due to spatial inconsistencies and/or improbable ecological successions. *In situ* monitoring data acquired by the Coral Reef Evaluation and Monitoring Project (CREMP) for the eight reef sites between 1996 and 2002 showed a loss in coral cover of 52% (8.7%/year), whereas the Landsat-derived coral habitat areas decreased by 37% (6.2%/year). A direct trend comparison between the entire CREMP percent coral cover data set (1996–2004) and the entire Landsat-derived coral habitat areas showed no significant difference between the two time series (ANCOVA; *F*-test, $p=0.303$, $n=32$), despite the different scales of measurements.

1. Introduction

Coral reefs worldwide are under multiple stresses and their health and extent are declining (Pandolfi et al., 2003). Among the different habitats found in coral reefs, coral-dominated habitats are degrading in extent and quality (Wilkinson, 2004). Coral cover often decreases in these coral habitats and may not return to the previous levels if stressors are chronic. Coral-dominated habitats are thus phase-shifting into algal-dominated and rubble habitats. Strategy shifts have also been reported in coral habitats, from one type of slow growing coral community towards other opportunistic, fast growing, type of coral community (Done, 1999). Phase and strategy shifts induce coral habitat loss. The loss can be massive (after a hurricane for instance), or patchy (after a bleaching or disease event), but it leads to fragmentation of coral reef habitats at both regional or reef scales. This fragmented state can be permanent or temporary. However, it implies that for a certain amount of time, coral diversity, habitat diversity and ecosystem processes can be degraded due to decreasing connectivity between regions, reefs and habitats. This can lead to a shift towards less complex, less diverse systems. This dynamic may be a confounding factor when measuring biodiversity patterns, since the chosen reference may be an already degraded ecosystem. This was referred to as the "shifting baseline" syndrome (Pauly, 1995). Putting coral reef

* Corresponding author. Current address: Fish and Wildlife Research Institute, Florida Fish and Wildlife Conservation Commission, 100 8th Ave. SE, St. Petersburg, FL 33701, USA. Tel.: +1 727 896 8626.
E-mail address: david.palandro@myfwc.com (D.A. Palandro).
[1] Deceased.

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habitat monitoring results into a large temporal and spatial context should be a priority.

In the Atlantic Ocean and Caribbean Sea reefs, live coral cover has declined markedly over the past 30 years (Gardner et al., 2003). In the Florida Keys, stressors associated with coral habitat decline include poor water quality (Boyer and Jones, 2002), overfishing and changes in water temperature (Dustan, 1999; Dustan, 2003). These stresses have increased the frequency in coral colony diseases (Patterson et al., 2002), bleaching (Hoegh-Guldberg, 1999) and algal overgrowth (Koop et al., 2001). As a result, systematic monitoring programs have been implemented over the large spatial extent of the Florida Keys National Marine Sanctuary (FKNMS) (Dustan, 1999; Klein and Orlando, 1994; Murdoch and Aronson, 1999; Ogden et al., 1994).

The FKNMS was established in 1990. Subsequently, the Environmental Protection Agency (EPA), the National Oceanic and Atmospheric Administration (NOAA) and the state of Florida established the Water Quality Protection Plan (WQPP) in 1995 to monitor water quality and benthic habitats (i.e., coral and seagrass habitats) in the FKNMS. As part of the WQPP, coral cover has been monitored at 40 sites in the FKNMS under the Coral Reef Evaluation and Monitoring Project (CREMP), formerly the Coral Reef Monitoring Project (CRMP) (Beaver et al., 2006; Porter et al., 2002). This data set is unique and provides the basis for a comprehensive study of change in coral cover over time. The annual surveys provide live coral percent cover by species, as well as the percent cover of broader benthic categories (e.g., substrate, sponges, macroalgae). Beyond the CREMP data, several change detection studies have been performed in the FKNMS using *in situ* and remote sensing data (Cockey et al., 1996; Dustan & Halas, 1987; Dustan et al., 2001; Hallock et al., 2003; Miller et al., 2002; Palandro et al., 2003a; Palandro et al., 2003b; Porter and Meier, 1992; Porter et al., 2002). Of these, only two studies have looked at more than one site (Porter & Meier, 1992; Porter et al., 2002). The CREMP effort is significant and collects precise information, but synoptically monitoring the entire FKNMS is simply not possible due to the size of the sanctuary.

Remote sensing technology has been used to map shallow coral reef habitats in a variety of sites worldwide (e.g., Ahmad & Neil, 1994; Andréfouët et al., 2005; Mumby et al., 1997). For local mapping studies, at reef-scale, the current trend is to use high spatial resolution data (e.g., Quickbird and IKONOS), available since 1999 (Andréfouët et al., 2003). A recent line of work for coral reef change detection studies employed spatial statistic operators (textural measurements) to detect changes in heterogeneity, assuming that high heterogeneity reveals good 'reef health' (LeDrew et al., 2004). A recent study separating branching and boulder coral assemblages used spatial autocorrelation with the same philosophy (Purkis et al., 2006). The Landsat suite of satellites carrying the Thematic Mapper (TM, Landsats 4 and 5) and the Enhanced Thematic Mapper Plus (ETM+, Landsat 7) sensors provides the longest time series of medium resolution images since 1984. This unique resource often provides the only way to go back in time for many reefs worldwide. Landsat provides 16-day repetitive coverage for sites at a 30 m spatial resolution. TM and ETM+ data generally allow the study of habitat distributions, and in some cases habitat dynamics as well (Andréfouët et al., 2001; Andréfouët et al., 2003; Dustan et al., 2001; Palandro et al., 2003b).

Here, our objective is to measure changes in coral reef habitat extent using an 18-year (1984–2002) time series of Landsat TM and ETM+ images for eight sites in the FKNMS, thus spatially extending the results previously acquired on only one reef (Carysfort Reef, Palandro et al., 2003b). The results are compared with the percent coral cover measurements from CREMP (1996–2002). This application is challenged by availability of remote sensing data, by their processing, and by the different ecological scales that need to be considered when comparing *in situ* and remotely sensed information captured at two different spatial scales.

2. Materials and methods

2.1. Study sites

Four sites were selected in the Upper Keys (Carysfort Reef, Grecian Rocks, Molasses Reef and Conch Reef), one site in the Middle Keys (Sombrero Reef) and three sites in the Lower Keys (Looe Key Reef, Western Sambo and Sand Key Reef) (Figs. 1 and 2). Each site is a Sanctuary Preservation Area (SPA). They represent the three Florida Keys regions (Upper, Middle, Lower) (Shinn et al., 1989). They are monitored by the CREMP as 'Offshore Shallow' sites, with reef crest depths less than 6 m. The 6 m threshold was suitable to use all three Landsat visible bands (blue, green, red) since only 10% of light in the red band (630 nm–690 nm) can reach 5.6 m in depth, even in pure water (Kirk, 1994; Pope & Fry, 1997).

The selected sites are representative of other FKNMS reefs and display typical reef habitat zonations found throughout the Atlantic–Caribbean region (Jaap & Hallock, 1990). Although *Acropora palmata*

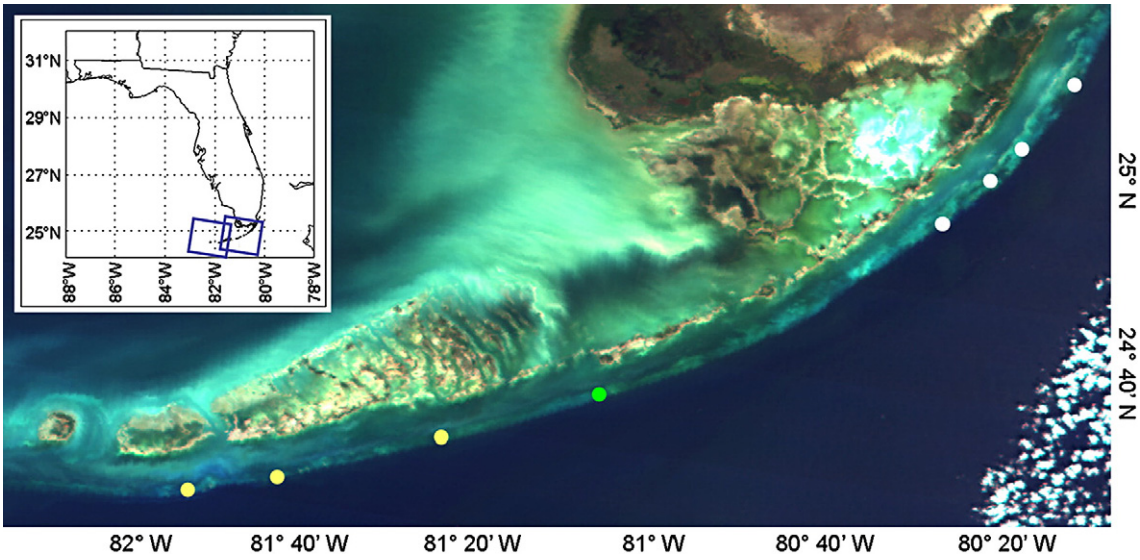

Fig. 1. RGB image with locations of the eight reef sites used in this study. They are, from north to south; Upper Keys (white) — Carysfort Reef (25.20°, −80.25°), Grecian Rocks (25.10°, −80.30°), Molasses Reef (25.00°, −80.42°), Conch Reef (24.94°, −80.49°): Middle Keys (green) — Sombrero Reef (24.61°, −81.09°): Lower Keys (yellow) — Looe Key Reef (24.55°, −81.40°), Western Sambo (24.47°, −81.75°), Sand Key Reef (24.43°, −81.92°). Inset map shows location and extent of path/rows 15/43 (north) and 16/43.