Remote Sensing of Coral Reef Community Change on a Remote Coral Atoll: Karang Kapota, Indonesia

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Abstract The importance of and worldwide threats to coral reef ecosystems have created an urgency to develop methods to study reefs on a global scale. Analyzing satellite imagery offers a relatively low-cost alternative to traditional field studies, but most analysis techniques currently being used require extensive ground-truthing expeditions and *a priori* knowledge of the reef. Such conditions are rarely met; for most reefs, little or no ecological information exists to guide managers and researchers. Using a time series of five Landsat TM and ETM+ images of Karang Kapota atoll, in Indonesia, we explored the utility of temporal texture as a diagnostic tool to detect ecological change in remote coral reef communities. We used a time series of precisely co-registered images to calculate the temporal variation in the brightness of each pixel, rather than statistically placing each pixel into a specific habitat class. In-situ expeditionary fieldwork on Karang Kapota atoll corroborated the finding that pixel brightness in disturbed habitats is more variable than in less disturbed areas due to the changing reflectance characteristics of the substrate and water column. Regions of the atoll with degraded reef communities exhibited higher levels of temporal texture than an area with robust, healthy-appearing coral communities. We propose that the further development of such remote sensing techniques may lead to the establishment of an index of habitat variability similar to the climatology index of SST anomalies calculated by NOAA in their coral beaching hotspot analysis. Such an index could alert resource managers to potential problems on remote reefs that otherwise would go undetected.

Keywords: Remote sensing, change detection, coral, reef, Landsat, texture, ecosystem monitoring, time series

Introduction

Traditionally, coral reef condition is estimated using underwater survey techniques that limit the synoptic surveying of large areas. Consequently, reefs that are easily accessible, especially those near developed countries, tend to be more widely studied than isolated reefs. Satellite remote sensing may help resolve the issue because it provides a synoptic view that trades fine-scale resolution for increased spatial and temporal coverage. The archive of available imagery spans more than 30 years, effectively providing a window to the past. With appropriate analysis techniques, it is possible not only to understand the current extent and status of reefs, but also to detect patterns of change in these environments. However, as attractive as this proposition is, implementing these techniques presents formidable challenges.

Satellite remote sensing has been used to map reef habitats (Nagarathinam et al. 1990; Luczkovich et al. 1993; Ninsawat and Tripathi 2003), to detect bleached corals (Lindell et al. 2000), to characterize environmental conditions integral to the health of the ecosystem (Goreau et al. 1997), and to investigate temporal changes in reflectivity that may correlate with ecological status (Dobson 1998; Dobson and Dustan 1999; Dobson 2000; Dustan et al. 2001). However, further work is required to refine techniques and develop more sophisticated analytical tools that can provide definitive information even when *in situ* data are limited. It is important to lay the groundwork for methods that can elucidate the nature of regional and global degradation of reefs.

Remote Sensing of Reef Condition

Remote sensing has been used not only to map habitats, but also to characterize surrogate aspects of coral reef health. Because of limitations imposed by spatial and spectral resolution, satellite imagery is not able to assess the health of individual corals. In fact, the characterization of a coral as "healthy" or "unhealthy" is challenging even when using *in situ* observations. Many stressors affecting coral health are invisible until they are manifested in dead or dying coral polyps. However, remote sensing can be used to evaluate the "health" or ecological state of the reef as a whole, using measurements that can serve as a proxy for the health of the corals. This is analogous to describing the health of a forest as opposed to that of a single tree, by measuring variables such as the relative percentages of live and dead trees.

The presence or absence of macroalgae is an informative indicator of the condition of the reef, but the "phase shift" from coral to macroalgae can be difficult to discern remotely when using broad-band multispectral imagery because of the close spectral similarity between the photosynthetic pigments of the organisms. This is especially a problem as depth increases, as the signals tend to converge (Lubin et al. 2001). High resolution reflectance spectra and airborne hyperspectral imagers can discriminate between algal pigment groups and corals, but such data are not yet available from orbiting sensors (Hochberg et al. 2003; Karpouzli et al. 2004). In order to improve accuracy using currently operational techniques and satellite sensors, classifications must be tailored to individual reefs by using groundtruthing observations.

The degradation of benthic habitats, often accompanied by corresponding changes in the water column, causes changes in reflectance properties that can be remotely detected. However, since it is problematic to accurately determine from a single image which pixels correspond to healthy or non-healthy corals, and, in some cases, even to definitively differentiate between corals and algae, it is important to explore the use of other analysis techniques. Our solution is to investigate an image time series, as opposed to classifying pixels at a given time of interest.

Time Series Analysis and Temporal Texture

Comparing multiple images of a single reef over time provides information on the variability of the signal reflected from a reef. This type of analysis can detect changes in community structure, relate these changes to habitat degradation, and make predictions about the future condition of the reef (Dustan et al. 2000). In effect, time series analysis is like watching a movie instead of viewing a single photograph, and may be able to alert managers to ongoing problems such as dynamite fishing or coral bleaching on even the most remote reefs.

Multiple techniques have been used to investigate change on reefs. In post-classification change, images from two or more dates are classified independently and the differences between habitat coverage at each time period are measured. In a study of Carysfort Reef, in the Florida Keys, Palandro et al. (2003) showed that the number of "coral-dominated" pixels decreased at approximately the same rate as coral coverage that had been measured *in situ* (Dustan 2003). There was a corresponding rise in "algal-dominated" pixels, indicating a phase shift from coral to algae. The sensitivity of this type of change detection relies on the accuracy of habitat classification in each image of the series. However, change can also be measured by analyzing spatial or spectral differences between images acquired on different dates, irrespective of classification.

LeDrew et al. (2000) used the Getis statistic, a measurement of spatial homogeneity, to investigate a remote coral reef, a stressed area, and coral that had been damaged by a toxic chemical spill and consequently colonized by filamentous algae. The stressed area, where tourists and fishermen tended to walk across the coral, became more heterogeneous, perhaps as a result of increased patchiness. The spill areas increased in homogeneity, as would be expected from algal colonization of dead corals. The healthy coral, however, also had a significant trend towards homogeneity, which was unexpected. Although these results are equivocal, they illustrate a method of analysis that does not rely on extensive *a priori* habitat knowledge.

Dustan et al. (2001) performed an analysis of pixel-scale variation through time, termed temporal texture, with a series of Landsat images of the northern Florida Keys from 1982 to 1996. With satellite images and *in situ* observations, Dustan et al. (2001) used texture calculations to show that the process of reef degradation altered both the spatial patterning and variability of pixel brightness. In the spatial domain, high texture values result when there is wide variation in pixel brightness across an image. Low texture is the dominant feature when there is small variation in brightness. High texture is characteristic of heterogeneity, and homogeneous areas are characterized by low texture. In the temporal domain, high texture is a measure of variability over time (heterogeneity), and low texture is a measure of stability (homogeneity). In a series of images, areas where little or no change has occurred over time are described as having low temporal texture. Areas where change has occurred are quantified by high temporal texture values.

Unlike traditional change analysis that utilizes the differences between two classified images, temporal texture reveals the variability of pixel brightness over time. In landscapes that have been altered, temporal texture is sensitive to resolving the location of change, but not the course of events. Habitats that have not been disturbed are characterized by low variability, suggesting that the signal from degradation is much greater than from natural phenology (Dustan et al. 2001). Temporal texture detects changes by revealing the variability component of change in multiple images over discrete time spans. Should areas of high variability be identified, more targeted, finer scale habitat classification or in-situ studies can be efficiently directed to the site. As the archive of available satellite imagery grows over time, this technique will become increasingly more effective. In the case of reef communities, the amplitude of natural successional changes are small when compared to the change in reflections resulting from coral bleaching, community phase shifts, or physical storm or shipwreck damages.

The current research utilizes satellite information to gain insight into regional and global reef degradation. It applies temporal texture to a coral atoll in Indonesia to investigate the utility of the technique on a large scale in a location that has not been previously well-studied. Landsat imagery was chosen because of the availability of a ten-year time series of images of the study site, as well as the presence of a blue band, useful in water penetration.

Study Site

Karang Kapota atoll (5º 30' S, 123º 25' E), in the Wakatobi Archipelago of southeast Sulawesi, Indonesia, is located in a marine reserve. While there are no published descriptions of Kapota, the report of the Snellius II expedition contained one paragraph about Karang Kaledupa, an atoll just south of Kapota (Borel-Best and Moll 1985). In December 1999 the R/V Heraclitus, in transit from Kendari to Manado, made a three-day reconnaissance of the central and northern sections of Kapota. In 2002 the R/V Heraclitus again stopped at the atoll to make more detailed ecological observations on the distribution and condition of the coral reef habitats. Five Landsat images of Karang Kapota spanning an 11-year time frame (1990-2001) were analyzed using temporal texture, and the results compared to the present ecological state of the reef as determined by field observations. A combination of field research and image analysis techniques was used to evaluate the ability of temporal texture to reveal patterns of ecological change in areas with little *a priori* information.

Methods

Field Studies

The R/V Heraclitus Planetary Coral Reef Expedition visited Karang Kapota in January 2002 to collect field observations. A 1999 SPOT image was used to guide field data collection. Twenty-five ground control points around the reef were located, enabling georeferencing of the image (Jensen 1996).

The locations of approximately 75 representative samples of ecological communities on the atoll (sand, seagrass, coral, etc) were mapped. Approximately 600 random points were generated on an initial classified image and 145 of these points were located on the atoll for quality control (QC) and accuracy assessment (Erdas Imagine, 8.4). Once the locations were identified on the reef, the QC point positions were recorded with cross calibrated GPS instruments (Garmin GPSMap 76 and Sokkia GIR 1000).

Image Acquisition and Processing

A series of five Landsat TM images of Karang Kapota, from April 1990, March 1994, November 1997, April 1998, and October 1999 were purchased from Geoscience Australia (GA) ("small scene" product). These images were transformed to align to a map grid, rather than oriented to the satellite path. In the process, pixels were resampled to 25 meters using nearest-neighbor techniques (Geoscience Australia 2003).

The final image used in analysis was a December 2001 Landsat ETM+ image, obtained from the United States Geological Survey (USGS) Landsat program with Level 1G systematic correction. Since the pixel size is delivered as 28.5 meters, it was resampled to 25 meters using nearest-neighbor techniques to match the GA TM imagery. The acquisition date of this image was only 17 days before fieldwork began, so it is most closely matched to field observations.

Although the images were acquired at different times of the year (October-December, March-April), they all fell within the transition period between the northeast and southwest monsoon seasons, thus minimizing any differences in imagery due to seasonality. The northeast monsoon typically lasts from approximately November until March in that part of Indonesia. Difference in tide heights at acquisition of the six images was relatively minor; tide levels differed by a maximum of 1.1 meters.

The ETM+ product as delivered by USGS was very closely aligned to the SPOT image that had been georeferenced with field data points. It was manually adjusted slightly in the x and y direction to fit the SPOT image even more precisely, and the rest of the Landsat images were aligned to the ETM+. These also only required minor adjusting in the x and y direction, and resampling was unnecessary. The registration of the images was done with great care, and the ERDAS swipe function was used to ensure that there would be negligible effects due to misregistration.

Since the ETM+ image was acquired close to the date that fieldwork began, it was chosen as the basis for a post-field classification. Since the size of the image subset was not large, we assumed that uniform atmospheric conditions prevailed, and an unsupervised ISODATA classification was performed on the original ETM+ image before it had undergone atmospheric correction. Each class was assigned to one of the following six habitats: coral, sand, seagrass, deep sand (> 3m), rubble/hard bottom, and an "edge" category (Fig. 1).

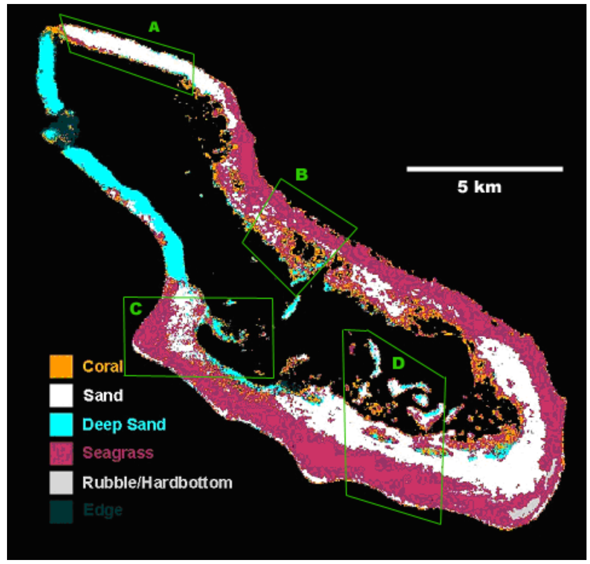

Fig. 1. Classified image of Karang Kapota, with locations of representative quadrants marked.

The edge category included approximately 5% of the entire atoll, primarily very deep areas of the atoll where the bottom was barely visible and therefore deeper than the resolving power of the sensor. The classified image was also resampled to 25m pixels to match the rest of the imagery. One hundred thirty-nine of the 145 quality control points were used to test the accuracy of the classification scheme. Six of the points that were collected fell outside of the area of the atoll visible in the imagery.

In order to compare image pixels directly, the images were normalized to one another to minimize differences due to the atmosphere. Image pixels were converted from radiance to reflectance (Markham and Barker 1985), then a simple dark object subtraction was employed to remove the effects of atmospheric aerosols (Raabe and Stumpf 1997). This simple method of atmospheric correction was chosen because more complex methods do not necessarily increase classification accuracy (Song et al. 2001). After completing this process, the 1999 image was dropped from analysis due to extreme atmospheric haze that blanketed most of the image.

The southeastern end of the 2001 image had an area that reflected strongly in bands 5 and 7, middle-infrared bands. Since these are both absorbed within the first few millimeters of water, it was determined that the strong reflection was due either to clouds, breaking waves, or sunglint. This section was masked out of all images in further analyses.

Texture, as it is traditionally calculated using a convolution kernel, is a measure of the spatial heterogeneity of an image. Heterogeneity can also be calculated temporally to quantify the variability of a given pixel over time, using a chosen statistic such as standard deviation or coefficient of variability (COV). This technique of temporal texture was used to calculate change in the images due to the very narrow (in most cases, one pixel wide) coral habitats that do not lend themselves to traditional spatial texture analysis. The mean, standard deviation, and COV for each pixel were calculated across the five images (Dustan et al. 2001) for bands 1, 2, and 3. The COV measures variability as a percentage of the mean (Sokal and Rohlf 1995), and therefore allows direct comparisons of variability between habitats. The deep water was masked out of the images.

Image Segmentation

COV images were segmented by habitat using the final classified ETM+ image to create habitat masks for coral, sand, and seagrass. Images were also segmented by representative quadrants (Fig. 1). These quadrants were chosen on the basis of their ecological character as observed during field studies on the atoll. Coral condition was used as a proxy for ecological status, because sand and seagrass habitats did not exhibit obvious differences between quadrants.

The median COV for each habitat and each quadrant were calculated for each of the three bands. The Kruskall-Wallis nonparametric test was performed to determine whether differences between the median COV values were significant at the 0.05 level (Statistica, v. 6.0). When significant differences were found, a multiple comparisons test was used to determine precisely which values differed significantly (Hollander and Wolfe 1973).

Results

In December 1999 the dense coral communities of the central and northern sections of Kapota appeared relatively healthy. Fish were abundant and large pelagic fish species were relatively common. Two years later, during field studies in January 2002, the coral communities showed signs of degradation. Fewer large fish and pelagic species were seen, suggesting that fishing intensity may have altered the fish community composition and, through the release of top down controls, the composition of lower trophic levels.

Habitat Classification

A classification was performed on the ETM+ image based on the results of field observations (Fig. 1), and then an accuracy assessment was carried out using 139 of the 145 ground control points that had been collected on the atoll. Six of the points were not useable because the location of the observation fell outside the bounds of the classified area of the atoll. The overall accuracy of the classification scheme was 69.7%.

Ecological status of quadrants

The corals on the northwestern tip of the atoll and along the outer edge (quadrant A) generally appeared to be thriving, with extremely dense coverage. (Fig. 2, photos 1 and 2).

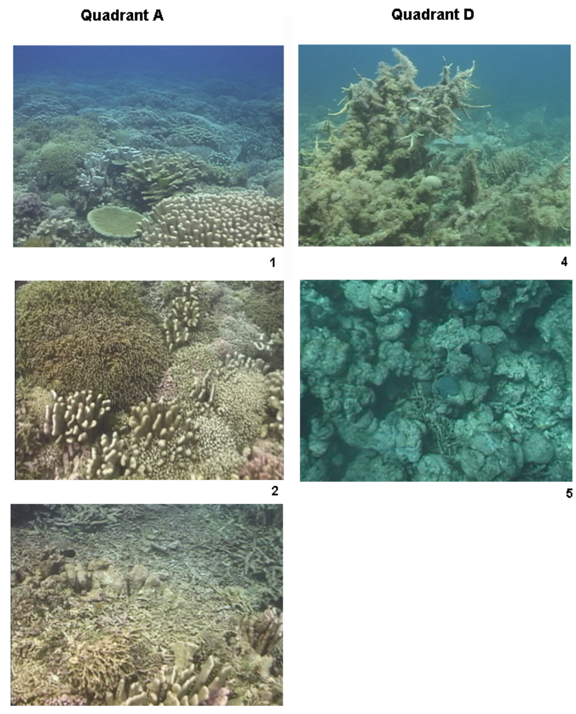

Fig. 2. Photos of coral condition in quadrants A and D. Photos 1 and 2 show the high coral coverage and healthy corals in quadrant A. Photo 3 is an example of the results of dynamite fishing. Photo 4 shows skeletons of dead corals that have been colonized by filamentous algae. Photo 5 shows the bare skeletons of dead corals which have not been colonized by algae.

There were occasional patches of isolated coral rubble with the characteristic shape and rubble field associated with dynamite fishing (Fig. 2, photo 3). Other than in these scattered areas, corals appeared to be in good condition. There was very little macro- or microalgal overgrowth, encrusting sponges, or excess sedimentation visible. It was difficult and often impossible to see the underlying substrate, due to the high coverage of hard and soft corals.

Corals in quadrant D were not nearly as vibrant, particularly inside the lagoon. The coral condition in that area stood in great contrast to that of corals in quadrant A. Inside the lagoon, there were large areas of dead coral, often covered with algae and sometimes physically damaged or lying on their sides, out of growth position. Some of the corals were draped with mucous-like strands of filamentous algae (Fig. 2, photo 4). The morphology and abundance of the skeletons indicated that at one time, coral coverage and habitat complexity would have been high in places, similar to that of quadrant A. Few live corals remained, and in most areas dead corals predominated, in stark contrast to the extremely high live coral coverage in quadrant A. Some areas of quadrant D contained copious amounts of filamentous algae; in other areas, dead coral skeletons were covered by short turf algae or were completely bare (Fig. 2, photo 5). Quadrant D was the only quadrant in which substantial amounts of filamentous algae were noted. The condition of corals in quadrants B and C appeared to lie somewhere in between that of quadrants A and D. Although there were sites with dead coral skeletons covered by turf algae, areas dominated by vibrant living corals were also abundant.

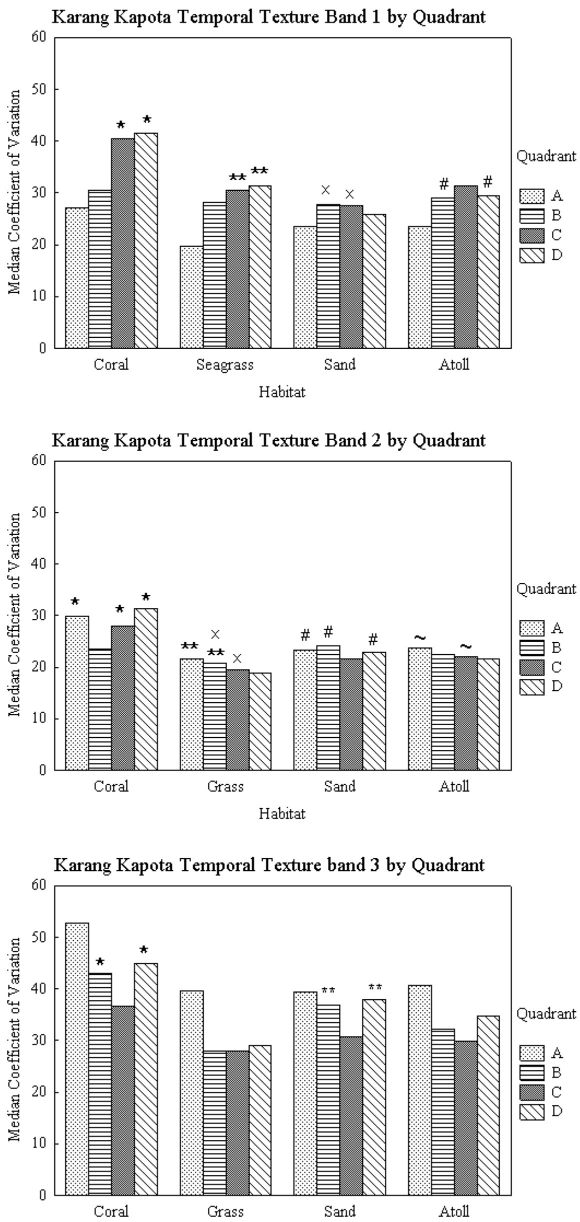

Fig. 3. Median coefficient of variability (temporal texture) in bands 1-3 for coral habitats, grass habitats, sand habitats, and the entire atoll. Habitats are also divided by quadrant. Symbols above the bars indicate values that are not statistically different within each habitat.

Temporal Texture Analysis

Temporal texture analysis focused primarily on band 1 (blue) because bands 2 and 3 (green and red) do not penetrate water as deeply, and are therefore affected more by depth and potentially by between-date differences in water clarity (Luczkovich et al. 1993; Lubin et al. 2001). A primary objective of this research is to identify change without relying on *a priori* knowledge, which includes accurate depth information. Depth was not used as a controlling factor in the selection of ecological analysis areas, so the quadrants comprise a variety of depth regimes. Band 1, with the greatest water penetration, should be least affected by depth. Therefore, unless otherwise stated, texture statistics discussed here reflect band 1 values.

Images were segmented by habitat and by presumed ecological status (quadrants A-D). The mean COV (temporal texture) for each quadrant was calculated to determine whether areas of the reef with differing ecological states would exhibit statistically different temporal texture values (Fig. 3).

In band 1, the coral habitat showed the greatest difference in temporal texture between quadrants. Quadrants D and C were not significantly different from one another, but they had a significantly higher median COV than either of quadrants A and B. The seagrass habitat exhibited a similar trend of COV increasing from quadrant A to quadrant D, with no significant difference between D and C. The sand had fairly similar mean temporal texture values across all four quadrants, with B and C showing no significant differences. Over all habitats, quadrant C was slightly more variable than quadrants B and D (which didn't exhibit significantly different COV from one another), and quadrant A was the least variable.

Discussion

Coral condition and algal biomass were used as the primary indicators of the reef ecological condition in the different atoll quadrants. Corals are very sensitive to environmental change and they form the reef structure. Therefore, they provide the most responsive indicator of the condition of the reef, and may also serve as an early warning system for reef decline (Crosby 1997). Algal biomass (including general community composition) has also been used as an indicator of both top down and bottom up stress on coral reefs.

One aspect of assessing the health of a coral reef takes advantage of the fact that corals grow slowly in place. If one observes living corals of any consequential size, it is assumed that they have been alive for a reasonable number of years. An abundance of the larger size classes of living and healthy-appearing colonies is probably a reliable indicator of a healthy reef environment. At Kapota, sites with relatively healthy coral communities, exhibiting little or no coral colony mortality or algal overgrowth (such as in quadrant A), were assumed to have changed less than those dominated by dead or algal-covered skeletons. Corals in quadrant A appeared robust, and had very high coverage (see results section for further detail). Although there were some areas that had obviously experienced change, such as the dynamite fishing craters, these were relatively rare, and the community as a whole appeared to be thriving. It was the most luxuriant area observed.

In contrast, the corals in quadrant D were often dead and overgrown by turf algae and, in some instances, filamentous algal mats (Fig. 2). The abundance of dead coral skeletons in growth position indicate that at one time, coral communities in this region were probably luxuriant and thriving, as in quadrant A. Indeed, during the 1984 expedition to the nearby atoll of Kaledupa, the Snellius II expedition found "extensive patches with high coral cover" within the lagoon (Van der Land 1986). It is highly unlikely that all mortality occurred prior to the first image in the time series, 1990, because boring sponges and other natural processes probably would have degraded the coral skeletons over that length of time. Therefore, it can be assumed that corals in quadrant D varied more during the dates in question (1990-2001) than those in quadrant A. These field observations correlate with temporal texture values calculated from the imagery. The median COV for corals, seagrass, and all habitats combined in quadrant A was significantly lower than for quadrant D ($p<0.001$), suggesting that quadrant D has changed more than quadrant A. The clear and significant difference in median COV values between corals in quadrants A and D support the hypothesis that ecological change can be identified using temporal texture statistics.

These two areas provided the most striking contrast on the reef. Quadrants B and C comprised a mixture of degraded and undegraded coral communities. The presence of dead and unhealthy corals shows that they have undergone some ecological change, though not as drastic as in quadrant D. One would therefore expect that the temporal texture would lie somewhere between that of quadrants A and D. This is the case for quadrant B in both the coral and seagrass communities. However, there is no significant difference between the temporal texture of quadrants C and D in either coral or seagrass. Since these field observations are subjective, and the survey did not quantify the ecological state of the quadrants, one possible explanation for the similar temporal texture between quadrants C and D is that ecological change in quadrant C was of a similar scale to that of quadrant D.

The only habitat that did not show significant differences in COV between quadrants A and D was sand. This is probably because sand does not generally exhibit a biological (spectral) response to environmental change that is large enough to be detected by Landsat TM.

Analyzing all pixels of the atoll within each quadrant, the results are more ambiguous. Although quadrant A has the lowest temporal texture, the differences between the other quadrants are less pronounced; indeed, there is no significant difference between quadrants B and D, and quadrant C has the highest variability. These results indicate that quadrants B, D, and especially C, have undergone more change than quadrant A, but they do not highlight the increased degradation of corals as observed in quadrant D. One possible explanation is that coral habitats represent a very small proportion of the shallow area of this atoll. Although the ecological status of the quadrants was determined by observations of the condition of the coral communities, variability in other habitats contributes more to the overall median COV for each quadrant. More research is needed to fully elucidate the ecological state of the entire reef ecosystem in each quadrant and how that correlates with the variability measured in the imagery. However, although the results do not distinguish between the differing degrees of ecological degradation as defined by coral condition in quadrants B, C, and D, they do demonstrate that temporal texture analysis can determine the presence of change, though perhaps not the magnitude of coral cover change using these techniques. Quadrants B, C, and D all exhibited a greater degree of habitat degradation than quadrant A, and their higher texture values reflect this.

Temporal Texture and Observed Variability

The goal of this research was to determine whether temporal texture analysis of Karang Kapota provides a measure of reef variability that corresponds to community condition. Current remote sensing studies have gone to great efforts to produce habitat maps, and a comparison of these maps over time can reveal change. However, the errors inherent in habitat classification can actually mask change detection as corals and algae have very similar spectral signatures. Given this similarity, it could be argued that temporal texture might not be able to detect the often rapid phase shift from coral colonies to algal dominance, particularly if the time series is not sufficiently robust. On the level of an individual coral colony, this might indeed be the case if the coral dies and is overgrown in between the dates of two images. However, on the scale of the entire reef community, changes generally occur over a longer time period, and will be manifested not only in the coral to algal shift, but also in other associated changes. Reef corals form the structural elements of a reef, but their condition is not the only indicator of the health of the reef. Coral reef degradation is a whole ecosystem process, manifested in other biological communities and even in water quality. Changes in water quality due to increased nutrients, sedimentation, or other organic matter often occur in conjunction with the deterioration of benthic communities. Measures of variability such as temporal texture incorporate changes in both water quality and in benthic habitats, and thus may provide broad interpretations about the variability of the ecosystem as a whole. Temporal texture can detect these changes because it does not rely on classification, but simply the variability of substrate and water column reflectance. Although this variability might also occur as a result of improvements in the coral community rather than degradation, global observations suggest that few, if any, reefs are improving rather than declining.

Because we had in-situ observation of Kapota, we could have chosen any of a number of different ways of partitioning the imagery, including depth, geomorphology, zonation, etc. We chose to divide the entire reef into quadrants. Although the choice of quadrants was, in this case, guided by observations, in future studies the quadrants can be chosen by random, or not at all. We did also segment by habitat, using the classified image, which required field observations to verify. We hoped that by this procedure we could gain insight with respect to the scale of pattern detection. Indeed, the temporal texture trends are evident over the entire image results, as well as just within the classified habitats. The benefit of field observations allowed us to draw conclusions from our data but does not invalidate the utility of this approach. Field observation, like any ground truth effort, allowed us to compare a remote sensing index of change with observed ecological status.

Future Research and Applications

Despite the constraints of limited funding and data availability, this research supports the hypothesis that the variability of spectral characteristics over time of Landsat imagery of Karang Kapota atoll correspond to ecological changes in reef communities But many more hurdles remain before temporal texture becomes a routine analysis tool. Several questions are unanswered by this research. For example, since both coral and algae reflect most strongly in the green band, it seems that Band 2 should be more sensitive to phase shifts. It would also be interesting to partition which part of the variability is due to water column signals as opposed to benthic reflectance. Unfortunately, Landsat TM does not possess the spectral resolution to address these questions well.

While it is clear that coral reef remote sensing could be much better served with an orbiting sensor with higher spectral resolution tuned to the bio-optical properties of coral reef organisms (Dustan et. al 2001, Hochberg et al. 2003, Karpouzli et al. 2004) we have demonstrated that simple multi-band sensors can be used to detect change in coral reef communities. The failure of the Landsat 7 SLC now makes it important to identify a reasonably priced replacement. Commercially available imagery such as SPOT, IKONOS, or Quickbird will work at the scale of coral reef ecosystems. Unfortunately, the imagery is more expensive and therefore out of reach for many developing nations and NGOs. Additionally, with the exception of SPOT, these newer sensors do not have a very long historical record. They might be able to be merged with older TM records, and, in time, be used to move the technique forward.

Regardless of the satellite, temporal texture analysis is useful in detecting ecological change and degradation in remote or well-known reefs. This is a simple but powerful tool that can be used by scientists and managers alike, to remotely assess the relative condition of coral reef communities without extensive field verification. With further testing and development, the technique could be used to create a baseline map of the variability of reef communities worldwide, which could be updated as new imagery becomes available. This technique can be used not only to find degraded reefs to target for more in depth field studies, but also to locate those reefs that are relatively unchanged. These areas could be designated as no-take zones or marine protected areas, to preserve the best examples of living coral reef ecosystems. NOAA presently operates a Coral Bleaching Hot Spot Analysis website based on the detection of sea surface temperature anomalies. We see the development of a similar hot spot tool using temporal texture to monitor reef variability as a logical and necessary next step towards the goal of global coral reef conservation. As new technologies are developed, and programs such as the Millennium archive project increase the available archive of coral reef imagery, temporal texture will become an increasingly powerful tool.

Conclusions

This study used Landsat imagery to investigate changes on a little known remote Indonesian atoll to test whether temporal texture can be used to identify ecological change in remote reefs under sparse information conditions. Differences in the median coefficient of variability of coral pixels in four different areas of the atoll corresponded to differing ecological states of the coral communities observed in these areas. These differences were also observed in the coefficient of variability of the seagrass pixels. While promising, more research and development of this method is needed to better understand the links between temporal texture and ecological change. In addition, in the course of this work we realized that on this ‘coral atoll’, a mere 9% of the surface area is actually composed of coral communities. This data further heightens the importance of protecting these shrinking resources.

The results of this research demonstrate that it is possible to use the satellite record to gain insight into regional and global reef degradation, even when, as is the case for most reefs, the availability of *in situ* knowledge is minimal. It sets the stage for developing a change detection hot spot analysis tool, which may prove to be a useful for managers and scientists alike. There are many applications of this research for coral reef conservation. With the ability to remotely detect ecological change, this technique can be used as an early warning for coral reef degradation, or, conversely, used to site marine protected areas in regions that have undergone little change.

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