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Simple and effective monitoring of historic changes in nearshore environments using the free archive of Landsat imagery

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ABSTRACT

The recently released archive of Landsat imagery can be used to detect historic changes in nearshore environments. We used a series of free Landsat images spanning the years from 1984 to 2009 to detect changes in the spatial extent of dominant substrate types, coral, algae, and seagrass, around Bawe and Chumbe islands in Zanzibar, and we compared the use of true-colour composites and supervised classifications. Results indicate temporal changes in the spatial extent of seagrass meadows are easily mapped with Landsat imagery, whereas temporal changes in algae cover and particularly coral cover pose greater challenges because of the similarities in spectral reflectance properties between the relevant substrate types. Supervised classification requires substantially more processing than the simple display of true-colour composites, but does not improve interpretation in our study. We suggest that historic Landsat imagery, obtained at no cost and processed minimally with free software, is the best available data source for studies of historic changes in the nearshore environments of East Africa.

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1. Introduction

The nearshore environments of East Africa contain numerous resources crucial to the economy of the region, including hundreds of fish and invertebrate species that are either exported or consumed locally (Gössling et al., 2004; Torell et al., 2007), mangrove trees that are harvested for construction or left standing for shoreline protection, as well as coral reefs and white beaches that attract millions of tourists every year (United Nations, 2002). Pressures on these resources have intensified along with increases in the human population (McClanahan et al., 1999), making appropriate coastal planning and management crucial for sustainable development (Cohen et al., 1997; Small and Nicholls, 2003). Information on the magnitude and spatial location and extent of changes in the nearshore environment, either natural or resulting from human impacts, will therefore be essential for the development of management responses. Such information, however, can be difficult and expensive to generate, especially in the least developed regions of Africa where the nearshore environment is most crucial for local livelihoods. The time series of data necessary to monitor environmental change are usually only available for a few sites located in easily accessible locations (Gullström et al., 2002), and research funding and capacity is often too limited to expand in situ monitoring. The recently released archive of Landsat imagery is an alternative data source, one that is both temporally and spatially extensive and now freely available for download over the Internet (http://glovis.usgs.gov/). The archive contains imagery from 1972 to the present, and covers most coastal regions of the world (Arvidson et al., 2001). With very limited processing, change detection using this imagery can provide scientists and managers with the necessary information on environmental change in otherwise data-poor areas.

In this study, we investigate what changes are identifiable in the tropical nearshore environment with a time series of Landsat imagery, focusing on the three major living substrate types in this environment: corals, seagrasses and algae. We use 27 Landsat images covering the period from 1984 to 2009, along with recent field data (from 2007 to 2008), to assess long-term trends in these three substrate types around two small islands in Zanzibar. In addition, we assess the magnitude of seasonal variations in substrate reflectance and its effect on interpretations of the time series of Landsat images, and we assess whether the use of supervised classification provides information in addition to what can be obtained by visual inspection of true-colour composites.

2. Study area

Zanzibar consists of two main islands, Unguja and Pemba, with numerous smaller islands surrounding them. We focus our study

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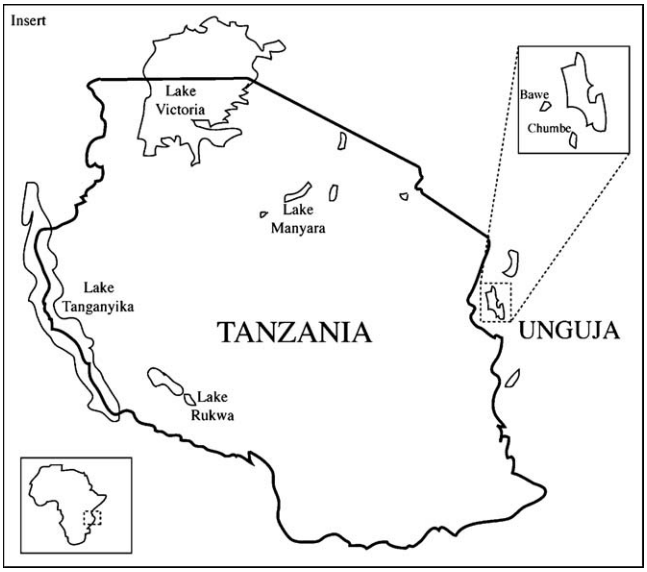


Fig. 1. Map showing Unguja, Zanzibar's main island, in relation to Tanzania and Africa.

on the shallow (<10 m depth) inter-tidal and sub-tidal areas around two small islands, Chumbe and Bawe, both located off the west coast of Unguja, the main island of Zanzibar (Fig. 1). The nearshore areas around Chumbe and Bawe islands represent two extremes of human exploitation. Bawe Island, located 5 km from Zanzibar Town, is a popular fishing ground, visited daily by fishermen using both legal and illegal fishing gear (Jiddawi and Ohman, 2002). Chumbe Island is located southeast of Bawe, 12 km from Zanzibar Town, and the reef on its western side is protected by a strictly enforced Marine Park (Tyler, 2005).

3. Data and methods

A total of 27 Landsat images were used in this study (Table 1), all freely available for download from the Landsat archive. Images were preprocessed to the 1G, 1Gt or 1T levels (USGS, 2009), technical details for Landsat imagery are provided in Table 2.

All images were geometrically corrected to the 2009 image with <20 m RMSE. In addition to our study area, the full Landsat scenes (path 166, row 64) also cover Unguja and nearby islets, the southern part of Pemba Island, and part of the Tanzanian mainland coast, so Chumbe and Bawe islands (with surrounding nearshore areas) were cropped out of the original scenes to ease further processing.

Table 1
Sensor types and acquisition dates for all Landsat images used in this study.

Long-term trend analysis		Seasonality analysis	
Sensor	Acquisition date	Sensor	Acquisition date
TM	09 May 1984	ETM+	18 February 2004
TM	26 April 1985	ETM+	21 March 2004
TM	27 February 1987	ETM+	08 May 2004
TM	06 February 1988	ETM+	11 July 2004
TM	09 December 1989	ETM+	28 August 2004
TM	11 February 1990	ETM+	29 September 2004
TM	24 June 1992	ETM+	15 October 2004
TM	17 February 1995	ETM+	31 October 2004
ETM+	19 November 1999	ETM+	16 November 2004
ETM+	25 February 2001	ETM+	18 December 2004
ETM+	11 November 2002		
ETM+	27 September 2003		
ETM+	08 May 2004		
ETM+	04 February 2005		
ETM+	23 February 2006		
ETM+	08 October 2007		
ETM+	03 May 2008		
ETM+	03 March 2009		

Table 2
Landsat technical specifications.

Sensor	TM	ETM+
Spatial resolution	30 m (120 m – thermal)	30 m (60 m – thermal, 15 m pan)
Number of bands	7	8
Temporal resolution	16 days	16 days
Swath	185 km	183 km
Spectral range band 1	0.45–0.52 μm	0.45–0.515 μm
Spectral range band 2	0.52–0.60 μm	0.525–0.605 μm
Spectral range band 3	0.63–0.69 μm	0.630–0.69 μm
Spectral range band 4	0.76–0.90 μm	0.75–0.90 μm
Spectral range band 5	1.55–1.75 μm	1.55–1.75 μm
Spectral range band 6	10.4–12.5 μm	10.4–12.5 μm
Spectral range band 7	2.08–2.35 μm	2.09–2.35 μm
Spectral range band 8	n/a	0.52–0.9 μm

Two approaches were compared for the long-term trend analysis. In the first approach, true-colour composites of the islands were displayed for each scene (left side of Table 1), and contrast enhancement was applied manually to reduce the effects of noise, clouds, and differences in tidal stage on the colours of sub-tidal and inter-tidal areas. The true-colour composites were then inspected visually, and a number of areas were identified that showed recognizable change through time. 728 field observations of substrate were available for ground validation; these were used to identify the prominent substrate type in the areas showing change. All field observations were based on substrate photos from 2007 or 2008, each covering a minimum of 4 m^2 and georeferenced with a handheld GPS.

The second approach to long-term trend analysis was to produce supervised classifications of the major substrate types for each scene. The 728 field observations were used to identify homogeneous training areas in which visual inspection suggested that the substrate changed only negligibly from 1984 to 2009; areas with cloud cover in any of the satellite images (except the 1988 image of Chumbe) were then eliminated from the set of training areas. Field observations outside the training areas were used for accuracy assessment following the classification. The classes used were "Land", "Deep Water" (no distinguishable substrate reflectance), "Shallow Sand" (sandy substrate, depth <5 m), "Deep Sand" (sandy substrate, depth >5 m), and "Coral" (>25% coral cover). In addition, an "Algae" class (>25% algae cover) was used on Bawe, and a "Seagrass" (>25% seagrass cover) was used on Chumbe, to reflect the presence of these substrate types where they occur.

For the seasonality analysis, similar true-colour composites were displayed for each image (right side of Table 1) and visual inspections were carried out. Specific attention was paid to any change in spectral reflectance between the two major seasons in Zanzibar, the northern 'kaskazi' winds (November–March) and the southern 'kusi' winds (April–October) (Ngoile, 1990), as well as stochastic fluctuations caused by differences in tide height or other environmental variables.

4. Results

4.1. Assessment of seasonal changes in the nearshore environment

The 10 images of Bawe Island and the surrounding area from 2004 are shown in Fig. 2.

Although no general pattern of seasonal change is seen in Fig. 2, several areas display variations in brightness throughout 2004. The

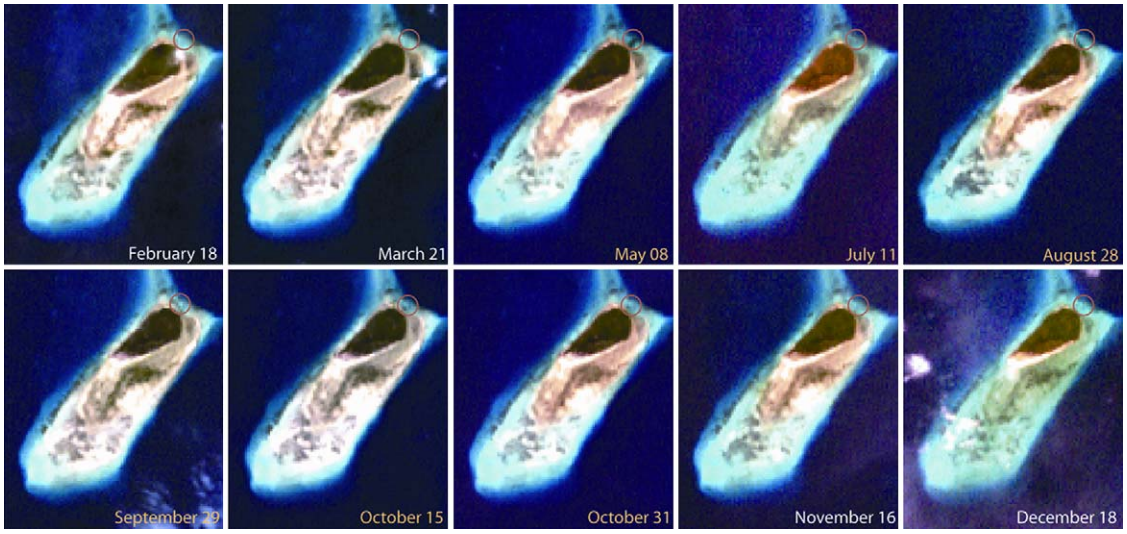


Fig. 2. Ten true-colour composites of Bawe Island and the surrounding area, acquired from February to December 2004. Images from the season of the southern '*kusi*' winds are marked with yellow text, while images from the season of the northern '*kaskazi*' winds are marked with white text. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

seemingly stochastic changes correspond to variations in tidal height at the time of image acquisition, which could not be adequately corrected for with the manual contrast enhancement. However, one area northeast of the island, highlighted with a red circle in Fig. 2, is noticeably darker in May 2004 than at any other time of that year, while the surrounding area does not show the same change over time. Field observations indicate that this is a shallow sub-tidal area with a hard limestone substrate and limited algae growth at the time of field observation (fall 2008), suggesting that the darkness in May is caused by algal growth. Although this explanation cannot be confirmed with the available data, the substantial change seen over a short period of time, from March to May and again to July, does indicate that erratic changes in the time series from 1984 to 2009 may be caused by seasonal or other effects that are attributable to a single image. On that basis we conclude that only change observed over several years, and in images from different seasons, can be taken as evidence of consistent environmental change. This conclusion is supported by a review of all 2004 images from Chumbe Island, not shown here.

4.2. Assessment of long-term trends around Bawe Island

True-colour composites and classified images for Bawe Island are presented in Figs. 3 and 4, respectively.

Three of the most noticeable areas of change around Bawe have been marked with red circles in both figures. In the true-colour images, B1 and B2 both undergo a gradual lightening through time; this change is reflected for B2, but not for B1, as a gradual shift from

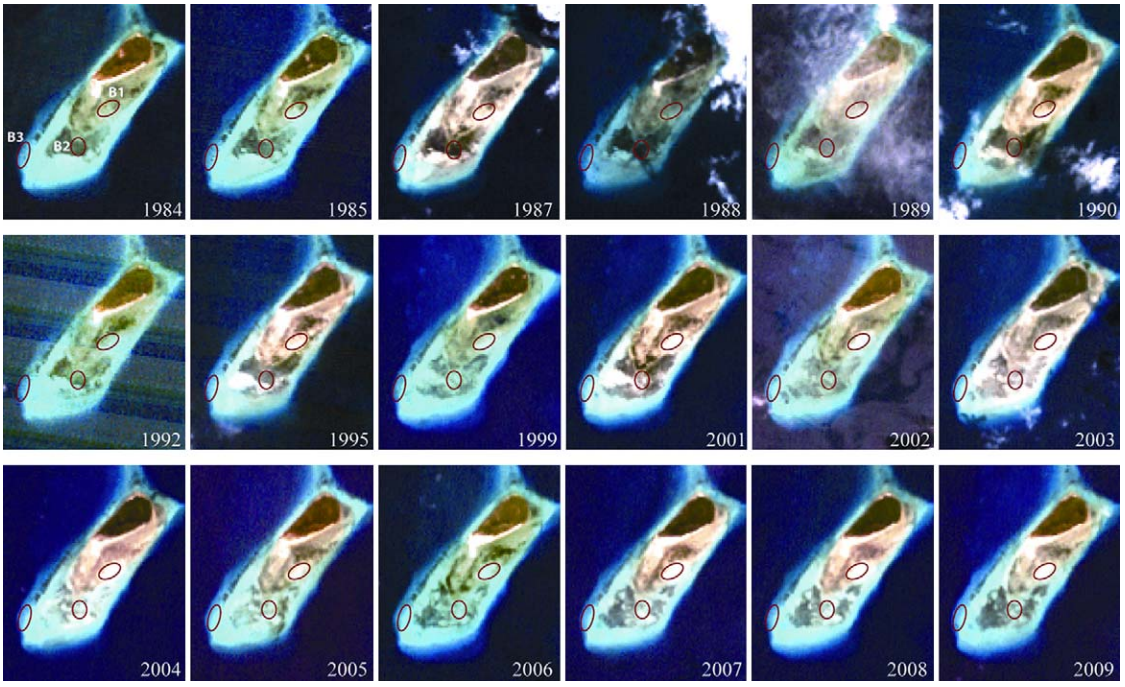


Fig. 3. 18 true-colour composites of Bawe Island and the surrounding area, illustrating changes from 1984 to 2009.

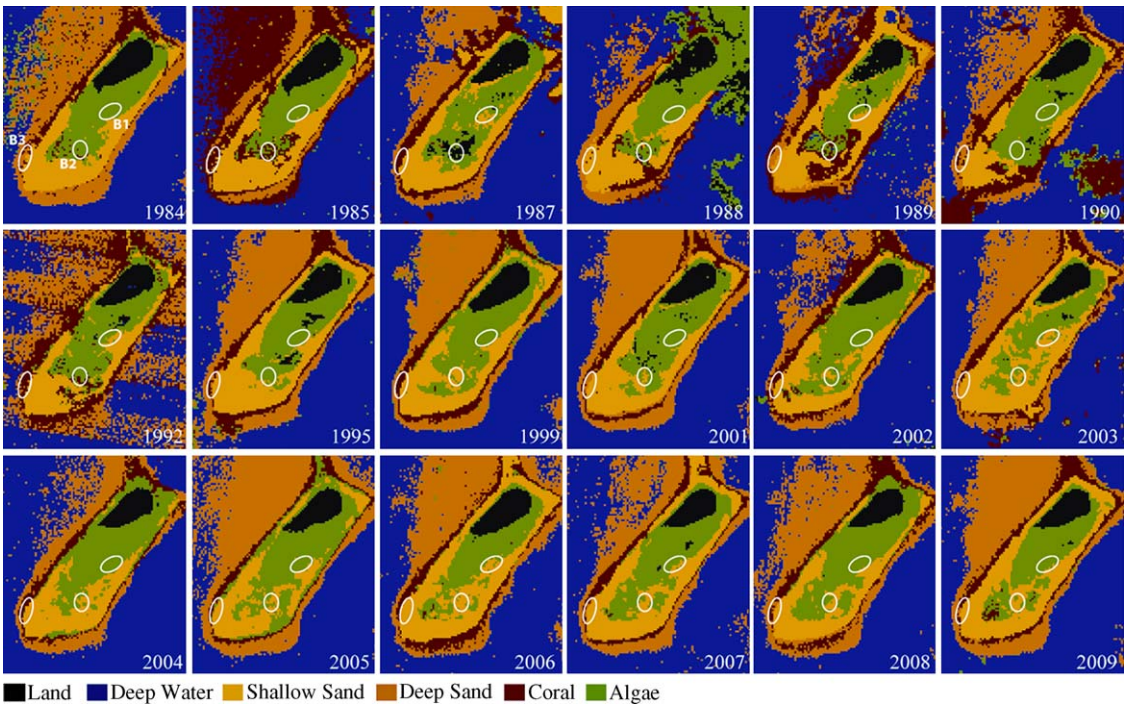


Fig. 4. Supervised classifications of Bawe Island.

"Algae" to "Shallow Sand". Field observations (2008) indicate that both areas have a hard limestone substrate with limited algal growth, mostly *Turbinaria* spp., and the lightening through time suggests a gradual reduction in algal cover. B3 also undergoes a (barely noticeable) lightening through time in the true-colour composites; in the classified images most of this area is classified as either "Deep Sand" or "Coral" from 1984 to 1992, and increasingly classified as "Shallow Sand" from 1995 to 2009. Field observations (2008) show that this area is covered by large amounts of mostly cemented coral rubble with a sparse cover of turf algae and newly settled soft and hard corals, which indicates that a previously substantial cover of live coral was killed in the not-so-recent past, leaving the area open to slow recolonization.

4.3. Assessment of long-term trends around Chumbe Island

True-colour composites and classified images for Bawe Island are presented in Figs. 5 and 6, respectively.

Seven of the most noticeable areas of change around Chumbe have been marked with red circles in both figures. The areas C1 and C2 show very similar patterns of consistent dark areas which almost completely disappear in the period between (February) 2001 and (November) 2002, followed by a period of recovery which remains incomplete by 2009. These dark patches are classified as "Seagrass" (occasionally as "Coral" or "Land") until 2001; then the areas are classified largely as "Shallow Sand" from 2002 onwards, with the recovering dark patches classified as "Seagrass" or "Coral". Field observations (2007) reveal that these areas are indeed covered by seagrasses, mostly *Thalassia hemprichii* and *Cymodocea rotundata*, with no signs of previously existing corals. C6 follows the patterns of C1 and C2, except that it darkens in the period from 1990 to 1995 instead of being consistently dark until 2001. This gradual darkening from 1990 to 1995 is not registered in the classified images although the darkening after 2002 is, mostly classified as "Seagrass" but occasionally as "Coral" (e.g. 2009). Field observations (2007) show that this area is currently a mix of sand and several species of seagrasses, mostly *Thalassia hemprichii*. The areas C3, C5 and C7 are consistently dark from 1984 and until the period between 2001 and 2002, but do not show consistent signs of subsequent recovery in the true-colour images. These areas are classified as a mix of "Seagrass" and "Coral" until 2001, a mix of "Seagrass" and "Shallow Sand" from 2002 to 2008, and finally as a mix of "Coral" and "Shallow Sand" in 2009. Field observations (2007) show unvegetated sand substrate at C3, and a sparse cover of seagrasses, mostly *Thalassia hemprichii*, at C5 and C7. Area C4 shows dark areas that disappear between 2001 and 2002, but a smaller and more isolated dark area is then re-established from 2005 to 2009. Both these changes are registered in the classified images as a shift from a mix of "Seagrass" and "Coral" to "Deep Sand" between 2001 and 2002, and a return to the "Seagrass"/"Coral" mix from 2005 to 2009. Field observations (2007) show this area to be a dense seagrass meadow dominated by *Cymodocea serrulata* and *Syringodium isoetifolium*.

4.4. Classification accuracy

Due to noise and clouds of variable thickness in the images, the classification accuracies obtained in our study are highly variable. Classifications of tropical nearshore environments typically reach accuracies of 70% when using a scheme similar to ours (Mumby et al., 1997a), which corresponds well with the highest accuracy obtained in our study (69%). The majority of misclassifications not related to cloud cover occur between the "Seagrass" and "Coral" classes around Chumbe Island, as seen for the areas C1 and C2 where field observations indicate that little or no coral exists.

5. Discussion

What changes in the nearshore environment were identifiable in the Landsat imagery, and was there a significant difference between the quick and simple use of true-colour composites, and the more time-consuming use of supervised classifications?

The shifting spatial extent of seagrass meadows seen around Chumbe Island was easily identified in the true-colour composites, and also seen in the supervised classifications, although somewhat confused by misclassifications between "Seagrass" and "Coral".

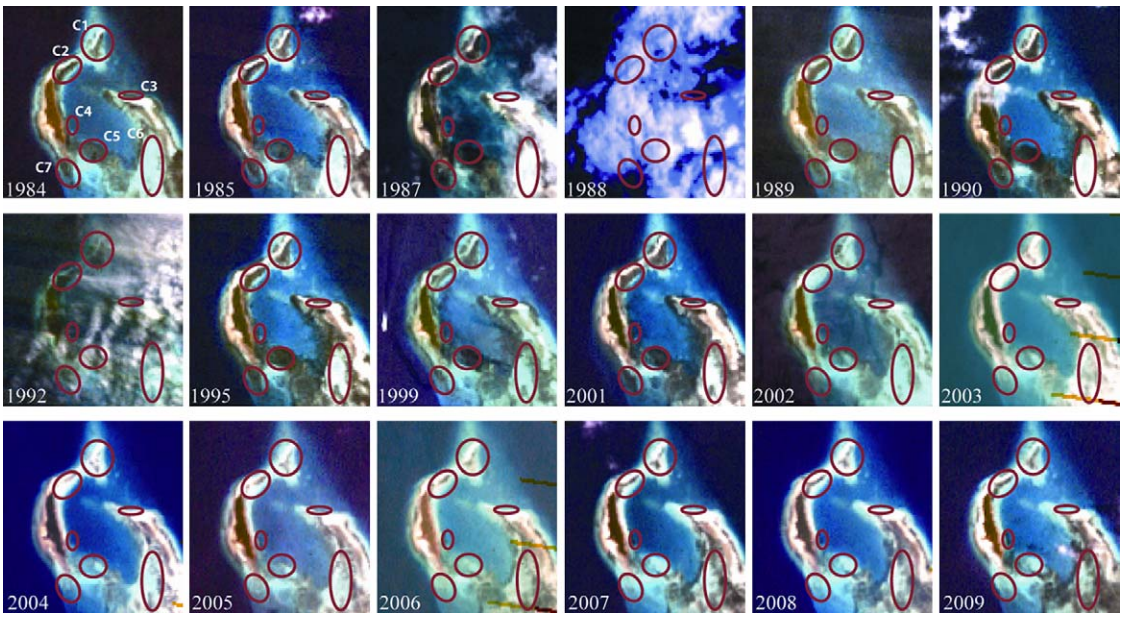


Fig. 5. 18 true-colour composites of Chumbe Island and the surrounding area, illustrating changes from 1984 to 2009.

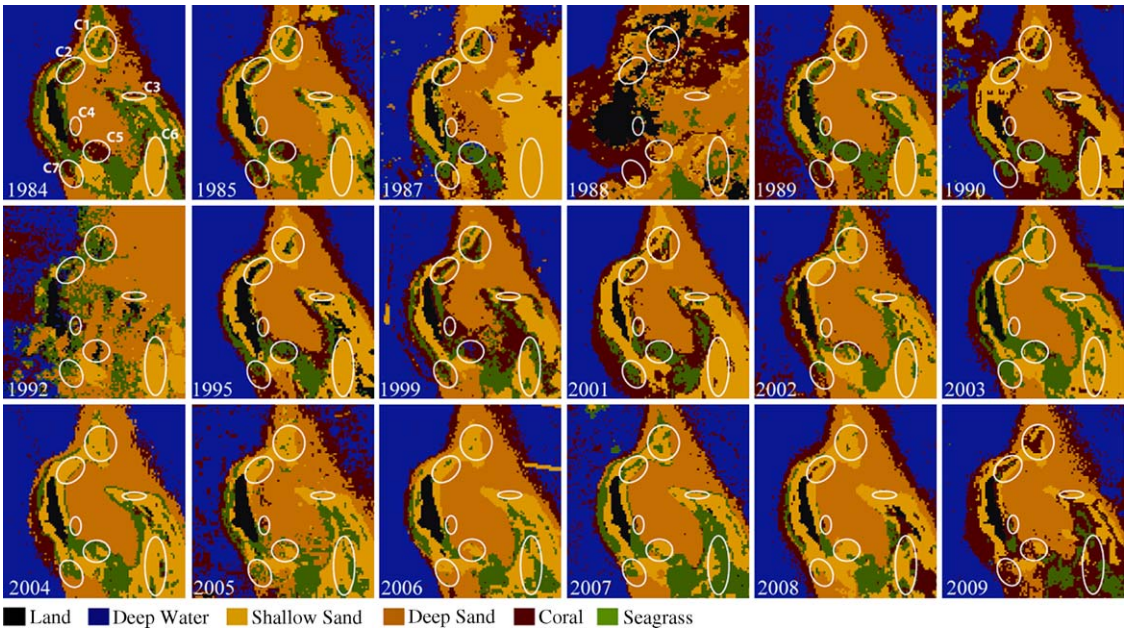


Fig. 6. Supervised classifications of Chumbe Island.

However, the two approaches portray the changes differently. The recovery of the seagrass meadows after 2002 is shown in the true-colour composites as a gradual increase in density, seen as a darkening of the recovering seagrass patches, in addition to the areal extension of the meadows. The same recovery is seen in the classified images exclusively as an increasing number of pixels classified as "Seagrass" (or misclassified as "Coral" in 2009). The shifting spatial extent of seagrass meadows is easily identified because of the strong contrast in spectral reflectance between the sandy substrate when it is bare and when it is covered by seagrasses (Hochberg et al., 2003). Casual observations made throughout the period from 1994 to 2009 by the head ranger (O. Nyange) stationed on Chumbe Island indicate that the sudden decline of seagrasses from 2001 to 2002 was caused by an unusually powerful northerly storm in late 2001, which deposited a large amount of sand in the area, burying many of the existing seagrass meadows (O. Nyange, personal communication). The subsequent recovery indicated by the true-colour composites in several of the highlighted areas is also confirmed by these field observations.

The changes in algal cover around Bawe Island, in B1 and B2, are less noticeable than the shifting seagrass meadows. As opposed to the juxtaposition of seagrass or bare sand covering an area around Chumbe Island, changes in the algae-dominated areas around Bawe are a change in density – a "more-or-less" rather than an "all-or-nothing" distinction. The limestone substrates on which the *Turbinaria* spp. algae grow are covered by a small amount of turf algae most of the year, and long-term trends in algal density are also masked by seasonal variations in algae growth, stronger than the seasonal variations in seagrass growth (A. Knudby, personal

observation). Whether a change in algal cover is registered in the classified images is therefore a question of the magnitude of the change, as well as the reflectance of the underlying substrate. This suggests that visual inspection of the true-colour composites enables identification of smaller changes than does the use of supervised classification, as in the case of area B1. No historic field observations are available to indicate a cause for the changes in algal density around Bawe Island, although a dramatic increase in populations of the long spined sea urchin *Diadema setosum*, seen around both islands, is likely to increase herbivory and decrease algal cover (McClanahan et al., 2009).

The shift from dominance of live coral to rubble with a sparse cover of algae and hard and soft corals at B3 is barely noticeable in the true-colour composites, but registered in the classified images, although partly obscured by frequent misclassification between "Coral" and "Deep Sand" until 1995. The detection of this change is complicated by the similarity of the spectral signatures of corals and algae shown by extensive field studies (Hochberg et al., 2003), which causes these two classes to be the least accurately mapped in most remote sensing-based studies of tropical nearshore environments (Mumby et al., 1997a; Andréfouët et al., 2003). In the B3 area, change detection is further complicated by the depth of the area (8 m), but eased by the limited re-settlement of algae and corals that has taken place on the rubble.

Changes from coral-dominance to a mixed cover of turf and erect macroalgae and recently settled soft and hard corals is typical of phase shifts on coral reefs (Hughes, 1994). Given that these phase shifts, and the global decline in coral cover that accompany them (Bruno and Selig, 2007; Gardner et al., 2003) present one of the greatest threats to reef sustainability, the limited ability to identify such changes from Landsat imagery is unfortunate. It is therefore important to consider if more advanced processing of time series of Landsat images can produce better results. Other researchers, working in different environments, have indeed produced convincing results with supervised classification of Landsat imagery. Working on Carysfort Reef in Florida, Dustan et al. (2001) used a measure of gradual textural homogenization to identify an ecological shift from dominance by the coral *Acropora palmata* to fragmentation of this coral and subsequent overgrowth by turf algae. However, the shallowness of the area (<1.2 m) and the massive change in question – a 95% relative decrease in coral cover over 26 years (Dustan and Halas, 1987; Palandro et al., 2003), made this a best-case scenario for change detection by remote sensing. Palandro et al. (2003) identified the same coral decline around Carysfort Reef using five Landsat images spanning the period from 1984 to 2000. They corrected images for sensor noise and atmospheric effects and compared them following a supervised classification, showing a dramatic decline in the spatial extent of the "coral" class (defined as >50% coral cover). However, they also showed that these dramatic changes were easily identifiable in the true-colour composites, which questions the necessity of using supervised classification. Furthermore, the processing used by Palandro et al. (2003) requires both a sophisticated noise-reduction correction, as well as an atmospheric correction algorithm that, when applied to images acquired before 1997, depends on meteorological data typically not available in developing countries. Compared to the 95% decline in coral cover seen on Carysfort Reef and other similar declines experienced elsewhere in the Florida Keys (Palandro et al., 2008), very modest changes in coral cover have been observed on the reefs around Chumbe and Bawe islands. Coral cover on Chumbe's western reef has changed from 47.5% in 1994 to 34.0% in 2000, and again to 52.0% in 2005, a 9% increase over 11 years; the corresponding numbers from Bawe's northern reef are 57% in 1992, 54% in 2000, and 43% in 2005, a 25% decrease (Muhando, unpublished data). Complicating change detection further, these two reefs are deeper that those at Carysfort Reef, with coral cover extending from the surface to approximately 12 m (A. Knudby, personal observation). Despite the known location of the monitoring sites, these more subtle changes in coral cover are not identifiable in the Landsat imagery, and based on the subtle spectral differences between corals and algae (Hochberg et al., 2003), and the known difficulty of applying spectral unmixing in the marine environment (Kutser et al., 2006; Hedley et al., 2004; Mumby et al., 2004), we find it unlikely that any amount of processing of Landsat imagery would reveal them.

Our results demonstrate that the combination of historic Landsat imagery and recent field data can yield information about historic changes in nearshore environments, and is better suited for detection of changes in the spatial extent of seagrass meadows than changes in algal and coral cover. This is supported by other studies, which have successfully used Landsat images to map both spatial extent (Ferguson et al., 1993; Wabnitz et al., 2008), percentage cover (Gullström et al., 2006), and aboveground biomass (Mumby et al., 1997b) of seagrasses. Changes in seagrass meadows are different from those in coral- or algae-dominated areas, in that they are primarily spatial – the seagrasses colonize adjacent sandy areas by extension of their rhizomes, or shifting sands overwhelm and bury nearby seagrass areas. This is qualitatively different from changes in coral- or algae-dominated areas, which mostly consist of re-settlement of spectrally similar new organisms soon after local mortality has freed up space on existing hard substrate. In addition, our results suggest that a quick and simple visual inspection of a series of true-colour composites is as effective for change detection as the use of supervised classification, especially for detection of changes in density/cover.

The changes in seagrass meadows around Chumbe Island are important to note in Zanzibar today, in a region where seagrass meadows are believed to be under threat from increasing populations of sea urchins and overexploitation by humans (Bandeira and Björk, 2001). The sudden reduction in the extent of seagrass meadows around Chumbe Island at the end of 2001 (proximally caused by a severe storm), followed by a gradual recovery in some areas, suggests that seagrass meadows in at least part of the area are resilient to sudden impacts, and that specific conservation measures for seagrass meadows may not be needed at this point in time. The changes in algal cover around Bawe Island are both less extensive and less consistent in comparison. Although these areas may serve as useful field sites where studies can be undertaken to establish the cause for the decline in algal cover, the observed changes cannot adequately inform management without an identified cause. Changes in coral cover are known better from field data (C. Muhando, unpublished data) than from this study, and management measures in the form of establishment of marine protected areas have already been implemented in several locations around Zanzibar (Levine, 2007).

6. Conclusion

In this study, we have outlined a simple method for investigating historic changes in a tropical nearshore environment containing coral reefs and seagrass beds, using a type of dataset typically available to researchers at minimum cost: a set of (free) historic Landsat images, and a set of recent field observations. Results indicate that changes in the spatial extent of seagrass meadows are easy to identify on true-colour composites of Landsat imagery, whereas subtle changes in algal and coral cover are less noticeable. We have shown that visual inspection of true-colour composites is simpler and produces comparable or superior results to what can be obtained through use of supervised classification. The visual inspection of true-colour composites is technically simple and can be used with freely available data, processed with

free software, and implemented by staff with a minimum of training in image processing. In Zanzibar, this simple approach has revealed some patterns of long-term seagrass dynamics around Chumbe Island, as well as some pattern of change in algal cover around Bawe Island.

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