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Analysis of cover change (1995–2005) of Tanzania/Mozambique trans-boundary mangroves using Landsat imagery

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ABSTRACT

1. Despite the ecological, environmental, and economic importance of mangroves, they are declining at an alarming rate worldwide, mostly as a result of human activities.
2. Along the eastern African coast, Mozambique has the largest mangrove area. Fishing and farming are the main economic activities in the area, and people harvest mangrove vegetation for tannins, fuel wood, traditional medicine, boat-building, carpentry, and crafting.
3. Landsat 5 TM imagery was used to map the distribution of trans-boundary mangrove areas along the Mtwara–Quirimbas Complex. Results for 1995 and 2005 are presented for the entire coastline and in more detail for the Ruvuma estuary, Quiterajo, Ibo/Quirimba islands, and Pemba Bay. Results were validated with a ground-truthing excursion in 2006, showing an overall thematic accuracy of 73%.
4. Total estimated area of mangrove was 357 km^2 in 1995 and 368 km^2 in 2005, with the small net gain of 3% corresponding to a total gain of 32 km^2 and a total loss of 21 km^2 over this decade.
5. Results suggest that although Landsat TM imagery can be effective in mapping mangrove distribution, caution must be used in inferring its ecological condition.

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KEY WORDS: remote-sensing; satellite imagery; Mnazi Bay Ruvuma Estuary Marine Park; unsupervised classification; classification accuracy

INTRODUCTION

Mangroves are important for the livelihoods of coastal communities: they protect the shoreline from extreme events such as storms and tsunamis, acting as 'bio-shields' (Carter, 1988; Dahdouh-Guebas *et al*., 2005; Giri *et al*., 2007, 2008), they filter land-based pollution (PUMPSEA, 2007) and, in developing countries, they are sources of food, medicine, fuel, and building materials (Dahdouh-Guebas, 2002; Giri *et al*., 2007). Despite their importance, mangrove forests are declining at an alarming rate worldwide, with an estimated 25% decline globally between 1980 and 2000 (FAO, 2005; Giri *et al*., 2007). In eastern Africa, the underlying root causes of mangrove degradation are associated with the population growth in the coastal areas, leading to over-exploitation of mangrove resources, conversion of mangrove areas to other land uses, poor land use practices, and diversion of fresh water flow (Abuodha and Kairo, 2001; Barbosa *et al*., 2001; Taylor *et al*., 2003; FAO, 2005; Beentje and Bandeira, 2007).

Mangrove areas in most of the countries in the region have decreased by almost 15%, with the largest losses in South Africa, Comoros, and Seychelles (FAO, 2005). In Mozambique, between 1972 and 1990, 2.6% of the total mangrove area was lost, and in Tanzania the area of mangrove forest decreased by 1.3% between 1990 and 2000 (Taylor *et al*., 2003; Wang *et al*., 2003). The present study contributes to these estimates by focusing on the coastline known as the 'Mtwara-Quirimbas Complex', along the Tanzania/Mozambique trans-boundary area. This seascape, comprising more than 350 km of coastline, is considered a site of global

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importance within the Eastern African Marine Ecoregion (EAME) (WWF, 2002).

The main objectives of the study were: (i) to map the distribution of mangrove forests throughout the study area; and (ii) to quantify the area covered and assess change over a decade (1995 to 2005). Remote sensing was used as it is a cost-effective approach for the synoptic sampling and mapping of resources of large areas over time for land planning and monitoring purposes (Mumby *et al.*, 2000; Mumby and Edwards, 2000; Dahdouh-Guebas, 2002; Thu and Populus, 2007; Giri *et al.*, 2008). Landsat Thematic Mapper (TM) imagery was chosen as it provided the best combination of spatial resolution (30 m on the ground), temporal resolution (16 days return period), availability of archive images (TM sensors have been operating on Landsat satellites since 1982), and cost with temporal resolution being an important consideration in the selection of imagery in tropical areas where cloud cover is a key constraint. Landsat TM imagery has been used by several authors in the mapping of large areas of mangrove because of its cost-effectiveness, and compares favourably with SPOT imagery (Gao, 1999; Green *et al.*, 2000; Green and Mumby, 2000; Mumby *et al.*, 2000).

METHODS

Study region

Mozambique has the largest mangrove area along the eastern African coast, totalling nearly 4000 km^2, whereas Tanzanian mangroves cover up to 2500 km^2 (Spalding *et al.*, 1997; Barbosa *et al.*, 2001; FAO, 2005; Beentje and Bandeira, 2007). Major mangrove areas include Maputo Bay, the Zambezi delta, and the Quissanga–Ibo Island stands in Mozambique, the Rufiji delta in Tanzania, and the Ruvuma Estuary on the Tanzania/Mozambique border (Semesi, 1998; Barbosa *et al.*, 2001; Beentje and Bandeira, 2007). In both countries, eight species of mangrove plants occur: *Avicennia marina*, *Ceriops tagal*, *Rhizophora mucronata*, *Bruguiera gymnorhiza*, *Lumnitzera racemosa*, *Xylocarpus granatum*, *Heritiera littoralis*, and *Sonneratia alba*. Fishing and farming are the main economic activities in the area, but people harvest mangrove vegetation for tannins, fuelwood, medicine, boat-building, carpentry, and crafting (Semesi, 1998; Barbosa *et al.*, 2001; Kairo *et al.*, 2002). The study area covers over 350 km of coastline from Mtwara Bay (Tanzania), north of the mouth of the Ruvuma estuary, and south along the Quirimbas archipelago to Pemba Bay (Mozambique).

Image analysis

Coastal habitats along the study area were mapped using Landsat 5 TM L1G radiometrically and geometrically corrected imagery (seven spectral bands with a spatial resolution of 30 m) (http://landsat.gsfc.nasa.gov/references/glossary.html♯l). In the L1G product used, band 6 (thermal band) is also provided with a 30 m resolution, after resampling of the original ground resolution of 120 m. Low cloud coverage scenes were selected for anniversary dates (April–July 1995 and April–June 2005), to minimize differences in mangrove cover due to seasonal effects (Table 1).

Ground control points (GCPs) were obtained from GPS coordinates (Magellan Explorist 100) collected during ground-truthing fieldwork and from coordinates read from Google Earth (GE). High-resolution images from GE (Digital Globe © and Terra Metrics ©) available online for the entire study area (typically orthorectified Quickbird satellite images with 0.7–2 m pixel size) allowed for a better identification of landmarks (e.g. crossroads) on Landsat images. Both GPS and GE coordinates were obtained as Lat/Lon (Datum WGS84). Georegistration onto local coordinates (UTM37S WGS84) was carried out with a first degree polynomial adjustment using ArcGIS 9.0 georeferencing tools. Subsequent image geo-correction and co-registration to known ground control points (GCPs) was applied as recommended by USGS (2006). The average root mean square (RMS) error of the resulting rectified images was kept within 15–22 m, which corresponds to the suggested threshold of about half the original pixel size (30 m for TM Landsat 5) (Eastman, 2003). Original 30 m pixel size was retained for all subsequent analyses. The rectified images were windowed to retain only the relevant working areas (Table 2). Subsequent image classification was performed using IDRISI Kilimanjaro vs 14.02, by Clark Labs, Clark University, © 1987–2004. No atmospheric corrections were applied to the images due to the relative uncertainty of the currently available algorithms (Giri *et al.*, 2007).

Since the key objective was to uncover major land cover classes present in each image without prior knowledge to what they might be, an unsupervised classification procedure based only on their spectral response uniqueness/specificity was applied (Mather, 1999; Lillesand and Kiefer, 2000). Two different classifiers available in Idrisi Kilimanjaro were tested: CLUSTER, and ISOCLUST (Eastman, 2003). To retrieve the full array of coastal habitats (terrestrial, intertidal, and subtidal) best results were achieved by applying the ISOCLUST classifier to all seven bands, including the thermal band (Leak and Venugopal, 1990; Alavi Panah and Ehsani, 2004), with five iterations. This methodology was used in every windowed image, producing 40–65 clusters per working area. All clusters were attributed to one of the following classes: water, clouds, and cloud-covered areas

Table 1. Imagery data for 1995 and 2005: Path and row of Landsat scenes, date of image acquisition, and percentage cloud cover (values in parentheses) for every working window (see Table 2 for coordinates of working windows)

Image area	Path/Row	1995	2005
Ruvuma (Tanz./Mozamb. border)	165/067	15.04.95 (0.3%)	10.04.05 (0%)
Cabo Delgado	164/067	—	06.08.04 (0%)
Quirimbas Archipelago (North)	164/068	29.07.95 (0.9%)	22.06.05 (5.3%)
Quirimbas Archipelago (South) to Pemba	164/069	29.07.95 (1.5%)	22.06.05 (1%)

Table 2. Rectified image data. Coordinates of working windows. All coordinates are UTM 37S WGS84. Average RMS = 15–22 m (equivalent to ±1 pixel in Landsat TM imagery)

Path/Row	*X*min	*Y*min	*X*max	*Y*max	COLS	ROWS
165/67	616477	8776025	676507	8879705	2001	3456
164/67	662842	8803414	685260	8842514	747	1303
164/68	636360	8639270	691350	8829500	1833	6341
164/69	641195	8545080	681125	8659560	1331	3816

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(where no terrain information was available), intertidal flats, seagrass beds, terrestrial habitats (roughly 1/2 to 2/3 of the total number of clusters produced by the classification), and mangroves. The distinction between potentially confusing areas of mangrove and terrestrial vegetation, including ecotone areas, and the discrimination of patches of terrestrial vegetation within areas of mangrove forest was made on the basis of visual interpretation of the imagery available from GE from ground-truthing information, and, when the latter was unavailable, from the expertise of researchers familiar with the study area. The final maps of the total area of mangrove for each year were produced through masking of all the non-mangrove classes and creating a mosaic of the individual working windows.

There is no single best method to analyse change detection, since each method has advantages and disadvantages and methodologies should be adapted to the characteristics of the specific study (Civco *et al*., 2002; Seto *et al*., 2002). To detect and assess change in mangrove cover, a post-classification change analysis technique was used. A map of change was produced by subtracting the 2005 map from the 1995 map, resulting in the mapping of areas of loss (areas of mangrove

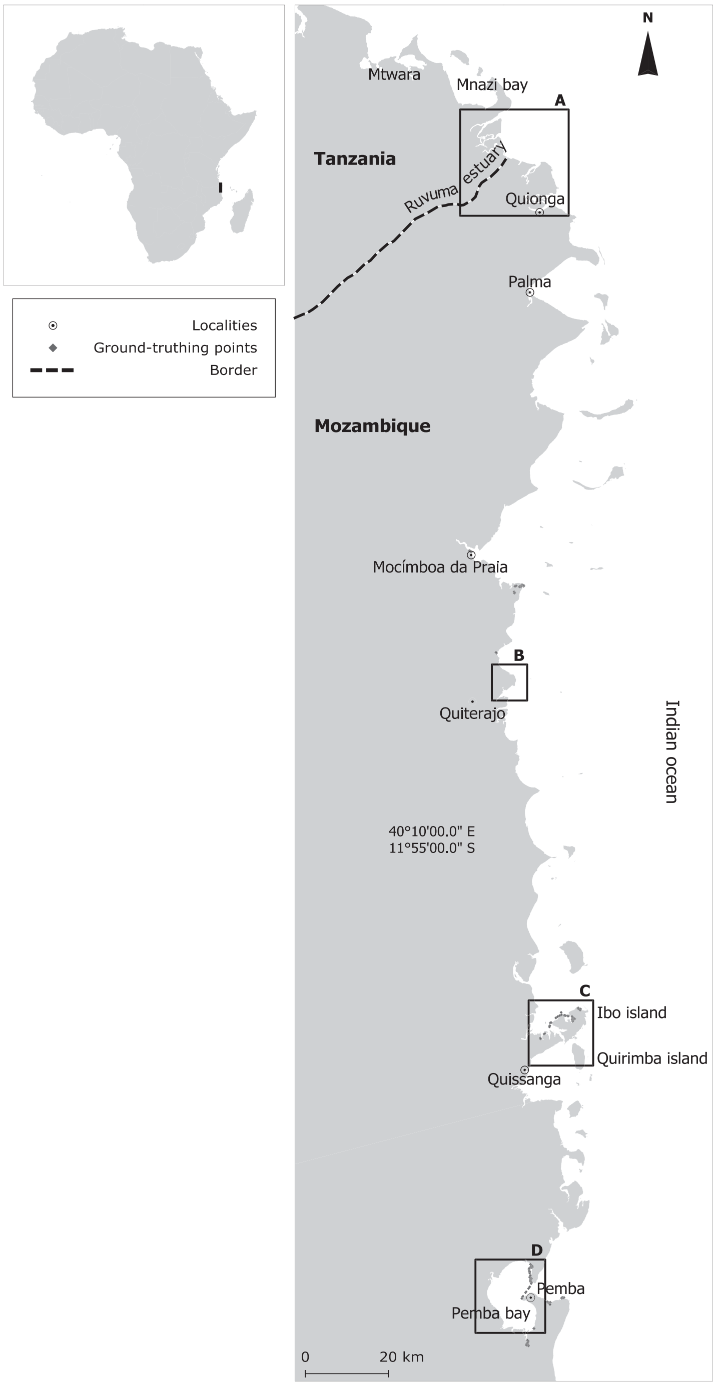

Figure 1. Location of the study area on the African coast. Distribution of ground-control points throughout the study area.

appearing only in the 1995 map), gain (2005 only) and constant (common) areas. An index of relative change was also calculated as (loss+gain)/(loss+gain+common), according to Frederiksen *et al.* (2004), where 0 would correspond to no change, and 1 to a complete shift of the habitat being evaluated.

This change detection approach may suffer from three sources of uncertainty (Giri *et al.*, 2007): (i) semantic differences in class definitions between maps; (ii) positional errors; and (iii) classification uncertainty. To minimize (i) the same number of classes was used for both dates; to minimize (ii) the contours of mangrove areas were vectorized and re-rasterized onto blank images (blank matrices) with exactly the same corner coordinates, which allowed for a further reduction of the positional error; classification uncertainty can only be dealt with through field gauging of the results, which was only available for the present (2005) situation.

Ground-truthing and accuracy assessment

Two ground-truthing field excursions were undertaken to specific locations within the study area: Ulo, Mocimboa, Luchete, and Ibo–Tandanhangue in July 2006, and the area in and around Pemba Bay in September 2006. A hand-held GPS (Magellan, Explorist 100) was used, with a reported accuracy of 3–30 m, depending on the available satellite constellation and on the presence of physical obstacles such as land relief or tall vegetation. For each location, a descriptive and photographic record was made. A total of 90 ground-control points (GCPs) were taken throughout the visited area (Figure 1), 30 of which in areas of mangrove.

Field data on the distribution of major habitats was used to produce an error (or confusion) matrix of classification or thematic accuracy, i.e. the correspondence between the class label and the 'true' class on the ground. This confusion matrix allows for the estimation of user accuracy (the probability that a pixel classified on the image actually represents that category *in situ*) and producer accuracy (the probability that any pixel in that category has been correctly classified) (Mumby and Green, 2000). Overall accuracy (the proportion of pixels correctly classified), and the Tau coefficient were calculated according to Mumby and Green (2000), and the Kappa coefficient was calculated according to Mather (1999).

RESULTS AND DISCUSSION

Mangrove forests occur along most of the coastline, but are mainly concentrated around the mouth of the Ruvuma estuary, in the Quiterajo area, and from north of Ibo island to Pemba Bay (Figure 2). Total estimated area of mangrove was 357 km^2 in 1995 and 368 km^2 in 2005, with an estimated overall increase of about 3%. A total of 21 km^2 of mangrove were lost during the 1995 to 2005 decade, whereas 32 km^2 were gained, and 336 km^2 remained unchanged, which translates into a relative change of 0.14 (Frederiksen *et al.*, 2004) (Table 3; Figure 3). It is important to note that georeferencing errors were not completely removed despite the additional geo-correction efforts undertaken to minimize them. Residual location errors below pixel dimension that cannot be corrected for (Coppin and Bauer, 1994), generate artefacts or false alarms (Giri *et al.*, 2007), visible in the maps of change, mostly

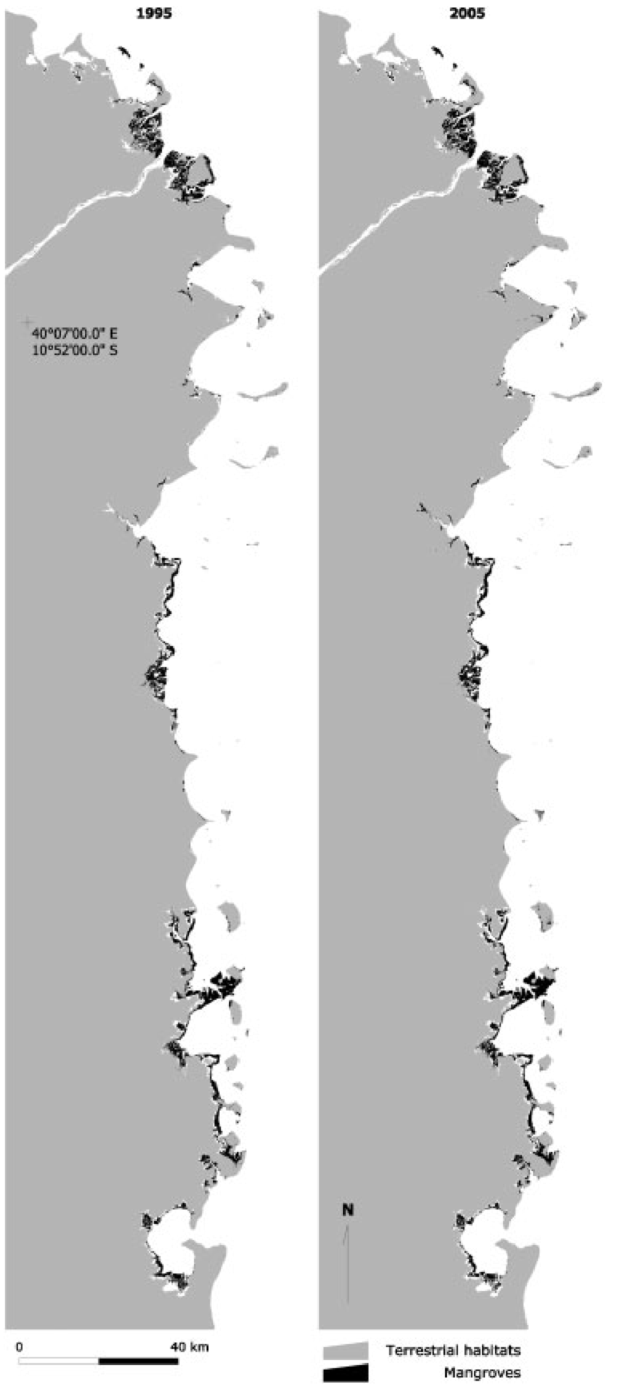

Figure 2. Mangrove distribution in the study area in 1995 and 2005 (UTM 37S coordinates).

Table 3. Estimated coverage of mangrove forest for the whole study area and for the detail areas considered (areas in km^2). Values refer to the comparison between 1995 and 2005. C: constant area; L: area lost; G: area gained; I: Index of relative change

Location	C	L	G	I
Total area	336	21	32	0.14
Ruvuma	95	3	8	0.10
Quiterajo (detail)	6	0	1	0.14
Ibo/Quirimba Islands	43	1	2	0.07
Pemba Bay	27	2	1	0.10

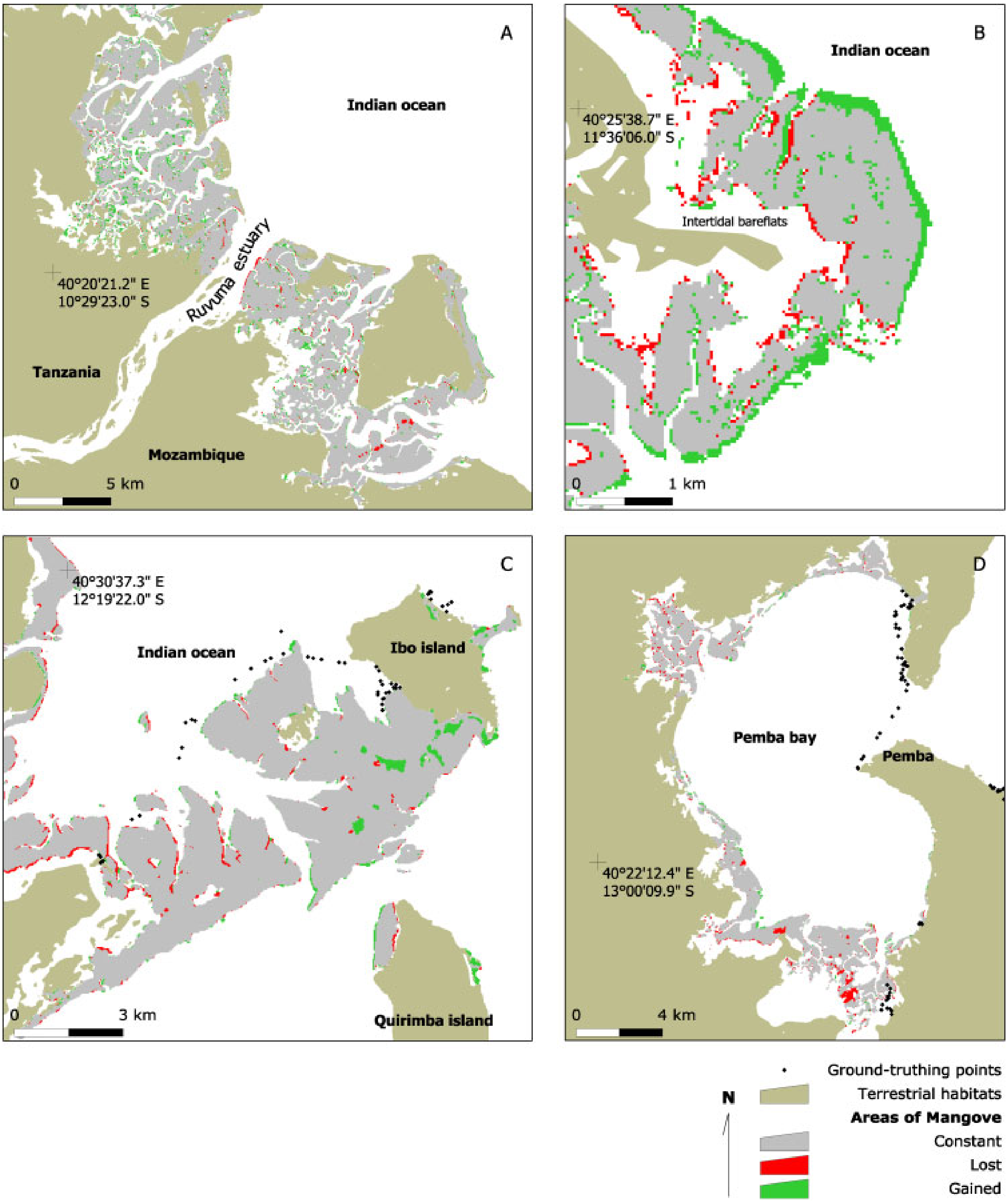

Figure 3. Detailed maps of mangrove change. A: Mangrove areas around the mouth of the Ruvuma estuary (Tanzania/Mozambique border). B: Small area of mangrove close to Quiterajo. C: Mangrove areas of the Ibo/Quirimba islands. D. Mangrove areas around Pemba Bay. (UTM 37S coordinates.)

along parallel running channels or shores, with areas of systematic loss on one bank and areas of gain on the other, and are a limitation of any change detection methodology based on digital imagery (Coppin and Bauer, 1994). This inevitably affects the values of the estimated lost and gained areas and, consequently, the index of relative change.

In the areas of the Ruvuma, Quiterajo, and Ibo (Figure 3A, B and C) there was a net gain of mangrove forest. The increase along the Quiterajo coast also shows an effective increase of the mangrove area (Figure 3C), probably as a result of sediment accretion and subsequent colonization by mangrove vegetation (Blasco *et al.*, 1996). Around Pemba Bay, the results suggest a net loss of mangrove forest (although residual), which is consistent with the construction of some aquaculture ponds and urbanization around Pemba city (Figure 3D).

Table 4. Estimation of thematic or classification accuracy: error or confusion matrix for the mangrove map of 2005

	Reference data					
	Mangrove	Intertidal	Seagrass	Terrestrial	Row total	User accuracy
Classification data						
Mangrove	17		2		19	0.89
Intertidal	7	35	9		51	0.69
Seagrass			9		9	1.00
Terrestrial	6			5	11	0.45
Column total	30	35	20	5	90	
Producer accuracy	0.57	1	0.45	1	90	

Accuracy assessment

Of the 30 mangrove sites, 17 were correctly classified as mangrove and 13 as other habitats (Table 4). The calculated producer accuracy (the probability that any pixel in that category has been correctly classified) is thus 57%. Conversely, the omission error for mangrove is 43%. Of the 19 sites that were classified as mangrove, 17 were actually mangrove. Extrapolating to the entire area, the probability of a pixel labelled as mangrove corresponding to mangrove *in situ* is 89% (estimated user accuracy for mangrove). The Kappa coefficient was 0.61, and the Tau coefficient, considered by some authors as the most meaningful, was 0.63 meaning that the classification process correctly classified, respectively, 61% and 63% pixels more than a completely random process would. Overall classification accuracy was 73%, which is similar to the ~75% overall accuracy found by Green and Mumby (2000) for mangrove discrimination through unsupervised classifications of Landsat TM imagery.

Low producer accuracy was probably a result of the small number of GCPs in mangrove areas, and of their distribution. The location of major areas of mangrove forest was confirmed by visual interpretation of the base satellite imagery and of high resolution satellite imagery available in Google Earth, and by confirmation from researchers familiar with the study site. Ecotones of the mangrove, where most of the GCPs used were taken, are the areas of highest classification uncertainty for a number of factors:

- Each Landsat TM pixel corresponds to a terrain area of 900 m^2 (30 m × 30 m), and in transition areas, the presence of different ground units or mixed habitats, may reduce the field observer's capacity to accurately describe ground cover.
- Areas with low densities of mangrove plants, or patchy landscapes, will yield a mixed signature (mixels) that will probably translate, correctly, as non-mangrove, even though the observer noted the area as mangrove.
- Errors, both in the geometric correction of the images and in GPS positioning may result in some correctly classified mangrove pixels being mapped to locations that *in situ* observation classifies as other habitats.

Building a link between mangrove cover change and mangrove condition

Based on the results of this study, the area of mangrove along the Mtwara–Quirimbas Complex appears to be relatively stable, with an estimated overall increase of about 3% in mangrove cover between 1995 and 2005. However, this may be an incomplete depiction of reality as Bandeira *et al.* (2009) found that all the sites showed varying degrees of disturbance due to cutting for construction and fuel.

Mangrove cutting does not necessarily lead to loss in cover but, most importantly, to a change in forest structure. Observations in Kenya, have found that disturbed areas have lower stand density, basal area, and complexity when compared with undegraded stands (Kairo *et al.*, 2002). Studies in Tanzania (Semesi, 1998) and Madagascar (Radhika, 2006) have shown that disturbed stands initially occupied by *Rhizophora* were recolonized by *Ceriops* species after cutting. Consequently, areas identified as having similar coverage can have qualitative and quantitative differences in land-cover changes. Both can occur as a result of natural phenomena and human activities: qualitative human-induced changes in landscapes include selective logging, whereas quantitative land-cover change occurs mostly as a result of forest clearing and agricultural and urban expansion (Seto *et al.*, 2002). Our findings and those of Bandeira *et al.* (2009) show that the selective cutting and logging may not be detectable with the 30 m sensor resolution.

It is suggested that although Landsat TM imagery can be effectively used to map the extent of the mangrove forest and to detect quantitative land-cover changes, such as the clearing of areas for the construction of saltpans or aquacultures, caution must be used in the inference of mangrove condition (Giri *et al.*, 2007). Thus, the rate of actual mangrove loss for Mozambique and neighbouring countries estimated from remote sensing at a similar resolution (e.g. FAO, 2005) might be underestimated. Promising results were obtained for limited stretches of the East African coast using mangrove distribution and condition analysis based on higher resolution imagery (Neukermans, 2004; PUMPSEA, 2007). Results suggest the need for complementary studies between higher resolution remote sensing and field-based assessment of mangrove condition.

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