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Mapping of mangrove forest land cover change along the Kenya coastline using Landsat imagery

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ABSTRACT

Mangroves in Kenya provide a wide range of valuable services to coastal communities despite their relatively small total area. Studies at single sites show reductions in extent and quality caused by extraction for fuel wood and timber and clearance for alternative land use including saltpans, aquaculture, and tourism. Such studies suggest that Kenyan mangroves are likely to conform to the general global trend of declining area but there are no reliable recent estimates of either total mangrove extent or trends in coverage for the country. The total extent of Kenyan mangroves was estimated at four points in time (1985, 1992, 2000 and 2010) using Landsat satellite imagery. Due to its medium resolution, Landsat may underestimate mangrove areas in Kenya where relatively small, linear, coastal features occur. There is also a high frequency of clouds in the coastal areas which can cause data gaps during analysis. However comparison with aerial photographs taken in 1992 showed satisfactory levels of accuracy (87.5%) and Cohen's Kappa (0.54) validating its use in this context. These 1992 data provided an independently validated baseline from which to detect changes (fore- and hind-casted) in other periods after removing cloud coverage. We estimated total mangrove coverage in 2010 at 45,590 ha representing a loss of 18% (0.7% yr^{-1}) in the 25 years between 1985 and 2010. Rates of mangrove loss for Kenya varied both spatially and temporally with variations possibly due to legislative inadequacies and differences in habitat alteration patterns. Hence freely available Landsat images proved adequate to detect changes in mangroves and revealed that Kenya shows rates of decline similar to (although slower than) global estimates.

1. Introduction

Mangroves are dominant along many tropical and sub-tropical coastlines and are one of the most productive ecosystems on earth with a mean production of 8.8 t C/ha/yr (Jennerjahn and Ittekkot, 2002). They provide a wide range of ecosystem goods (including fuel wood, medicine, food, construction materials) and services (including fisheries nursery grounds, sediment trapping and sewage phytoremediation) of immense value to local, national and global communities (Barbier et al., 2008). Their ability to sequester and store carbon makes them important candidates for conservation efforts under schemes such as Reduced Emissions from Deforestation and Degradation (REDD+) (Donato et al., 2011). Despite this importance, these unique coastal forests are among the most threatened habitats in the world (FAO, 2007). Their estimated global coverage is 137,760 km^2 (Giri et al., 2010) which represents a decline of 23% in area compared with 1990 (Spalding et al., 1997).

Local communities living adjacent to mangrove ecosystems have traditionally collected fuel wood, fish and other natural resources from them at rates that were sustainable (Dahdouh-Guebas et al., 2000). However, in recent decades many coastal areas have come under intense pressure from rapid urban and industrial development, compounded by a lack of effective governance and/or power among responsible government institutions. Mangroves have been overexploited or converted to various other forms of land use, including agriculture, aquaculture, salt ponds, urban and industrial development and coastal roads and embankments. Analyses of the true economic value of mangroves indicate that their destruction for short term profit is usually economically irrational; in fact, the discrepancy between their value as intact systems and their value after destruction is one of the greatest for all habitats (Balmford et al., 2004). Given this market failure and the

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threats to this ecosystem it is crucial to accurately determine the current extent, rates of change and distribution of mangroves to allow effective conservation planning and management (Fatoyinbo et al., 2008).

In Kenya mangroves are found along the 536 km coastline which extends over 3° latitude from 1°42′ south to 4°40′ south (Fig. 1). Mangroves are common features in protected bays, creeks, estuaries, and river deltas spread all along the Kenya coast. Two communities of mangroves (fringe and creek) formations occur along the Kenya coast. The largest formations occur in the north coast around the Lamu area and at the River Tana delta, (Ferguson, 1993; Kairo et al., 2001). Nine species of mangroves are found in Kenya with *Rhizophora mucronata* and *Avicennia marina* being the dominant species (Abuodha and Kairo, 2001). The responsibility for the management of mangrove forests is entrusted to the Kenya Forest Service (Abuodha and Kairo, 2001). A commonly quoted estimate of

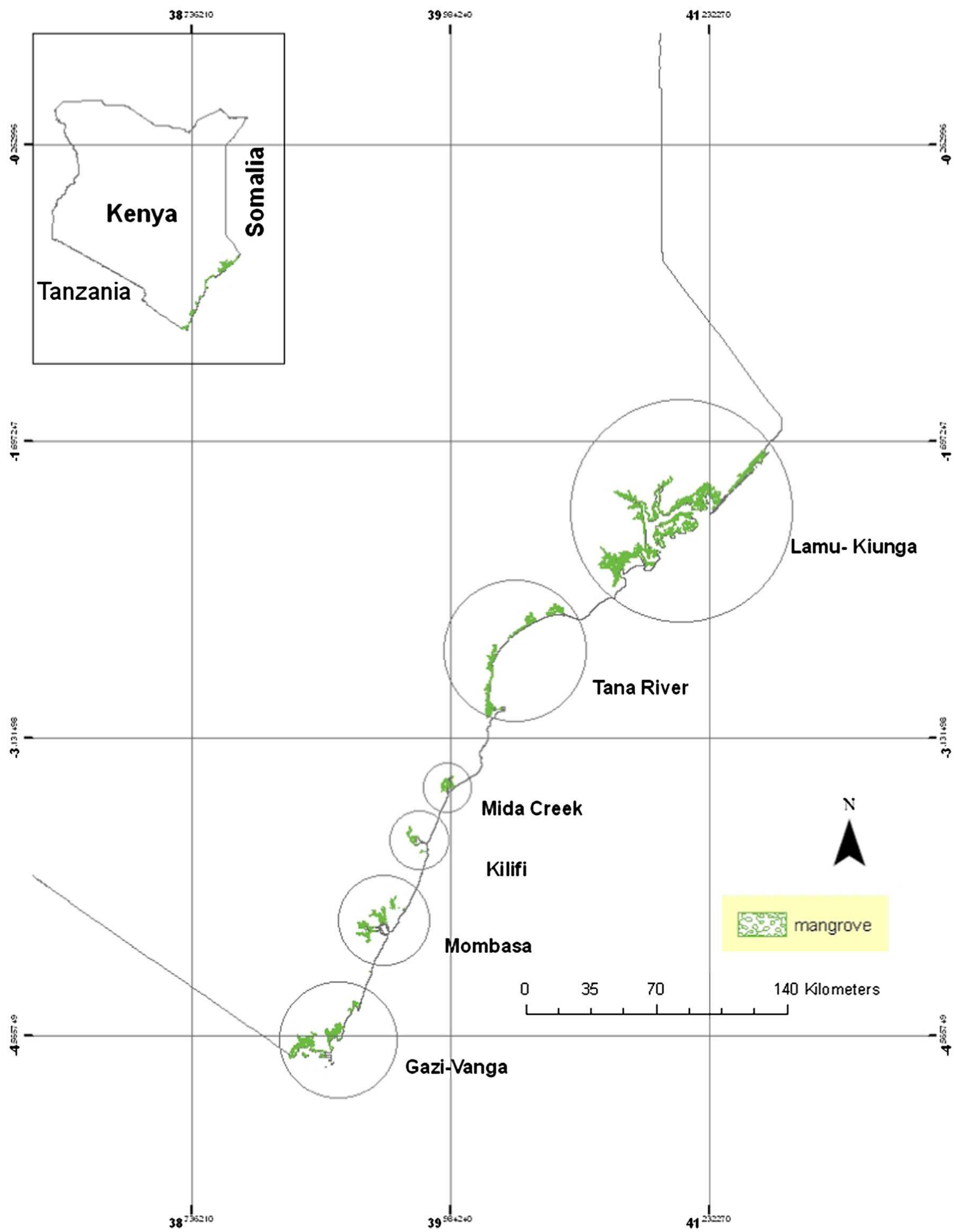

Fig. 1. The coastal area of Kenya showing major mangrove areas.

mangrove area in Kenya is 52,000 ha, a figure dating from 1981 (Doute et al., 1981). Subsequent estimates vary greatly and the methods used to derive them are not always clear (see reviews in FAO, 2003, 2007). A recent global estimate of mangrove coverage by Giri et al. (2010) was 12.3% lower than the estimates by Food and Agriculture Organization (FAO, 2007), implying large potential errors in previous estimates for individual countries especially those with relatively small total areas or where change has been rapid. There is thus a need for up to date estimates of mangrove coverage in the country, based on clear methodology, which could allow the assessment of current forest status and changes over time.

Remote sensing has been used to map coastal habitats and is often a reliable alternative to ground-survey methods of mapping, particularly in remote or inaccessible regions. Remote sensing applications have been applied to mangroves for inventory and mapping, change detection, and for management purposes. Landsat and SPOT XS data, as well as high spatial resolution airborne multispectral and SIR-C radar data were recently applied in mangrove management in Mozambique and Tanzania (Fatoyinbo et al., 2008; Ferreira et al., 2009). In Kenya remote sensing has been applied in a number of studies on mangrove status (Doute et al., 1981; Gang and Agatsiva, 1992; Dahdouh-Guebas et al., 2004a), species assemblages (Neukermans et al., 2008) and impacts of human disturbance (Dahdouh-Guebas et al., 2004b; Obade et al., 2004). However, only Doute et al. (1981) provided an overview of mangrove coverage for the country as a whole; the other studies were concerned with the exploration of high resolution imagery at local spatial extents.

The high costs of much commercially available high resolution satellite imagery preclude its routine use in many developing countries. The present study employed Landsat Thematic Mapper (TM) imagery because the free availability of archived images makes the development of capacity and techniques in its use with mangroves potentially transferable to projects without substantial funding. Landsat spatial (30 m on the ground) and temporal (16 days return period) resolution is less than for many recent commercial alternatives; this might cause particular problems in habitats that are fragmented or linear, such as mangroves. In addition extensive cloud cover (which is particularly common in coastal areas) reduces the accuracy and usefulness of the images. Although Landsat has limitations that might cause underestimation of mangrove areas, historical data goes back more than 30 years which makes it ideal for change estimates. Landsat has been used by several authors in the large scale mapping of mangrove (e.g. Liu et al., 2008; Giri et al., 2008, 2010). One objective of the current work was to explore the usefulness of Landsat to mapping mangroves in Kenya; where the coverage is relatively small and fragmented and where cloud cover is common along the coast. The existence of contemporaneous high resolution aerial images unaffected by clouds allowed the validation of the Landsat image classifications in Kenya. Other key objectives, having tested the feasibility of using Landsat images, were to establish the total current coverage in the country and to detect any changes over the last 25 years. Revised data on extent and conditions of mangrove forests in Kenya could provide critical information needed for policy-making and resource management.

2. Data and methodology

2.1. Study region

The Kenyan Coast is situated immediately south of the equator; it covers a distance of 536 km (Fig. 1) stretching from Ishakani at the Kenya-Somali boarder in the North to Vanga at the Kenya-Tanzania boarder in the South (UNEP, 1998). Its notable feature is a well developed fringing reef system running parallel to the coastline except where major rivers (the Tana and the Athi Sabaki) discharge into the Indian Ocean (Hamilton and Brakel, 1984). Other features of the Kenyan coast include mangrove forests (Fig. 1), rocky shores and sea grass meadows as well as a number of islands to the south. Approximately three million people inhabit the Kenyan coastal areas, and the rapidly growing population exerts pressures on most of the natural environments (Government of Kenya, 2009).

2.2. Data

Landsat images covering the entire Kenyan coastline were acquired from the US Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS) website (www.glovis.usgs.gov). Data collected within the same year and seasons are best for this kind of study. However simultaneous cloud-free images of the whole region were not available for all time periods, prompting the need to combine data taken from images spanning up to two years into four separate periods for use in tracking change: a) the '1985' imagery (including images from 1984 to 1985), b) the '1992' imagery (including images from 1990 to 1992), c) the 2000 imagery (including images from 2000 to 2002), and d) the '2010' imagery (including images from 2008 to 2010). A total of 5 images were required to cover the entire coastline of Kenya. Three bands were used (bands 3, 4 and 5) which are in the red, near-infrared and middle-infrared regions. Other bands were not used to avoid introduction of atmospheric artefacts that could cause classification errors (Buchanan et al., 2008).

Medium scale (1:25,000) black and white panchromatic aerial photographs taken in 1992 exist for the entire Kenyan coastline. The images are available at the Marine Data Center of the Kenya Marine and Fisheries Research Institute, Mombasa and provide a very accurate, cloud free estimate of coverage of mangrove areas along the whole coast. In the present study, a GIS layer derived from the aerial photographs was used as reference data for the assessment of the Landsat classification from the 1992 period; because of the high accuracy of the distributional data they provided a 'ground-truthing' image for the whole coastline at this point in time.

2.3. Image analysis

All images were processed from digital number values to at-satellite reflectance to make them comparable, using the correction procedures detailed in Chander et al. (2009). Individual images were mosaicked and then initially clipped to a 10 km buffer area around the coast, to reduce the area of image to be classified. Based on previous studies it is highly unlikely that mangroves would be present further away from the coast (Long and Skewes, 1996).

Image classification was undertaken using an unsupervised maximum likelihood classification algorithm. As only a narrow strip of coastal land was being classified, the number of classes specified was kept relatively low. Alternative classifications using between 10 and 20 classes were undertaken. Classifications with greater than 20 classes defined failed to converge to a stable classification. Changes in the number of classes had little effect on the identification of mangrove areas, so the results from a classification using 12 classes were used in all years. Following initial classification of images, areas classified as cloud cover or cloud shadow were identified based on examination of color composite images of the area. These areas were removed from the initial unclassified image, and replaced with cloud free areas from other images gathered within the same time period to generate images for analysis with the minimum cloud cover.

Analysis of the minimum cloud cover images used the same maximum likelihood technique, with 12 classes. Some areas far from the coast, which were unlikely to be mangroves, were also classified in the same class as more obvious mangrove areas. As mangroves are only found in low-lying coastal areas (FAO, 1994; Long and Skewes, 1996) a height-based filter was used to remove these mis-classified areas. Elevation data were obtained from the global Digital Terrain Model (DTM) derived from the Shuttle Radio Topography Mission (SRTM). SRTM data are influenced by the height of vegetation overlying the land surface, due to radar scattering in the vegetation canopy, and this effect has been used to estimate vegetation heights e.g. Simard et al. (2006). The absolute vertical error of SRTM data has been estimated as 16 m, although it is likely to be less in the area under consideration (Rodriguez et al., 2005). For the current application areas with an elevation of $\leq$8 m above sea level were defined as areas that would contain mangroves. This zone was found to contain 95% of the areas classified as mangrove in the 1992 aerial data, as was therefore deemed appropriate for use.

The minimum mapping unit for mangrove classification was chosen to be 0.18 ha. This was based on the distribution of mangrove areas found in the 1992 aerial-photograph data. Therefore any areas classified as mangroves, but smaller than this, were removed from the image, provided that they were not coincident with areas that were mangrove in the previous time period and hence could represent remaining areas that had been degraded. Once this had been completed, the total areas of mangrove for each of the four periods were determined.

The 1992 aerial photograph data provided an opportunity to assess classification accuracy. Therefore an error matrix was constructed based on comparisons of the 1992 aerial photograph and Landsat data from the same period. This was used to derive the percentage classification accuracy (i.e. the percentage of the area being considered that was classified correctly, either as mangrove or as non-mangrove) and Cohen's Kappa (κ, range 0–1), an alternative measure used to determine the extent to which the classification is better than random (Jensen et al., 1996).

Total area classified as mangrove could not be directly compared between periods due to variation in the areas covered by clouds in different periods. To allow between periods comparisons layers containing all areas classified as cloud in either period of each period – pair (i.e. 1985–1992, 1992–2000 etc.) were created. These areas were then removed from the mangrove layers for both periods, leaving images that were cloud free over the same locations at both points of time and thus allowing detection of change in these areas un-confounded by clouds. The cloud free areas for each year pair were between 68 and 73% of the aerial derived data from 1992.

The estimates of mangrove area derived from the Landsat images for each period did not represent the total area present due to the residual cloud coverage. In order to estimate the actual area of mangrove at each time point, the total area of mangrove from the 1992 high accuracy aerial derived data was determined. The proportion of this area which was classified as mangrove using the Landsat data was used to derive a total area estimate for the 1992 Landsat classification. Percentage changes calculated between periods after the removal of clouds were then applied to the 1992 baseline Landsat area to allow calculation of total areas in other time periods. In addition to estimating total area in this way, changes in coverage in different major mangrove areas (see Fig. 1) were also determined to compare rates of change in different areas.

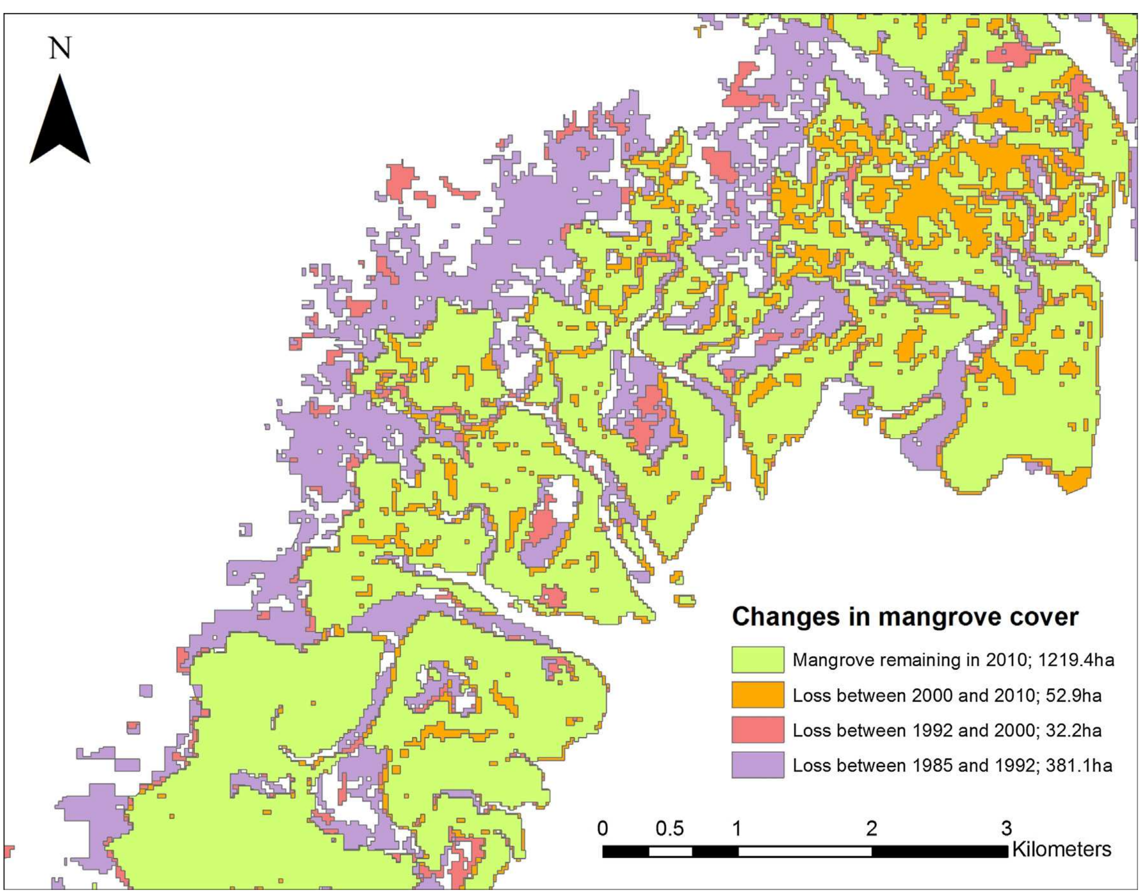

Fig. 2. Changes in mangrove at Gazi-Vanga system in south Coast Kenya between 1985 and 2010.

3. Results and discussion

The Landsat classification of mangroves in 1992 had a percentage accuracy of 87.5% and a kappa coefficient of 0.54, and was therefore assumed to have performed adequately for the purposes of assessing temporal change in mangrove extent in Kenya.

Temporal changes in mangrove cover at Gazi–Vanga system located in south Coast Kenya is shown in Fig. 2 and the temporal change in the extent of mangrove in different areas is shown in Fig. 3. The total area of mangrove has reduced continually in Kenya since 1985 although the overall rate of loss is not uniform and is slowing. In 1985 there was an estimated 55,280 ha of mangrove. By 1992 this had reduced to 51,880 ha, a loss of 6.2% over the period or an average of 0.89% yr^{-1}. Total coverage in 2000 was 46,930 representing a further loss of 9.5% (1.19% yr^{-1}) and in 2010 it was 45,590 ha (2.8% loss or 0.28% yr^{-1}). Hence in the 25 years between 1985 and 2010 Kenya lost 18% of its mangroves at an average rate of loss of 0.7% yr^{-1}. Rates of mangrove loss varied between areas, and over time (Fig. 3.), although average rates of loss were highest in the 1992–2000 period. Mangroves in the Kilifi area only make up a small proportion of the total area, but have seen the highest rate of loss, with an overall loss of ~76%, mostly in the period between 1985 and 2000. The large areas of mangrove in the Tana river and Lamu-Kiunga regions also showed higher rates of loss than other areas, with an overall reduction of 38% and 12% respectively. Loss rates across all areas were lowest in the 2000–2010 period. While no site- specific factors can be attributed to the observed variations in mangrove cover change, the main drivers of cover loss at local and national levels in Kenya have been identified as habitat alteration and inadequate legislation (UNEP, 2009). Whereas several factors may be responsible for the varying rates in mangrove cover loss, it is noteworthy that the period between 2000 and 2010 witnessed the lowest rate of loss which coincided with the presidential ban on harvesting of mangroves for domestic market. An earlier ban on mangrove export from Kenya was implemented in 1982; however this did not affect local harvesting until 2000 (Abuodha and Kairo, 2001).

The annual average rate of mangrove loss in Kenya is lower than that in many other parts of the world. For example, the tsunami-impacted region of South and Southeast Asia lost about 25% of mangrove forests from 1975 to 2005 (Giri et al., 2008). At the global scale, the estimates of total habitat loss within the past century vary from 25% to 50% (FAO, 2007). Conversion to aquaculture is the single largest driver of forest destruction in most Asian and Latin American countries; similar aquaculture developments are more recent and rarer in Kenya and other Western Indian Ocean region countries (Giri et al., 2008). The average annual rate of loss of 0.7% is similar to the estimated rate of loss of all types of forest in the country which currently stands at 0.8% (Karyn et al., 2010).

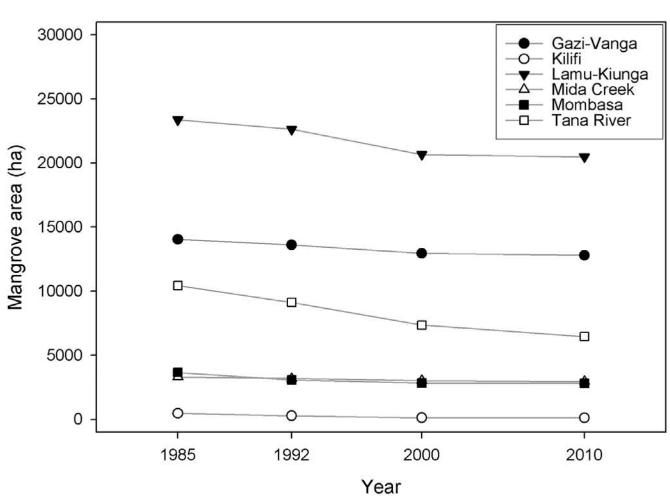

Fig. 3. Changes in areal extent of mangrove in Kenya over 25 years as estimated from Landsat imageries.

Earlier estimations of the extent of mangrove cover within Kenya vary widely ranging from 32,378 ha to 96 ha (summarized in FAO, 2003, 2007; Giri et al., 2010). Most of these studies- provide an estimate of total mangrove forest area of the country but do not provide information on the spatial distribution of forests. Variations in estimation of total cover of mangroves could be attributed to differences in estimation techniques, time of the survey and how areas considered to be mangroves were classified. For instance using aerial photography, the forest department of Kenya estimated the total area of mangroves in the country as 64,426.90 ha (Forest Department of Kenya, 1983) which is substantially higher than our estimate for 1985, but is likely to include smaller, fragmented mangroves which would not be well captured by the relatively coarse resolution Landsat data. Giri et al. (2010) recently mapped global mangrove cover using Landsat data from 1997 to 2000. Their estimate for Kenya was 32,378 ha which is much lower than our estimate for 2000 (46,930 ha). A number of reasons may be responsible for the observed variations. For instance, given the global approach they employed, they probably had to use a conservative mapping method, so as not to add areas that are not classified as mangroves and also their choice of minimum mapping unit may have excluded the small patches that occur in places in Kenya.

4. Conclusion

The information on the current status and rates of change of mangrove forest cover in Kenya presented here will be of value to forest managers, conservators and other stakeholders in a number of ways. The findings have improved our understanding of the spatial distribution of Kenya's mangroves and assessed their rates of deforestation. This can support countrywide decision making on the distribution of resources for the conservation and rehabilitation of mangrove forests. The new opportunities provided by payments for ecosystem services schemes, for the conservation and restoration of mangrove forests can be realized only with accurate data on their rates of historical loss and current extent.

Monitoring deforestation at a country level using moderate resolution satellite images over a long period of time requires the processing of large volumes of data. We used simple but efficient methods to analyze these data. Our approach applied semi-automated image analysis techniques to assess present status and to monitor the rates of change over a large area covering the entire country. Our analyses show the potential for producing consistent and timely mangrove forest databases, sufficient to show the baseline rates of deforestation required in REDD+ type analyses, using the historical archive of Landsat data. Crucially such data are freely available hence a similar approach could be adopted in other developing countries without requiring expensive commercial imagery. The full potential of remote sensing technology for identifying mangrove forests, measuring their biophysical properties, and detecting forest cover changes can only be realized through a robust and operational mangrove forest assessment and monitoring program. Future research is needed to map mangrove areas using high resolution satellite images combined with detailed ground truthing, which could go well beyond the current estimates of coverage alone and include data on species distributions and rates of degradation.

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