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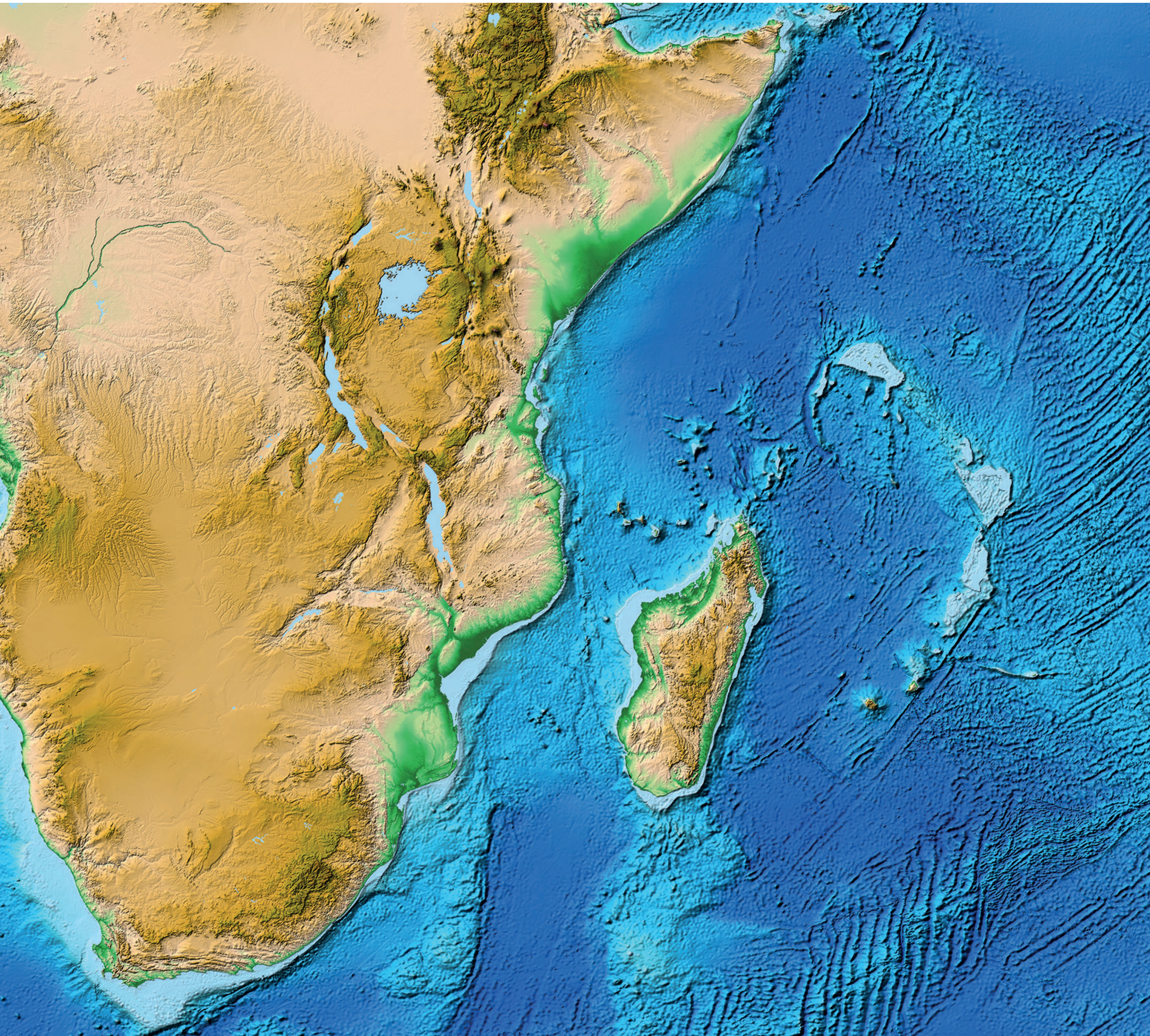

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Cover image: Relief model of the WIO surface that integrates land topography and ocean bathymetry. Amante and Eakins / National Geophysical Data Center, NOAA (2009)

Mangrove transformation in the Incomati Estuary, Maputo Bay, Mozambique

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Abstract

The mangroves around Maputo city in Maputo Bay were studied to assess changes in forest cover area and the effect of cutting pressure on the forest structure and conservation condition, by using GIS techniques and ground-truthing. On site, the forest was classified into semi-intact (predominantly intact trees), degraded (with many cut trees), degraded with reed invasion, dwarf mangrove, and new mangrove area. The results showed a 5% increase in forest area in 2003 as compared to 1991, with 64% of the total forest consisting of degraded mangroves. Deforestation took place at a mean rate of 17 ha $year^{-1}$ between 1991 and 2003. *Avicennia marina* dominated over the other 5 species. Overall, the forest was composed of small trees (mean height 2.6 m; mean DBH 7.45 cm); height and DBH varied significantly when comparing species and communities ($p < 0.05$ for both). In terms of forest conservation condition, only the semi-intact community had the structural characteristics of a healthy forest. Selective tree cutting targeted *A. marina* trunks with diameter of 6 - 12 cm. The regeneration potential of the forest was 181 individuals ha^{-1}; the new mangrove area had the highest density of juveniles (671 individuals ha^{-1}). By identifying the most critical areas of the Incomati Estuary and describing forest condition, this study shows the poor condition of peri-urban mangroves at locations such as this in eastern Africa, and highlights the need for further understanding of estuary regimes that may influence mangrove community changes, other that deforestation.

Keywords: peri-urban mangrove, deforestation, mapping, Incomati Estuary, Mozambique

Introduction

Mangroves are woody intertidal plants that grow on protected coasts in tropical and sub-tropical areas (FAO, 1997). They are ecologically important and provide numerous goods and services to the coastal community, ranging from habitat for fish and other wildlife (Laegdsgaard and Johson, 2001), exporting organic matter (de Boer, 2000; Dorenbosh *et al.*, 2004; Mumby, 2006), shoreline protection (Thampanya *et al.*, 2006), control of water quality (Twilley *et al.*, 1997; Ye *et al.*, 2001) and carbon sequestration (Kristensen *et al.*, 2008; Komiyana *et al.*, 2008). From a socio-economic perspective, mangroves are important sources of livelihood for communities, providing firewood, building poles as well as being sites for the development of economic activities, such as bee keeping, fishing, aquaculture and ecotourism (Taylor *et al.*, 2003; Walters *et al.*, 2008).

Despite their importance, mangrove ecosystems are under pressure worldwide. Major causes of loss and transformation of mangrove ecosystems include over-exploitation, conversion of mangrove areas to other land uses (particularly aquaculture, mining and urban development) and pollution effects (Hogarth, 1999). Other threats include erosion and sedimentation (Alongi, 2002; FAO, 2007; Rakotomavo and

Fromard, 2010) often related to poor agriculture practices upland, and climate change.

In developing countries, peri-urban mangroves (growing within or close to an urban area) are particularly vulnerable to degradation, because the population density is high, and local communities still have a high level of dependency on coastal natural resources. Some of the threats that occur more frequently in peri-urban forests include insufficient treatment of waste-water, urban expansion and overexploitation due to the dependence of peri-urban populations on resources such as fuelwood (Krutilla *et al.*, 1995). This has been seen in many countries in Asia, South America and Africa (Gomes *et al.*, 2008; Wickramasinghe *et al.*, 2009; UNEP/Nairobi Convention Secretariat, 2009). In Mozambique, the massive rural exodus that occurred during the 16 years of civil war overcrowded coastal cities, exceeding their capacities and heightening the exploitation of surrounding natural resources, mangrove forests included. Maputo and Beira cities are the most critical cases (UNEP/Nairobi Convention Secretariat, 2009). Although the situation is probably replicated in other parts of the country, very few studies in Mozambique have focused on mangrove forest transformations.

Remote sensing techniques are a powerful tool in monitoring the area and condition of mangrove forests (Blasco *et al.*, 2001, Kairo *et al.*, 2002a; Alonso-Pérez *et al.*, 2003). When combined with intensive ground-truthing, the use of remote sensed data with GIS is cost- and time-effective, and efficient in quantifying changes in forest structure and dynamics in the past and in real time (Jupiter *et al.*, 2007). Remote sensing has already been used to map mangrove distribution, determine species composition (Neukermans, 2005; Neukermans and Koedam, 2014), assess stand density (Verheyden *et al.*, 2002), and monitor these parameters over periods of time (Daudouh-Guebas *et al.*, 2004). Commonly, satellite imagery used in forestry include SPOT, LandSat Thematic Mapper and Enhanced Thematic Mapper (ETM) (Jupiter *et al.*, 2007). For higher resolution surveys, other types of imagery that have been used in mangroves include Quickbird (Neukermans *et al.*, 2007; Neukermans and Koedam, 2014), IKONOS (Kovacs *et al.*, 2005), and CASI hyper spectral images (Held *et al.*, 2001).

In Mozambique the application of remote sensing techniques for studying mangroves started relatively recently. Saket and Matusse (1994) estimated the total mangrove area of the country as 3.960,8 km^2 in 1990; a figure that was revised to 2.909 km^2 in 2002 by Fatoyinbo et al (2008). Using aerial photographs, de Boer (2002) studied changes in the mangroves of Maputo Bay between 1958 and 1991. In a similar study, LeMarie *et al.* (2006) used LandSat7 TM imagery to assess changes in the mangroves of Xefina Pequena and Benguelene Islands (Maputo Bay) between 1984 and 2003. More recently Ferreira *et al.* (2009) mapped the mangrove forests in the northern trans-boundary area between Mozambique and Tanzania, also using LandSat5 TM imagery. In all these studies, the general trend has been of decreasing forest cover, particularly in the densely populated areas of Maputo Bay. In the remote and accreting areas in the north of the country, mangroves have been seen to expand. None of the above mentioned studies looked at forest conservation condition.

The main objective of this study was to assess changes in forest cover, structure and conservation condition in the mangroves of the Incomati Estuary, a peri--urban forest around Maputo city. The forest comprises 22.3% of the total mangrove area of Maputo Bay (de Boer, 2002), and threats come from several sources, including pollution, urban expansion and wood exploitation by the local communities. The information generated constitutes an important tool for management of the peri-urban mangroves, and will aid in the implementation of a reforestation program for the degraded areas.

Material and methods

Description of study site

The Incomati Estuary is located in north western Maputo Bay, and includes 3 main islands (Benguelene, Xefina Grande and Xefina Pequena), with well established mangrove forests extending up to 7 km inland (Figure 1). The climate of the Bay is subtropical, with a cool dry season from April to October, and a warm wet season for the rest of the year. Mean annual rainfall is 837 mm. Water temperature varies between 17°C and 39°C, and salinity varies between 30-39ppt (mean 35ppt). The tides are semi-diurnal, and tidal range at the river mouth is about 3 m (Hoguane, 1998; UNEP/Nairobi Convention Secretariat, 2009). The estuary is located close to the major urban centre of the country, with an estimated population of about 1.5 million people in 2003 (Instituto Nacional de Estatistica, 2007). Agriculture and fisheries are two of the most important economic activities. Industry (cement, furniture, rubber, food industry, aluminium smelting, tourism, etc.) is flourishing in Maputo and its satellite

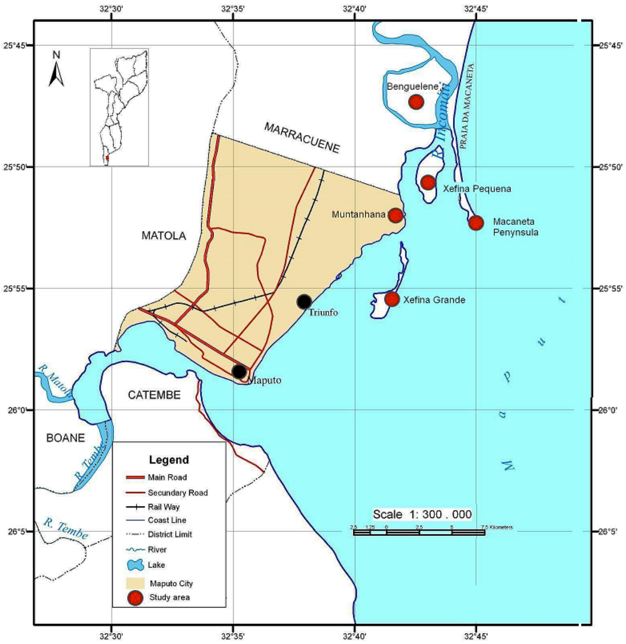

Figure 1. Geographic location of the Incomati Estuary, close to Maputo city and other large human settlements.

city Matola. Mangroves around Maputo (peri-urban) are exploited for wood, fuelwood and charcoal, mainly for domestic purposes. Brower and Falcão (2004) described markets dedicated to mangrove fuelwood in this area.

Methods

Mangrove change detection

Quantification of mangrove area and change detection was made over a timespan of 12 years, combining remote sensing techniques and intensive ground-truthing. Satellite images (Landsat TM 1991, and Landsat TM7+ 2000 and 2003) with a resolution of 30 m were obtained from CENACARTA, already ortho-rectified and cleared for noise. After performing band combination tests, the combination 4, 3, 2 was chosen. Analysis on ArcGIS3.2 (Image Analysis Extension) was performed (e.g. Ramirez-Garcia *et al.*, 1998). The changes in cover area where detected by comparing the results from mapping in different years. Mangrove tree communities were classified according to species composition and land use. Three categories were used for classification of mangrove communities when analyzing Land Sat images: 'Degraded mangrove', with many trees cut in different levels, and dwarf trees present; 'Degraded mangrove with reed (*Phragmites australis*) invasion', where reeds and mangrove trees were present; and 'Healthy mangrove', including regenerating communities and new mangrove areas.

Mangrove forest structure, conservation condition and regeneration status

Five mangrove forest communities were identified on the ground in the study area: semi-intact community, which was composed predominantly of intact trees; degraded community, where many trees were completely, severely or partially cut; dwarf mangrove, composed of very small adult trees or shrubs; and new mangrove area, where, after accretion, new mangroves were establishing just prior to or during the study. Mangrove forest structure and conservation condition were assessed using the quadrat methods elaborated in Kairo *et al.* (2002b) and Bandeira *et al.* (2009). Quadrats of 10x10 m were set in the upper, middle and lower parts of the mangrove forest, following transects that were set perpendicular to the coast line. A total of 60 plots were sampled. Sampled areas in the estuary included Xefina Grande and Xefina Pequena Islands, Benguelene Island, Ponta Macaneta and Muntanhana (Figure 1). All individuals inside the quadrats were counted and identified to species level. Diameter at breast height (DBH) was measured with a calliper, while height was estimated with a 5 m graduated stick. This data allowed the calculation of structural parameters of the forest, such as species density and frequency, basal area, and mean height and diameter (Cintron and Schaeffer-Novelli, 1984; Kairo *et al.*, 2002b; Bandeira *et al.*, 2009). It also allowed a height vs diameter distribution scatter graph to be generated for each community, which was useful to identify transformations in the structure of the forest (Kairo *et al.*, 2002). The ecological importance value (IV) of the species and the complexity index of the communities were calculated as described by Cintron and Schaeffer-Novelli (1984) and Holdridge *et al.* (1971). Measuring height and DBH also allowed classification of individuals in the quadrat as adults or juveniles, as described by Bandeira *et al.* (2009); those up to 1.5 m high and 2.5 cm wide (DBH) were classified as adults, and those below these figures were juveniles. This classification was useful to assess forest regeneration status.

To assess mangrove conservation condition, adult individuals in the quadrat were counted and grouped into four categories. These were: Intact, for trees with no sign of being cut; Partially cut, for those with one or more branches which had been cut, but the main trunk was intact; Severely cut, with most branches cut; and Stump, for those whose main trunk had been cut (Bandeira *et al.*, 2009). The diameter of stumps was measured to estimate preferred sizes for cutting.

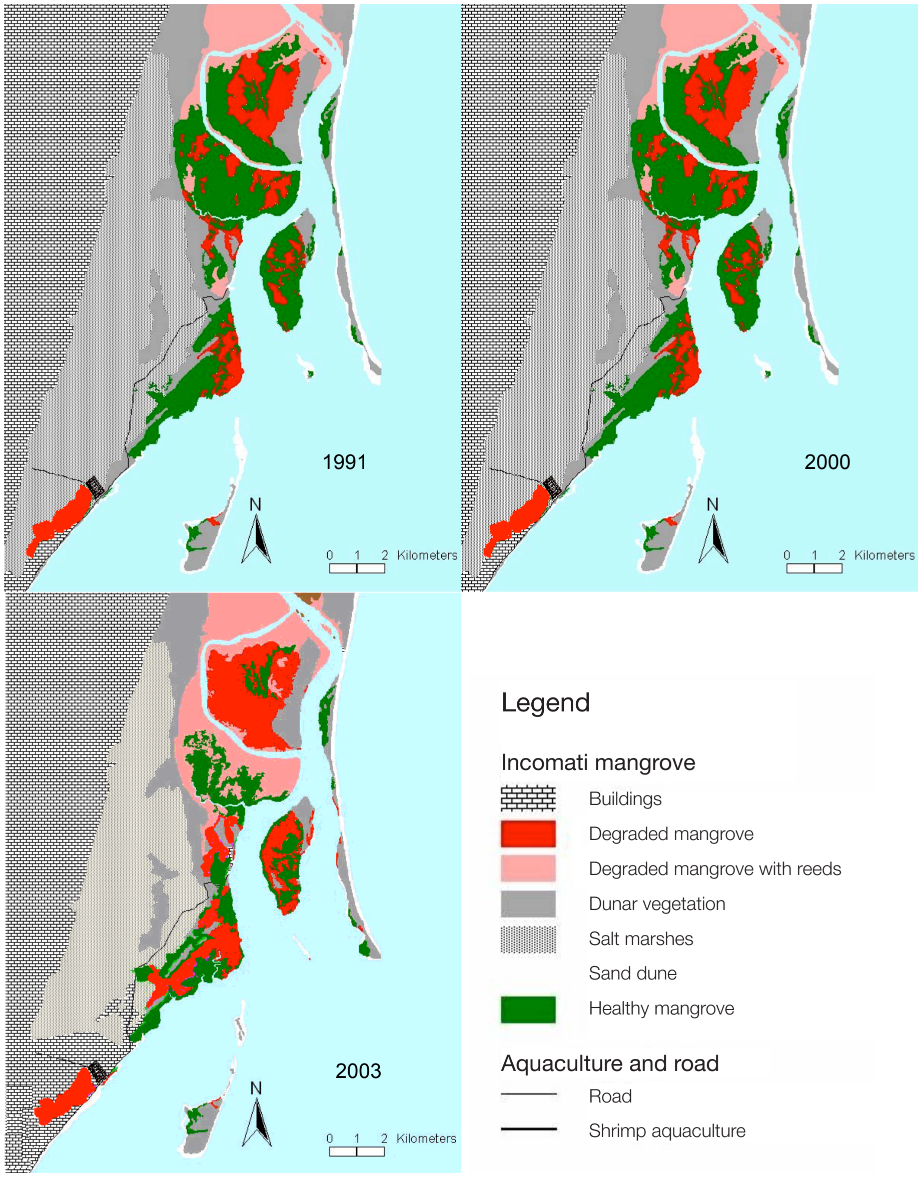

Figure 2. Mangrove area variation between 1991 and 2003. Healthy forest includes recovering mangrove and new mangrove area, while dwarf communities were considered degraded.

All juveniles within the quadrat were identified and counted to assess regeneration status of the forest.

Data on mangrove structure were subject to normality and homogeneity of variances tests. Multifactorial ANOVA was conducted to assess significant differences in parametric data, while Kruskal-Wallis was used for non-parametric data. All tests were performed at 0.05 probability level.

Results

Mangrove change detection

The total mangrove area in the Incomati Estuary increased from 4,231 ha in 1991 to 4,451 ha in 2003; an increase of 18 ha per year (Figure 2). However, the rates of change varied over this period. From 1991 to 2000, the 'Degraded area' increased by 113 ha, and 'Degraded with reeds' expanded by 218 ha into previous mangrove areas. 'Healthy' area decreased, but this change was compensated by an increase of 174 ha of new mangrove (also considered 'Healthy'). From 2000 to 2003, the 'Degraded' area increased by 91 ha and reeds took over a larger area (520 ha). The area of 'Healthy mangrove' decreased, but the total mangrove area increased by 46 ha. When comparing 1991 and 2003, 'Degraded mangrove' increased at a rate of 17 ha/year, while reeds gained 62 ha each year and the total area increased by 18 ha each year. In 2003, 'Total Degraded mangrove' (with and without reed invasion) made up 63.8% of the total forest area.

A rapid increase in degradation rate after 2000 was apparent. It is probable that the deforestation rate increased gradually between 1991 and 2000, with a mean value of 12 ha/year. Similarly, degradation rate for the whole period 1991-2003 was 17 ha/year, lower than that of the 2000-2003 period (Table 1).

Most changes occurred in Benguelene and Xefina Pequena Islands, while in Muntanhana changes were marked by reed invasion.

Forest structure

A total of 2,334 individuals of 6 species were sampled in the Incomati forest. *Avicennia marina* was the dominant species (71.46%), being present in all communities. *Rhizophora mucronata* and *Ceriops tagal* represented 17.15% and 6.56% of the total number of individuals respectively, while the other tree species (*Bruguiera gymnorhiza*, *Xylocarpus granatum* and *Lumnitzera racemosa*) accounted for less than 3% each. These figures where reflected in the ecological importance value of the species (Table 2). Mean stand density in the forest was 4,024 ind ha^{-1}. There were significant differences when comparing stand densities in the communities ($p < 0.05$), with the densest communities being 'New mangrove' (7833 ind ha^{-1}) and 'Semi-intact mangrove' (5646 ind ha^{-1}). 'Semi-intact mangrove' was also the most complex community (Table 3).

Structurally, this forest was composed of small trees (as defined by Cole *et al.*, 1999; Kairo *et al.*, 2002b; Kairo *et al.*, 2008). The mean height of the forest was 2.62 ± 0.03 m and mean DBH 7.45 ± 0.25 cm. A large majority of adult trees had DBH between 2.5 and 6 cm (Figure 3). Mean height varied significantly when comparing species ($p < 0.05$) and communities ($p < 0.05$), with *A. marina* being the tallest species, and 'New mangrove' the tallest community.

Lumnitzera racemosa had the highest mean DBH, while the greatest basal (proportional to DBH) area was found in the 'Semi-intact' community. Statistical analyses showed significant differences when comparing DBH among species and communities ($p < 0.05$).

Only 'Semi-intact' mangrove kept a size distribution (Height vs. DBH) typical of a healthy forest; that is having individuals in all size classes, but the majority had narrow stems (Figure 4). Structural differences between 'Degraded mangrove' and 'Degraded mangrove with reeds' were also apparent. In the 'Degraded with reeds' community, all diameters were very similar

Table 1. Mangrove area (ha) and dynamics between 1991 and 2003 in the Incomati Estuary.

Mangrove community	1991	2000	Change	Rate/year
Degraded	1,007.28	1,120.79	113.51	12.61
Degraded with reeds	889.20	1,107.66	218.46	24.27
Semi-intact	2,334.75	2,176.85	-157.89	-17.54
Total area	4,231.23	4,405.30	174.08	19.34
	2000	**2003**	**Change**	**Rate/year**
Degraded	1,120.79	1,211.56	90.77	30.26
Degraded with reeds	1,107.66	1,627.37	519.71	173.24
Semi-intact	2,176.85	1,612.29	-564.56	-188.19
Total area	4,405.30	4,451.22	45.92	15.31
	1991	**2003**	**Change**	**Rate/year**
Degraded	1,007.28	1,211.56	204.28	17.02
Degraded with reeds	889.20	1,627.37	738.17	61.51
Semi-intact	2,334.75	1,612.99	-722.46	-60.21
Total area	4,231.23	4,451.22	219.99	18.33

Table 2. Ecological importance of species in the Incomati Estuary. IV represents the importance value of species, which is obtained by summing the relative dominance, density and frequency (Cintron and Schaeffer-Novelli, 1984). Mean DBH and mean height ± standard error.

Species	Mean height (m)	Mean DBH (cm)	Relative values			IV
			Dominance	Density	Frequency	
A. marina	2.85± 0.03	6.85±0.29	71.46	77.72	52.22	201.4
B. gymnorhiza	1.82±0.09	6.29±1.31	1,16	1.37	5.56	8.09
C. tagal	1.63±0.04	5.23±0.27	6,56	9.34	13.33	29.23
L. racemosa	1.71±0.11	14.54±1.66	2,17	1.11	2.22	5.5
R. mucronata	1.95±0.09	13.62±0.94	17,15	9.38	15.56	42.09
X. granatum	2.49±0.2	10.47±1.94	1,50	1.07	11.11	13.68

Table 3. Structural parameters of the Incomati Estuary communities. Complexity index is the product of number of species, basal area, maximum tree height and stem density (Holdridge *et al.*, 1971).

	Semi-intact	Dwarf	Degraded	Degraded with reeds	New mangrove	Whole forest
Number of species	5	4	5	2	2	6
Density (ind ha^{-1})	5,646.15	3,893.33	1,460.00	1,533.33	7,833.33	4,024.14
Mean height (m)	2.61	2.02	1.60	2.55	3.44	2.62
Basal area (m^2ha^{-1})	3.6	0.67	0.97	0.32	1.30	3.75
Complexity index	9.15	0.41	0.43	0.04	1.33	3.26

and below 20 cm, whilst in the 'Degraded' community, sizes varied more and were greater than 20 cm.

Forest structure and conservation condition

Data analysis showed that this forest was subject to deforestation pressure. Cut trees (stumps) had different sizes, but preference was for those with a trunk diameter of 6 – 12 cm. However, the forest was composed mostly of intact individuals (Table 4). *A. marina* was the preferred species, while *B. gymnorhiza* was almost never cut.

Each community was composed of different proportions of tree categories. Intact trees were found mostly in 'Dwarf', 'New mangrove', and 'Degraded with reeds' areas (Figure 5).

The regeneration potential of the forest was low (181 juveniles ha-1). A. marina had the highest density of juveniles (178 ind ha-1) and dominated the forest in all communities, though with low densities in 'Degraded mangrove' and 'Degraded with reeds' areas. Other species had less than 4 juveniles ha-1. The highest regeneration was seen in the 'New mangrove' areas (Figure 6), with 671 juveniles ha-1, and in the 'Semi-intact mangrove' areas, with 422 juveniles ha-1.

Discussion

Forest transformation and conservation condition

The Incomati Estuary supplies the local community with forestry resources, mostly domestic fuel, wood and poles (local community, personal communication). In 1995 it was estimated that 9200 tonnes of mangrove firewood was extracted from Benguelene Island alone, for sale and domestic consumption (Hatton, 1995). It is thus an area of considerable importance as a source of livelihood for the local communities. Apart from wood resources, the Incomati forest and its surroundings are important for other income generating activities, such as the fish and shrimp fishery, and invertebrate collection (Barbosa *et al.*, 2001).

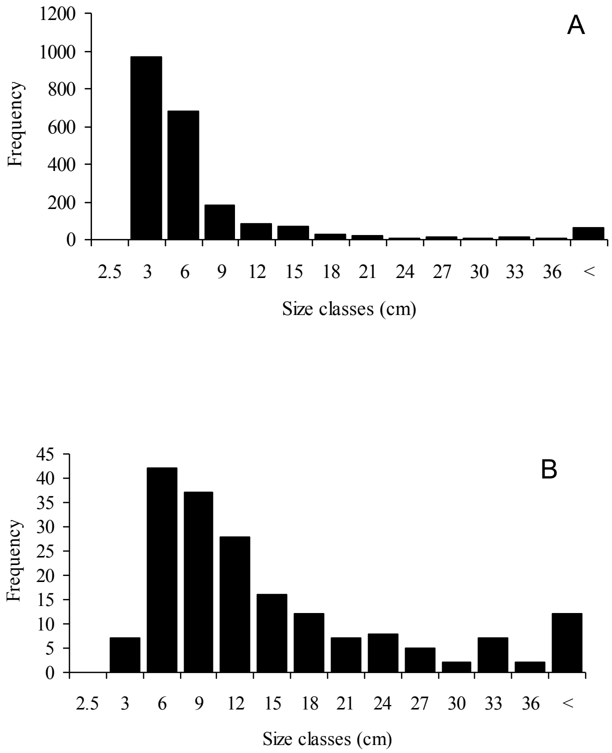

Figure 3. DBH size class distribution for live trees (A) indicates the presence of human disturbance; while the diameter size distribution for stumps (B) indicates clear preferences for 6-12 cm poles.

The results of this study show an increase of about 5% in total mangrove area over the study period. This trend of an increase in total forest cover has previously been recorded in other parts of the country such as Inhaca, Machangulo, Xefina and Benguelene Island in Maputo Bay (17% between 1958-1991), Maputo Province (6 km² between 1990-2002) , and the Rovuma-Quiterajo-Ibo-Pemba area in northern Mozambique (3% between 1995-2005) (de Boer, 2002; Fatoyinbo *et al.*, 2008; Ferreira *et al.*, 2009). Slight increases have also been recorded in other parts of the world, such as in the Sundarbans (India/Bangladesh) and Madagascar (Giri *et al.*, 2007; Rakotomavo and Fromand, 2010). However, the general global trend is one of decrease (Valiela *et al.*, 2001). Among African countries, Liberia and Mauritius were listed as the countries with the highest rates of mangrove loss. According to FAO (2007), they lost 6.1% and 5.9% of the total mangrove area in the period 2000-2005, respectively. In eastern Africa, Madagascar lost the largest mangrove area (3000 ha) in the same period, although this corresponds to only 1% of its total mangrove area.

Most mangrove studies are limited to a description of changes in cover area, while others combine it with structural aspects (Simard *et al.*, 2006; Krausse *et al.*, 2004),

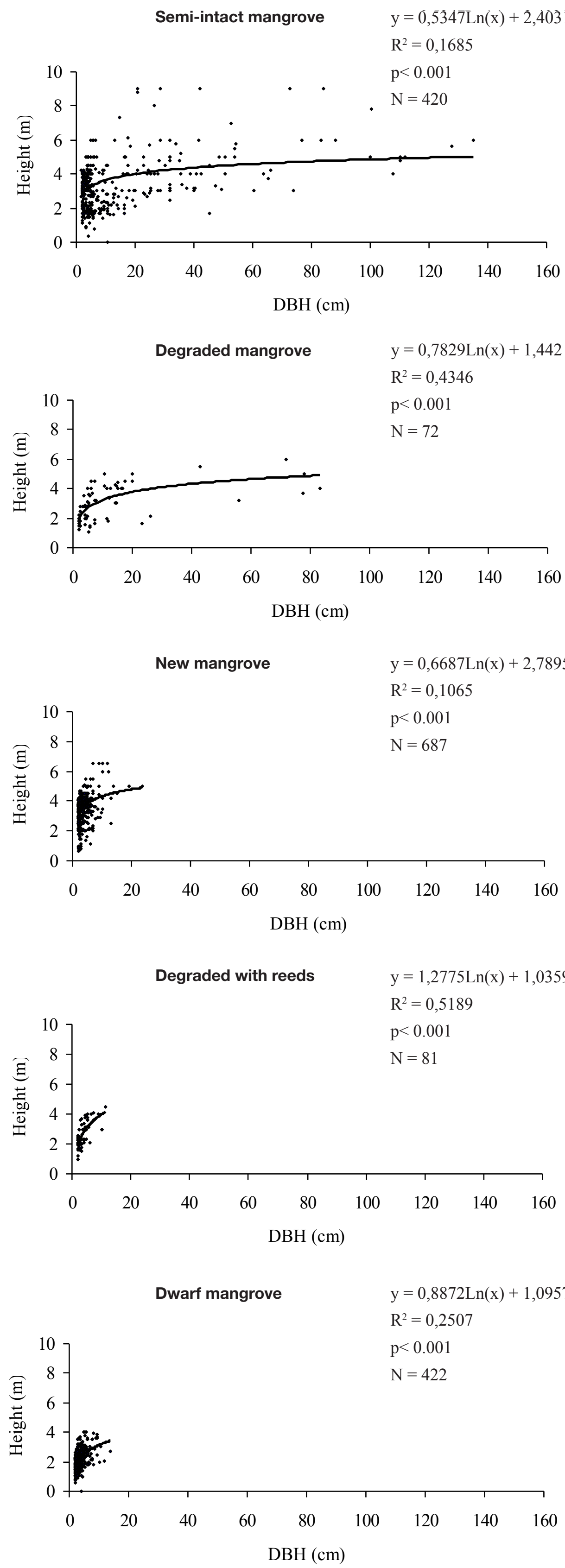

Figure 4. Height-diameter distribution of *Avicennia marina*, the dominant species in the Incomati Estuary. Structural differences can be seen in each community.

Table 4. Conservation per species

Species	Density (ind ha^{-1})			
	Intact	Partially cut	Severely cut	Stump
A. marina	2,301	287	305	232
B. gymnorhiza	51	1	1	0
C. tagal	322	13	15	24
L. racemosa	31	6	3	3
R. mucronata	181	72	65	58
X. granatum	25	8	8	0
Whole forest	**2,913**	**391**	**400**	**319**

but very few look at forest conservation condition. The combination of the three aspects as in this study provides more expansive information on the forest, and a more robust basis for informed decision-making. For instance, this study showed that a small increase in the area of mangrove cover is largely offset by a dramatic increase in degraded area (50% of the forest is degraded through cutting and reed invasion) and decrease in forest health. The presence of the reed *Phragmites australis* within a mangrove forest is often perceived as a sign of instability (Walters, 2005; Granek and Ruttenberg, 2008), and it can be an indicator of the presence of hydrological-related stresses (Vasquez *et al.*, 2005; Katering *et al.*, 2010), such as increased runoff and freshwater seepage. In the case of the Incomati Estuary, both phenomena occurred after the year 2000, when massive floods impacted the area, providing an explanation for the accelerated rate of colonization by the reed after 2000. Prior to this period, the hydrological regime of this estuary had reportedly being altered by water abstractions upstream (agriculture, urban and industrial consumption, dam construction, etc.) and increased salt intrusion downstream (Sengo *et al.*, 2005; Brockway *et al.*, 2006; LeMarie *et al.*, 2006; UNEP/Nairobi Convention, 2009). The overall effect of the floods, water abstraction and salt intrusion, and their influence on reed invasion in the estuary, is poorly understood and requires further study.

The comparison of community structural parameters reveals several interesting differences between the categories. For instance, the 'Degraded with reeds' community is composed mostly of intact trees, indicating that reed invasion does not only occur in cleared areas. In addition the presence of dwarf *A. marina* indicates stress, which can be related to nutrient shortage or high salinity (Naidoo, 2009). The influence of all these factors on forest health condition has not yet been assessed.

The regeneration potential of this forest is low. Other healthy forests in Mozambique (Saco, Sangala, Ibo, Pemba, Luchete) had more than 6000 recruits ha^{-1}

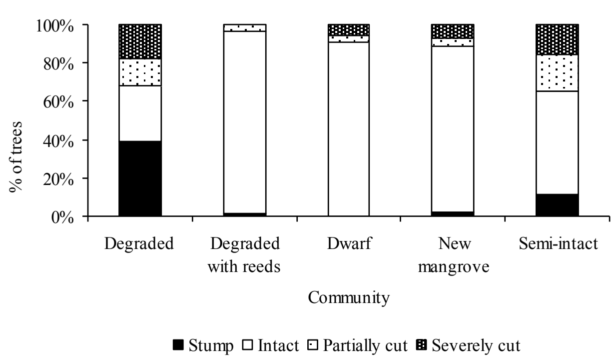

Figure 5. Conservation status of the different mangrove communities in the Incomati estuary.

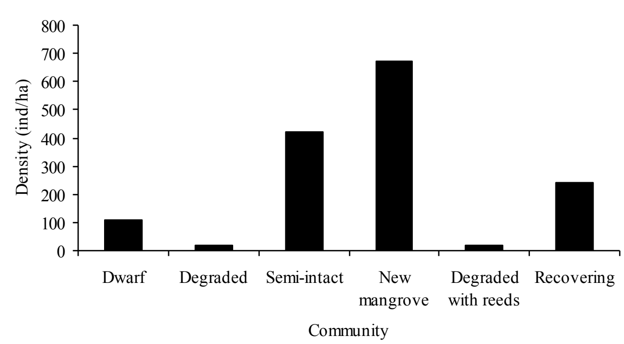

Figure 6. Regeneration per mangrove community in the Incomati estuary.

(Bandeira *et al.*, 2009). Similarly in Kenya, on less impacted and recovering replanted sites, the density of recruits per species varies between 700-5400 ind ha^{-1} (Kairo *et al.*, 2002b; Bosire *et al.*, 2003; Kairo *et al.*, 2008). The recruit density in the Incomati Estuary was comparable to other heavily deforested sites, such as Sematan in Malaysia and Mngoji in Tanzania (500 and 1000 ind ha^{-1}, respectively) (Ashton and Macintosh, 2002; Bandeira *et al.*, 2009). *A. marina* is the dominant adult species, and this explains why it has the best regenerative success. Additionally this species is vigorous and capable of adapting to changing environmental conditions such as changes in salinity; more so than other species (Bentjee and Bandeira, 2007).

Incomati Estuary: Is restoration possible?

Degraded areas can recover through natural processes. Sherman *et al.* (2000) reported that the creation of gaps may increase sapling density and growth rate of some species in forests with low cutting intensity, because competition for light and space is reduced. However, intensive forest cutting can decrease forest regeneration potential, by reducing the number of reproductive individuals and changing optimum environmental conditions (Hogarth, 1999, Granek and Ruttenberg, 2008).

Natural recovery in the Xefina and Benguelene Islands mangrove forest was reported by LeMarie *et al.* (2006). The authors verified that about 54 ha of degraded forest recovered to non-degraded forest between 1984 and 2003. In the present study, recovering mangrove and new mangrove areas were identified during ground-truthing, suggesting that the system can recover. However, human intervention may be helpful, as replantation could boost forest recovery and re-colonization of invaded areas. Mozambique has experienced at least one demonstration programme on mangrove replantation (in Lumbo, Northern Mozambique), where the local communities were trained in mangrove replanting techniques and alternative income-generating activities such as integrated aquaculture, ecotourism and silviculture (Veronica Dove, personal communication).

Some positive actions for restoration in the Incomati Estuary could include raising the level of education and awareness of local communities around sustainable harvesting of mangrove products. Mangrove replantation in severely degraded areas might also contribute to the process. The use of conservation practices (such as establishment of no-cut zones, regulation of harvesting, and diversification of mangrove uses like ecotourism, bee-keeping etc.) and resource management initiatives are required in order to make sustainable use of mangrove resources in the future. *A. marina* could be considered as a suitable pioneer species in any replantation programme (Bentjee and Bandeira, 2007; Lang'at, 2010).

This research shows the history of mangrove vegetation change in the Incomati Estuary during the period from 1991 to 2003. Although the forest area increased during the study period, the area of healthy forest decreased, while 'Degraded' areas expanded (63.8% of the total forest area). Structural differences were found in different forest communities, and only the semi-intact community had a structure that was similar to that of healthy forests. Although the regeneration potential of the forest is low, recovery is possible, as demonstrated by the presence of recruits and colonization of new mangrove areas. Efforts towards forest restoration should be accompanied by education and awareness of the user communities, mangrove replantation, and the introduction of management and conservation practices.

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References

Alonso-Pérez F, Luna-Ruiz A, Turner J, Berlanga-Robles C, Mitchelson-Jacob G (2003) Land cover changes and impact of shrimp aquaculture on the landscape in the Ceuta coastal lagoon system, Sinaloa, Mexico. Ocean and Coastal Management 46: 583-600

Alongi D (2002) Present state and future of the world's mangrove forests. Environmental Conservation 29: 331-349

Ashton E, Macintosh D (2002) Preliminary assessment of the plant diversity and community ecology of the Sematan mangrove forest, Sarawak, Malaysia. Forest Ecology and Management 166: 111-129

Bandeira SO, Macamo, CCF, Kairo J G, Amade F, Jiddawi N, Paula J (2009) Evaluation of mangrove structure and condition in two trans-boundary areas in the Western Indian Ocean. Aquatic Conservation: Marine and Freshwater Ecosystems 19: 46-55

Barbosa F, Cuambe CC, Bandeira SO (2001) Status and distribution of mangroves in Mozambique. South African Journal of Botany 67: 393-398

Beentje H, Bandeira S (2007) Field Guide to the Mangrove Trees of Africa and Madagascar. Kew Publishing, UK. 91 pp

Blasco F, Aizpuru M, Gers C (2001) Depletion of mangroves in continental Asia. Wetlands Ecology and Management 9: 255-266

Bosire JO, Dahdouh-Guebas F, Kairo JG, Koedam N (2003) Colonization of non-planted mangrove species into restored mangrove stands in Gazi Bay, Kenya. Aquatic Botany 76: 267-279

Brouwer R, Falcão MP (2004) Wood fuel consumption in Maputo, Mozambique. Biomass and Bioenergy 27: 233-245

Brockway R, Bowers D, Hoguane A, Dove V, Vassele V (2006) A note on salt intrusion in funnel-shaped estuaries: Application to the Incomati estuary, Mozambique. Estuarine, Coastal and Shelf Science 66: 1-5

Cintron G, Novelli Y (1984) Methods for studying mangrove structure. In: Snedaker SC, Snedaker JG (Eds) The Mangrove Ecosystem: Research Methods. UNESCO, Paris. pp. 91-113

Cole T, Ewel K, Devoe N (1999) Structure of mangrove trees and forests in Micronesia. Forest Ecology and Management 117: 95-109

Dahdouh-Guebas F, Van Pottelbergh I, Kairo J G, Cannicci S, Koedam N (2004) Human-impacted mangroves in Gazi (Kenya): predicting future vegetation based on retrospective remote sensing, social surveys, and tree distribution. Marine Ecology Progress Series 272: 77-92

de Boer F (2000) Biomass dynamics of seagrasses and the role of mangrove and seagrass vegetation as different nutrient sources for an intertidal ecosystem. Aquatic Botany 66: 225-239

de Boer F (2002) The rise and fall of the mangrove forests in Maputo Bay, Mozambique. Wetlands Ecology and Management 10: 313-322

Dorenbosh M, van Riel M, Nagelkerken I, van der Velde (2004) The relationship of reef fish densities to the proximity of mangrove and seagrass nurseries. Estuarine, Coastal and Shelf Science 60: 37-48

FAO (1997) Mangrove forest management guidelines. FAO Forestry paper 117. Rome

FAO (2007) The world's mangroves 1980-2005. FAO forestry paper 153. Rome

Fatoyinbo T, Simard M, Washington-Allen R, Shugart H (2008) Landscape-scale extent, height, biomass, and carbon estimation of Mozambique's mangrove forests with Landsat ETM+ and Shuttle Radar Topography Mission elevation data. Journal of Geophysical Research 113: 1-13

Ferreira MA, Andrade F, Bandeira SO, Cardoso P, Nogueira--Mendes R, Paula J (2009) Analysis of cover change (1995-2005) of Tanzania/Mozambique trans-boundary mangroves using Landsat imagery. Aquatic Conservation 19: 38-45

Granek E, Ruttenberg B (2008) Changes in biotic and abiotic processes following mangrove clearing. Estuarine, Coastal and Shelf Science 80: 555-562

Giri C, Pengra B, Zhu-Singh A, Tieszen L (2007) Monitoring mangrove forest dynamics of the Sundarbans in Bangladesh and India using multi-temporal satellite data from 1973 to 2000. Estuarine, Coastal and Shelf Science 73: 91-100

Gomes NCM, Borges LR, Paranhos R, Pinto FN, Mendonça-Hagler LCS, Smalla K (2008) Exploring the diversity of bacterial communities in sediments of urban mangrove forests. FEMS Microbiology and Ecology 66: 96-109

Hatton JC (1995) A status quo assessment of the coastal zone, Mozambique. Phase 1: Ponta do Ouro-Xai-Xai. IUCN, Maputo

Held A, Ticehurst C, Lymburner L (2001) Hyperspectral mapping of rainforests and mangroves. Geoscience and Remote Sensing Symposium, 2001. IGARSS '01. IEEE 2001 International 6: 2787-2789

Hogarth PJ (1999) The Biology of Mangroves. Oxford University Press. USA

Hoguane, A (1998) Information on Eastern African sea level – Mozambique. Unpublished

Holdridge L, Greeke W, Hatheway W, Liang T, Tosi J (1971) Forest Environment in Tropical Life Zones. Pergamon Press. New York.

Instituto Nacional de Estatística. Quadros do 3° Censo Geral da População e Habitação 2007". http://www.ine.gov.mz/censo07. Retrieved 2010-12-23

Jupiter SD, Potts DC, Phin SR, Duke NC (2007) Natural and anthropogenic changes to mangrove distributions in the Pioneer River Estuary (QLD, Australia). Wetlands ecology and Management 15: 51-62

Kairo JG, Kyviatu B, Koedam N (2002a) Application of remote sensing and GIS in the management of mangrove forests within and adjacent to Kiunga Marine Protected Area, Lamu, Kenya. Environment, development and sustainability 4: 153-166

Kairo JG, Dahdouh-Guebas F, Gwada P, Ochieng C, Koedam N (2002b) Regeneration status of mangrove forests in Mida Creek, Kenya: A compromised or secured future? Ambio 31: 562-568

Kairo JG, Langat JS, Dahdouh-Guebas F, Bosire J, Karachi M (2008) Structural development and productivity of replanted mangrove plantations in Kenya. Forest Ecology and Management 255: 2670-2677

Kettenring K, McCormick M K, Baron H M, Whigham D F (2010) *Phragmites australis* (common reed) invasion in the Rhode River subestuary of the Chesapeake Bay: disentangling the effects of foliar nutrients, genetic diversity, patch size, and seed viability. Estuaries and Coasts 33: 118-126

Krausse G, Bock M, Weiers S, Braum G (2004) Mapping land-cover and mangrove structures with remote sensing techniques: a contribution to a synoptic GIS in support of coastal management in north Brazil. Environmental Management 34: 429-440

Kristensen E, Bouillon S, Dittmar T, Cyril M (2008) Organic carbon dynamics in mangrove ecosystems: A review. Aquatic Botany 89: 201-219

Krutilla K, Hydeb W, Barnesc D (1995) Peri-urban deforestation in developing countries. Forest Ecology and Management 74: 181-195

Komiyana A, Ong JE, Poungpam S (2008) Allometry, biomass and productivity of mangrove forests: A review, Aquatic Botany 89: 128-137

Kovacs JM, Wang J, Flores-Verdugo F (2005) Mapping mangrove leaf area index at the species level using IKONOS and LAI-2000 sensors for the Agua Brava Lagoon, Mexican Pacific. Shelf Science 62: 377-384

Laegdsgaard P, Johnson C (2001) Why do juvenile fish utilise mangrove habitats? Journal of Experimental Marine Biology and Ecology 251: 229-253

Lang'at, J (2010) Species mixing boosts the below-ground root production of mangrove trees. Paper presented in: 2nd International Conference on Aquatic Resources of Kenya (ARK II) – Aquatic Research for Development. 16th-19th November 2010, Naivasha, Kenya

LeMarie M, van der Zaag P, Menting G, Baquete E, Schotanus D (2006). The use of remote sensing for monitoring environmental indicators: The case of the Incomati estuary, Mozambique. Physics and Chemistry of the Earth 31: 857-863

Mumby P (2006) Connectivity of reef fish between mangroves and coral reefs: algorithms for the design of marine reserves at seascape scales. Biological Conservation 28: 215-222

Naidoo G (2009) Differential effects of nitrogen and phosphorus enrichment on growth of dwarf *Avicennia marina* mangroves. Aquatic Botany 90: 184-190

Neukermans G, Dahdouh-Guebas F, Kairo KG, Koedam N (2007) Mangrove species and stand mapping in Gazi Bay (Kenya) using quickbird satellite imagery. Spatial Science 52: 75-86

Neukermans G, Koedam, N (2014) Saco da Inhaca mangrove vegetation mapping and change detection using very high resolution satellite imagery and historic aerial photography. In: Bandeira S, Paula J (eds.) The Maputo Bay Ecosystem, WIOMSA, Zanzibar Town, pp 131-134

Ramirez-Garcia P, Lopez-Blanco J, Ocana D (1998) Mangrove vegetation assessment in the Santiago River Mouth, Mexico, by means of supervised classification using Landsat TM imagery. Forest Ecology and Management 105: 217-229

Rakotomavo A, Fromard F (2010) Dynamics of mangrove forests in the Mangoky River delta, Madagascar, under the influence of natural and human factors. Forest Ecology and Management 259: 1161-1169

Saket M, Mathusse R (1994) Study for the determination of the rate of deforestation of the mangrove vegetation in Mozambique. FAO/PNUD/MOZ/92/013. Unidade de Inventário Florestal Departamento de Florestas DNFFB. Min da Agricultura, Maputo

Sengo DJ, Kachapila, A, van der Zaag P, Mul M, Nkomo S (2005) Valuing environmental water pulses into the Incomati estuary: Key to achieving equitable and sustainable utilization of transboundary waters. Physics and Chemistry of the Earth 30: 648-657

Simard M, Zhang K, Rivera-Monroy VH, Ross MS, Ruiz PL, Castañeda-Moya E, Twilley RR, Rodriguez E (2006) Mapping height and biomass of mangrove forests in Everglades National Park with SRTM elevation data. Photogrammetric Engineering & Remote Sensing 72: 299-311

Sherman RE, Fahey TJ, Battles JJ (2000) Small-scale disturbance and regeneration dynamics in a neotropical mangrove forest. Journal of Ecology 88: 165-178

Taylor M, Ravilious C, Green P (2003) Mangroves of East Africa. UNEP-WCMC

Thampanya U, Vermaat J, Sisamkul S, Panapitukkul N (2006) Coastal Erosion and Mangrove Progradation of Southern Thailand. Estuarine Coastal and Shelf Science 68: 75-85

Twilley R, Pozo M, Garcia V, Rivera-Monroy V, Zambrano R, Bodero A (1997) Litter dynamics in riverine mangrove forests in the Guayas River Estuary, Ecuador. Oecologia 111: 109-112

UNEP/Nairobi Convention Secretariat (2009) Transboundary diagnostic analysis of Land-based sources and activities affecting the Western Indian Ocean Coastal and Marine Environment. UNEP Nairobi, Kenya. 378 pp

Valiela I, Bowen J, York J (2001) Mangrove Forests: One of the World's Threatened Major Tropical Environments. BioScience 51: 807-815

Vasquez EA, Glenn EP, Brown JJ, Guntenspergen GR, Nelson S (2005) Salt tolerance underlies the cryptic invasion of North American salt marshes by an introduced haplotype of the common reed *Phragmites australis* (Poaceae). Marine Ecology Progress Series 298: 1-8

Walters B (2005) Ecological effects of small scale cutting of Philippine mangrove forests. Forests Ecology and Management 206: 331-348

Walters B, Roönnbäck P, Kovacs J, Crona B, Hussain S, Badola R, Primavera J, Barbier E, Dahdouh-Guebas F (2008) Ethnobiology, socio-economics and management of mangrove forests: A review. Aquatic Botany 89: 220-236

Wickramasinghe S, Borin M, Kotagama S, Cochard R, Anceno AJ, Shipin O (2009) Multi-functional pollution mitigation in a rehabilitated mangrove conservation area. Ecological Engineering 35: 898-907

Ye Y, Tam N, Wong Y (2001) Livestock Wastewater Treatment by a Mangrove Pot Cultivation System and the Effect of Salinity on the Nutrient Removal Efficiency. Marine Pollution Bulletin 42: 512-520