Western Indian Ocean J. Mar. Sci. Vol. 10, No. 1, pp. 25-38, 2011

Mangrove Forests of Northern KwaZulu-Natal: Sediment Conditions and Population Structure of the Largest Mangrove Forests in South Africa

Anusha Rajkaran and Janine Adams

Botany Department, PO Box 77000, Nelson Mandela Metropolitan University (NMMU), Port Elizabeth, South Africa, 6031.

Keywords: Population structure, mangrove distribution, *Avicennia marina*, *Bruguiera gymnorrhiza*, *Rhizophora mucronata*.

Abstract—The state of mangroves in the large forests of northern KwaZulu-Natal (KZN), South Africa, was assessed in terms of sediment characteristics and population structure in 2007. The tallest trees with the widest diameter at breast height were found at Mhlathuze (*Avicennia marina*) and Echwebeni (*Bruguiera gymnorrhiza* and *Rhizophora mucronata*) in Richards Bay. The height of trees at these estuaries increased with the age of the forest stands (2.4 m in the youngest to 14.3 m in the oldest stands). In South Africa, *Ceriops tagal* and *Lumitzera racemosa* occur under a narrow range of environmental conditions as they are only found at Kosi Bay. *Avicennia marina* and *Bruguiera gymnorrhiza* were found in all estuaries sampled in a wide range of conditions, from highly oxidised sediments (+125 to + 322.7 mV) to those that were very reduced (-360 to -35.8 mV), and from freshwater to saline conditions. *Bruguiera* occurred in drier habitats and tree density was negatively correlated with sediment moisture content. The density of *Avicennia marina* was not significantly correlated with any sediment parameter while the density of *Rhizophora mucronata* was positively correlated with pore water temperature. Although most forests were regenerating, indicated by their population structure (i.e. inverse, J-shaped curves), management plans are needed for each forest to ensure their long-term conservation as these mangroves have shown vulnerability to change in the past.

INTRODUCTION

In Africa, mangroves are a valuable resource for building, fire-making and trading, but it is the ecological services of mangrove forests that are most valuable (Gilbert and Janssen, 1998; Alongi, 2002; Dahdouh-Guebas *et al.*, 2005; Walters *et al.*, 2008). The products and services provided by a hectare of mangrove forest is valued at 200 000 – 900 000 USD (FAO 2003, Gilman *et al.*, 2008). The most recent estimate of mangrove cover along the coastline of Africa was 3 350 813 ha (FAO 2003) and South Africa has 0.05% of that area. In South Africa, their

Corresponding author: JA
E-mail: Janine.Adams@nmmu.ac.za.

natural distributional limit is at Kobonqaba Estuary (32°0'S, 28°29'E) in the Eastern Cape (Ward & Steinke, 1982; Adams *et al.*, 2004). The total mangrove cover in South Africa, as recorded by Ward and Steinke (1982), was 1058 ha. More recently, this has increased to 1634.7 ha (Pillay, pers. comm.; Adams *et al.*, 2004). The mangrove cover in KwaZulu-Natal (KZN) has increased from 786.0 to 1391.1 ha (Pillay, pers. com.), largely due to their expansion in the Mhlathuze Estuary. *Avicennia marina* (Forssk. Vierh.) is the most common of the six mangrove species in South Africa. It occurs in 24 estuaries, extending from Kosi Bay in KZN to the Nahoon Estuary in the Eastern Cape, where it was planted. It is considered a pioneer species and grows in both sand and mud (Steinke, 1999). *Bruguiera gymnorrhiza* (L.) Lam is also common throughout the east coast of South Africa and occurs in 33 estuaries. *Rhizophora mucronata* Lam. is found sporadically along the coast in five of the Eastern Cape estuaries and seven of the KZN estuaries. *Ceriops tagal* Perr. C.B.Robinson, *Lumnitzera racemosa* Willd. and *Xylocarpus granatum* König 1784 are only found at Kosi Bay in South Africa (Ward & Steinke, 1982; Steinke, 1999).

An assessment of the population structure of mangrove forests and comparison with past data can indicate how the populations respond to environmental conditions and regenerate from past disturbances (Sherman *et al.*, 2001, Dahdouh-Guebas & Koedam, 2002, Piou *et al.*, 2006, Rajkaran & Adams, 2010). Mangrove forests in the northern estuaries of the east coast of South Africa (Fig. 1) have been influenced by both natural and anthropogenic disturbances. Cyclones, such as Cyclone Claude in 1966 and Domoina and Imboa in 1983-1984 are infrequent, but their negative effects on the structure of the mangrove forests were well-documented (Moll *et al.*, 1971, Steinke & Ward 1989). Freshwater abstraction and poor bridge design has caused the mouths of some mangrove estuaries to close to the sea more frequently, leading to long-term inundation of roots and subsequent death of the mangroves (Breen and Hill, 1969; Bruton, 1980; Begg, 1978, Rajkaran *et al.*, 2009). More recently, large swells (KZN – 2007) have caused localised changes in environmental conditions in estuaries where mangroves are found (e.g. the mouth of St Lucia was opened after being closed for six years in 2002-2007 due to extreme waves; Taylor, pers. comm.). Rising water levels have been one of the main factors that have lead to localised mangrove disturbances and mortalities in Kosi Bay (1965-1966) and Mgobezeleni Estuary (74 km south of Kosi Bay) (Bruton, 1980). A further complication at Kosi Bay is the increasing number of fish traps in the tidal basin. Green *et al.* (2006) noted that fish traps lead to subsequent spreading of the mangroves through propagule trapping and sediment deposition. Generally, mangrove sediments are dominated by small particle sizes, usually from riverine sources, but they also include some marine sediment (Lovelock *et al.*, 2007). Particle size and composition of the sediment has a major influence on other biogeochemical characteristics such as redox potential, pH and organic and moisture content (Clarke & Kerrigan, 2000). These in turn affect the growth and population dynamics of mangrove populations and the exchange of organic materials with the near-shore environment. The age of a forest will also influence sediment characteristics such as organic content (27 year old forest – 12%, >50 yr old forest – 38%; McKee & Faulkner, 2000).

This paper investigated the present population structure and sediment characteristics of the mangrove forests at the following estuaries: Kosi Bay (27°0'S; 32°50'E), which lies on the border of South Africa and Mozambique, St Lucia (28°18'S; 32°26'E) and two forests in Richards Bay, viz. Echwebeni (28°48'S; 32°03'E), in the Richards Bay Harbour and Mhalthuze Estuary (28°47'S; 32°06'E) (Fig. 1).The purpose of this study was to determine the state of mangroves in the large forests of northern KwaZulu-Natal by assessing their population structure and relationship with sediment characteristics. The current population structure will determine their state of regeneration, degradation or colonisation (Dahdouh-Guebas & Koedam, 2002), and will add to an understanding of their management requirements for their conservation. The sediment conditions in a forest influence species distribution, as well as long-term growth and survival. Management of these forests is important and long-term monitoring is required to predict threats to their survival. Such long-term monitoring requires baseline data with regard to population structure and sediment characteristics which are provided in this paper.

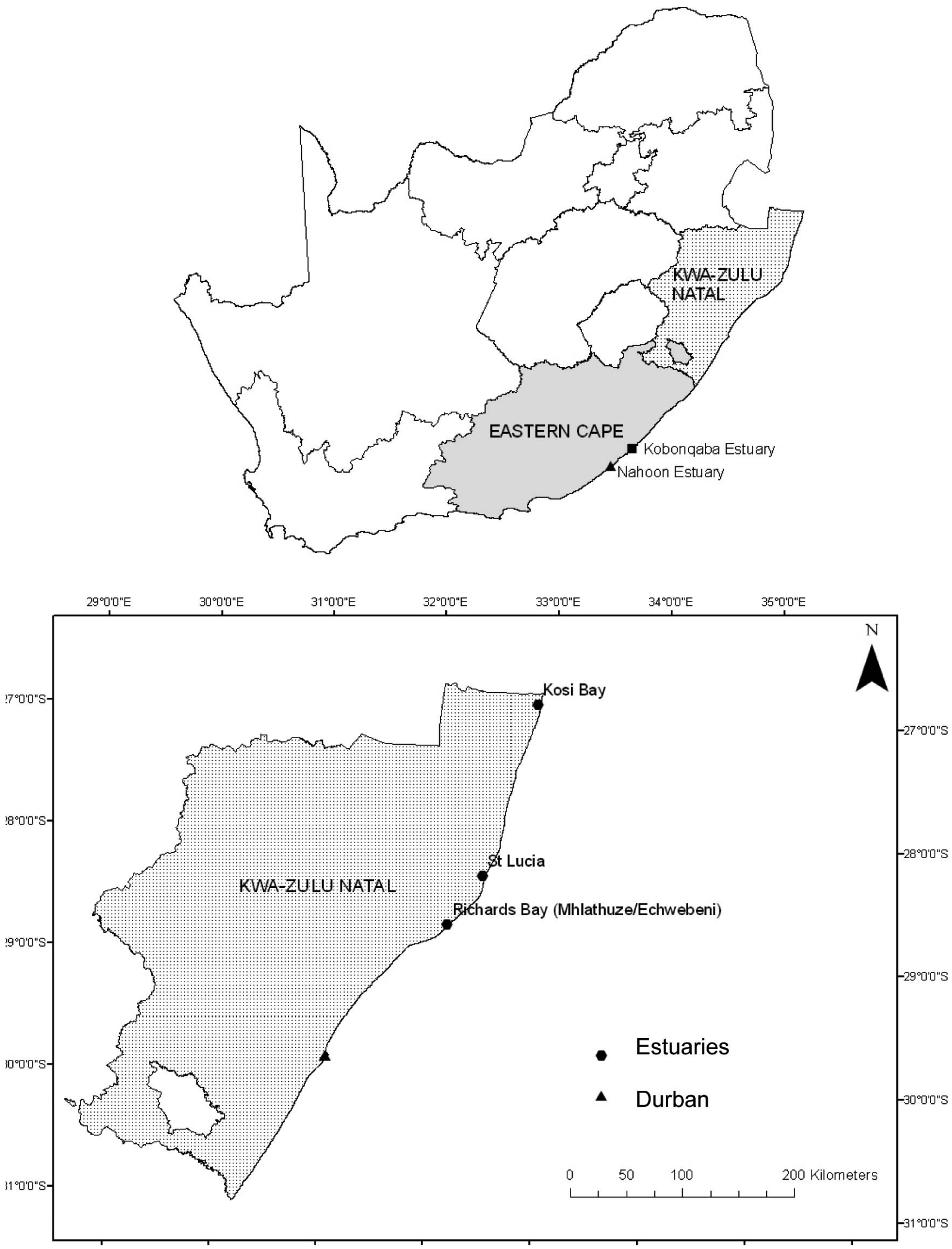

Figure 1. Location of mangrove study sites in KwaZulu-Natal estuaries, South Africa.

MATERIALS AND METHODS

Estuary descriptions

Kosi Bay

All estuaries with mangroves considered in this study fall within the subtropical east coast bio-geographical region of South Africa (Whitfield, 1998). The mean monthly rainfall at Kosi Bay was 79.9 mm. month^{-1} during the period 1951-2007, while the mean annual rainfall in the same period was 945 mm.yr^{-1}. Minimum temperatures in the region range from 11-22°C, with maxima of 23-29°C. A changing sea level and fluvial hydrodynamic regime during the Pleistocene and Holocene lead to changes in the coastline and the formation of the Kosi Estuary/Lake system (Wright *et al.*, 1997). A negligible increase in the area of mangrove forest from 59 ha (Ward & Steinke, 1982) to 60.7 (Pillay, pers. comm.) has occurred in recent years. There is a diversity of habitats and plant communities, which range from freshwater swamps, reeds and sedges to mangrove forests. There are two mangrove communities in Kosi Bay, viz. the mangrove associates (*Barringtonia racemosa* (L.) Roxb. and *Hibiscus tiliaceus* L.), and the mangrove proper (six species) which forms a fringing mangrove forest. Salinity in the tidal basins where the main mangroves areas are located may drop as low as 8 PSU during a spring low tide (Wright *et al.*, 1997). Kosi Bay is made up of four linked water-bodies that are influenced by freshwater at the head and seawater close to the mouth (Wright *et al.*, 1997). This results in a transition from freshwater to brackish water in the upper lakes to marine-dominated water in the tidal basin.

St Lucia Estuary

The mean monthly rainfall at St Lucia was 109.1 mm. month^{-1} during the period 1918-2007, while the mean annual rainfall for the same period was 1261 mm.yr^{-1}. Minimum temperatures ranged from 11.9-23.1°C in the period 1970-2007, with maxima from 19.6 -30.9°C. The St Lucia Estuary is the largest coastal lagoon in Africa. The surface area of the entire system is 350 km^{2} and its average depth is 0.9 m, i.e. it has a large surface area to volume ratio. The system consists of two parts; Lake St Lucia (North Lake, False Bay, South Lake) and St Lucia Estuary (consisting of the Narrows of 21 km), totalling 60 km in length, with tidal exchange during open mouth conditions (Taylor *et al.*, 2008). Mangroves extend from the mouth to where South Lake enters the Narrows, on both sides of the channel. The mangrove area has increased from 160 ha (Ward & Steinke, 1982) to 571 ha (Pillay, pers. comm.). Two mangrove species (*Avicennia marina* and *Bruguiera gymnorrhiza*) occur in the mid-tide to extreme spring-high tide level and form a fringing mangrove forest. The main physical determinates for this vegetation unit were tidal exchange, salinity, water level, inundation and temperature (Taylor *et al.*, 2008).

Richards Bay

The mean monthly rainfall at Richards Bay was 133.9 mm. month^{-1} during the period 1951-2007, while the mean annual rainfall for the same period was 1176 mm.yr^{-1}. Minimum temperatures ranged from 6.5-23.2°C in the period 1970-2007, with maxima from 10.3-32.4°C. The Richards Bay embayment consists of the Richards Bay Harbour, constructed in 1960, and the Mhlathuze Estuary. The Echwebeni Site of Conservation Significance is located in the harbour area. The site covers an area of approximately 54 ha. Three mangrove species are present at Echwebeni (*Avicennia marina*, *Bruguiera gymnorrhiza* and *Rhizophora mucronata*). Tides in the harbour are semi-diurnal, with an average neap tidal range of 0.52 m and a spring tidal range of 1.8 m (Schoonees *et al.*, 2006). Mangroves in the Mhlathuze Estuary function as a fringing mangrove forest (*Avicennia marina*, *Bruguiera gymnorrhiza*, *Rhizophora mucronata*) and cover an area of 652 ha (Ward & Steinke, 1982; Riddin, 1999). Richards Bay Harbour was constructed in the upper portion of the original estuary, while the sanctuary is in the lower portion and is referred to as Mhlathuze Estuary. A new mouth was constructed for the sanctuary, which resulted in a number of changes in the physical functioning of the estuary. The cross-section area of the new mouth increased after construction from 200 to 900 m^{-2} due to tidal scour. The tidal range increased from 0.1 m to 0.9 m and this resulted in the expansion of mangroves, mainly *A. marina* (Bedin, 2001; Rajkaran, 2011).

Study methods

Sediment characteristics

Mangroves in Kosi Bay, St Lucia Estuary and Mhlathuze Estuary were sampled on a spring tide at the end of April 2007. Echwebeni, situated in the harbour of Richards Bay, was sampled in September 2008. The KZN coastline experienced a sea storm with large swells (in height and frequency) during 19-22 March 2007 before sampling took place and, as a result, the mouth of St Lucia was opened after being closed for an extended period of time (June/July 2002-March 2007). The mouth closed again after 175 days in August 2007. All systems were tidal at the time of sampling. Three replicate holes were augured for sediment analysis at each site. Sediment was collected at two depths, the surface and 50 cm. All sediment was collected at low tide; redox potential (mV) and pH were not measured in the field but within 12 hours of collection (Middelburg *et al.*, 1996; Marchand *et al.*, 2004). Redox was measured using a Metrohm oxidation-reduction potential platinum electrode attached to a pH/redox meter (EDT Instruments, RE 357 Microprocessor, series 3) according to the methods of The Non-Affiliated Soil Analyses Working Committee (1990). pH was measured using a pH probe glass electrode (Mettler Toledo InLab 407) attached to an EDT Instruments, RE 357 Microprocessor, Series 3 pH meter, calibrated at pH 4.0 and 7.0 (Black, 1965). Moisture content (Black, 1965), organic content (Briggs, 1977), particle size (Day, 1965; Gee & Bauder, 1986) and electrical conductivity (EC-CyberScan 200 Handheld salinity, conductivity and temperature meter) were measured in the laboratory. In the field, pore water electrical conductivity, salinity and temperature were measured in each augured hole using a YSI 63 (Handheld salinity, conductivity and temperature meter). Depth to the water table was measured using a meter stick. The number of sites sampled per forest was determined by the population structure of the forest and the species composition.

Mangrove characteristics

A number of 25 m^2 quadrats was sampled at different sites in each estuary (Kosi Bay: 6 sites with 4 quadrats at each site; St Lucia: 2 sites with 4 quadrats at each site; Mhlathuze: 5 sites with 4 quadats at Site 1-3, 13 at Site 4 and 28 at Site 5; Echwebeni: 3 sites with 3 quadrats each) to determine the population structure of the mangroves. Site locations were determined by the distribution of mangroves so as to capture the population structure of each species. The position of each quadrat at each site was randomly selected. Seedlings (<100 cm), saplings (>100-129 cm) and trees (>130 cm) of all mangrove species were identified. The height of seedlings and saplings was measured. Height and diameter of each adult mangrove tree were measured at breast height (DBH = 1.3 m). If a tree was multi-stemmed, then only the main stem was measured.

Statistical analysis

The skewness and kurtosis of the population structure and the sediment and pore water data were tested to determine their normality. The data were not normally distributed and non-parametric tests were used to determine differences between estuaries, sites and depths. Kruskal-Wallis ANOVA was used to test between-site and depth differences and a multiple comparison of mean ranks was used to further test between individual means. All statistical analyses were run using Statistica (Version 8.0, 2008), and significance was determined at $p<0.05$ (StatSoft Inc. 2007).

RESULTS

Population structure

Lumitzera racemosa and *Ceriops tagal* were only found at Kosi Bay as this is the southern distribution limit for these species. At Mhlathuze Estuary, the average mangrove tree density was significantly lower ($H_{(df=3, N=198)} = 35.40$ $p < 0.05$; Table 1) than the other estuaries. The density of

Table 1. Population characteristics of each mangrove species (average±standard error) in some South African estuaries (*Avicennia marina*-AM, *Bruguiera gymnorrhiza*-BG, *Ceriops tagal*-CT, *Lumnitzera racemosa*-LR, *Rhizophora mucronata*-RM).

Estuary	Species	Density (number of individuals.ha^{-1})				Basal area (m^2.ha^{-1})
		Species	Seedling	Sapling	Tree	
Kosi Bay	AM	32 040 ± 8 495	28 780	183	1 383	5.7 ± 0.7
	BG	22 119 ± 4 544	18 733	1 316	2 066	3.4 ± 0.1
	RM	24 700 ± 9 299	20 850	1 000	2 850	6.3 ± 0.8
	CT	28 800 ± 1 911	19 500	3 200	6 100	2.3 ± 0.2
	LM	2 866 ± 948	933	0	1 933	4.7 ± 0.1
Mean		22 104 ± 5 100	17 759 ± 4 572	1 139 ± 570	2 866 ± 841	4.5 ± 0.7
St Lucia	AM	2 400 ± 954	800	0	1 600	12.1 ± 1.0
	BG	11 400 ± 5 373	0	0	11 400	4.0 ± 0.2
Mean		6 900 ± 4 500	400 ± 400	0	6 500 ± 4 900	8.2 ± 4.0
Mhlathuze	AM	6 982 ± 1 034	2 540	84	4 357	21.8 ± 0.5
	BG	11 900 ± 3 615	10 600	322	977	2.7 ± 0.1
	RM	2 200 ± 1 014	1 400	50	750	3.6 ± 0.7
Mean		7 027 ± 2 800	4 846 ± 2 895	152 ± 85	2 028 ± 1 166	9.1 ± 6.4
Echwebeni	AM	37 933 ± 13 884	23 466	533	13 933	6.4 ± 0.8
	BG	20 711 ± 6782	10 044	1 333	9 333	6.3 ± 0.3
	RM	78 000 ± 6157	64 533	6 666	6 800	5.8 ± 0.5
Mean		45 548 ± 16 970	32 681 ± 16 390	2 844 ± 1 924	10 022 ± 2 087	6.1 ± 0.2

Avicennia marina and *Bruguiera gymnorrhiza* trees was significantly lower at Mhlathuze Estuary compared to other sites (AM - $H_{(3, N= 88)}$ =26.50 p<0.05; BG - $H_{(3, N= 75)}$ =9.68 p <0.05), whereas the density of *Rhizophora mucronata* was similar at all estuaries where this species was found ($H_{(2, N= 19)}$ =2.96 p >0.05).

The greatest numbers of seedlings occurred at Echwebeni. This mangrove forest also had significantly more saplings of *Rhizophora mucronata* than the other estuaries ($H_{(2, N= 19)}$ =9.82 p <0.05). While there were no *Avicennia marina* saplings at St Lucia and Mhlathuze ($H_{(3, N= 88)}$ =23.63 p <0.05), there were no *Bruguiera gymnorrhiza* saplings at St Lucia. Overall, *Avicennia marina* saplings were significantly more abundant than *Bruguiera gymnorrhiza* ($H_{(3, N= 198)}$ =27.81 p <0.05). *Avicennia marina* trees were significantly taller at Mhlathuze and significantly shorter at Kosi Bay ($H_{(3, N= 823)}$ =290.93 p <0.05), while *Bruguiera* trees were significantly taller at Echwebeni (BG - $H_{(3, N= 716)}$ =273.14 p <0.05). *Rhizophora mucronata* trees were also taller at Echwebeni compared to Mhlathuze and Kosi Bay (RM - $H_{(2, N= 122)}$ =17.84 p <0.05; Fig. 2).

There were no significant differences (p > 0.05) between surface and bottom (50 cm) sediments at all sites in terms of moisture content, organic content, redox potential, pH and electrical conductivity. Average data are therefore presented for each estuary (Table 2). Site differences were found for some sediment parameters (see Rajkaran, 2011). Kosi Bay is a sand-dominated estuary compared to the other estuaries (Fig. 3). Similar quantities of silt (3.91– 62.5 µm) and clay (<3.91 µm) were found at Echwebeni, Mhlathuze and St Lucia. These values were significantly higher than those found at Kosi Bay: silt ($H_{(3, N= 96)}$ =74.84, p <0.05), clay ($H_{(3, N= 96)}$ =71.57, p <0.05). The following sand fractions were dominant at Kosi Bay: 250–500 µm (medium sand); 125–250 µm (fine sand) and 62.5–125 µm (very fine sand).

The moisture content of the sediment was significantly lower at Kosi Bay than St Lucia, Mhlathuze and Echwebeni ($H_{(3, N= 36)}$ =42.6, p <0.05, Table 2). Correlation analysis showed that moisture content was positively correlated to the amount of silt (r = 0.8, p<0.05)

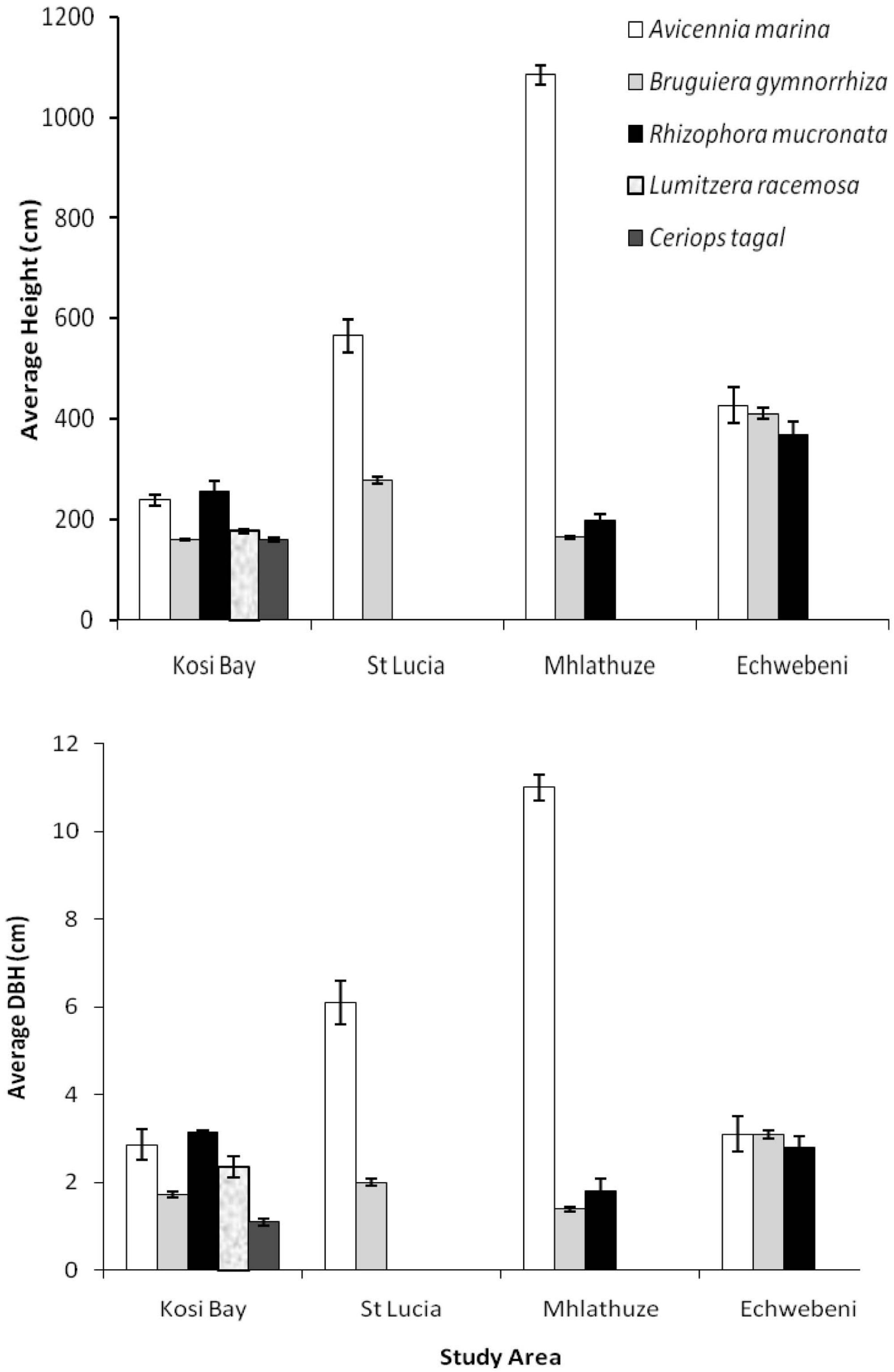

Figure 2. Average Height and DBH (with SE) of adult mangrove populations in some South African estuaries.

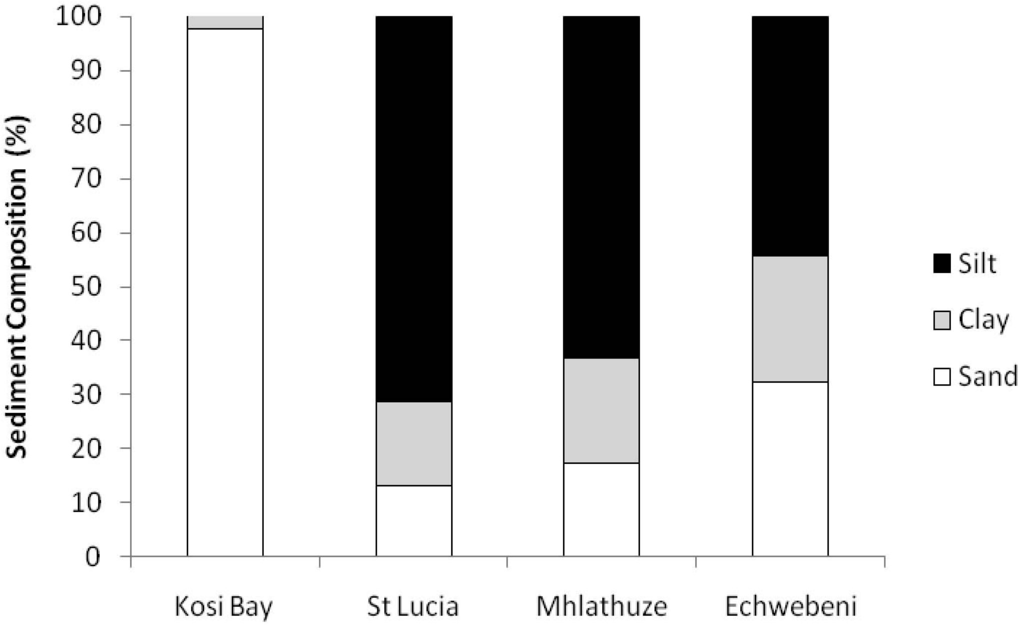

Figure 3. Sediment composition at mangrove study sites in some South African estuaries.

and organic matter (r = 0.6, $p<0.05$) in the sediment. The sediment organic content was similar at Kosi Bay, St Lucia and Mhlathuze (6-10%) but significantly higher at Echwebeni (>22%; Table 2). A range of oxidised to strongly reduced conditions were measured at the different estuaries, with reduced conditions at Mhlathuze and Echwebeni (-65 to -300 mV). The pH was similar at Kosi Bay, St Lucia and Mhlathuze but was significantly higher at Echwebeni (Table 2). Sediment electrical conductivity was significantly lower at St Lucia and Echwebeni compared with Kosi Bay and Mhlathuze (Table 2).

Pore water characteristics

The pore water salinity was significantly lower at Echwebeni than Kosi Bay and Mhlathuze (Table 2). The temperature of the pore water was significantly higher at Kosi Bay than all other estuaries (Table 2). The depth to the water table was significantly shallower at Mhlathuze and Echwebeni compared to St Lucia and Kosi Bay.

The prevailing sediment characteristics for each mangrove species provide an idea of the conditions required for their growth. Table 3 shows that, in South Africa, *Ceriops tagal* and *Lumitzera racemosa* occur under a narrow range of conditions as these two species only occur at Kosi Bay. Both species occur in oxidised sediments (high redox potential), in fairly saline conditions. The density of *Ceriops tagal* was positively correlated with the depth to the water table, while that of *Lumitzera racemosa* was not correlated with any parameter (Table 4). *Avicennia marina* and *Bruguiera gymnorrhiza* were found in a wide range of conditions (Table 3), from highly oxidised to reduced sediments, and from freshwater to saline conditions. The density of *Avicennia* was not significantly correlated with any sediment characteristics but the density of *Bruguiera* was greater in areas with lower moisture content. The density of *Rhizophora mucronata* was significantly correlated with pore water temperature (Table 4).

DISCUSSION

The largest mangrove areas in South Africa occur in northern KwaZulu-Natal and, to ensure their conservation, an understanding of their population structure and relationship with prevailing environmental characteristics is needed. Most of these forests showed

Table 2. Sediment characteristics of all mangrove sites (average ± standard error) and Kruskal-Wallis Multiple Comparison (2-tailed) test on significant differences between study areas (KB – Kosi Bay; STL – St Lucia; MHL – Mhlathuze; ECH – Echwebeni (Df = 3, P < 0.05).

	P < 0.05	**Kosi Bay (ECH, N = 9)**	**St Lucia (STL, N = 6)**	**Mhlathuze (MHL, N = 15)**	**Echwebeni (KB, N = 18)**
Moisture content (%)	KB < MHL/ECH	24.4 ± 0.7	37.2 ± 2.2	42.8 ± 5.0	68.3 ± 1.9
Organic content (%)	ECH > KB/MHL	6.6 ± 1.7	8.5 ± 1.1	10.1 ± 2.5	28.9 ± 2.3
Redox potential (mV)	KB/SLT > MHL; ECH < KB/STL	199.3 ± 3.9	282.8 ±17.1	-13.6 ± 42.1	-375.8 ± 11.9
pH	ECH > KB/ST/MHL	6.8 ± 0.1	6.2 ± 0.3	7.2 ± 0.1	8.1 ± 0.1
Sediment EC (mS)	STL/ECH < MHL/KB	36.9 ± 0.5	18.9 ± 1.7	32.8 ± 2.0	21.9 ± 4.0
Pore water salinity (PSU)	ECH < KB/STL/MHL	32.6 ± 0.9	29.6 ± 1.2	30.9 ± 3.7	18.8 ± 2.9
Pore water temperature (^{o}C)	KB > STL/MHL/ECH	25.5 ± 0.1	22.0 ± 0.05	23.2 ± 0.6	12.9 ± 1.1
Depth to water table (cm)	MHL/ECH < STL/KB	35.6 ± 2.8	26.7 ± 2.4	20.8 ± 0.2	6.6 ± 1.7

Table 3. Comparison of ranges of sediment and pore water characteristics for the five mangrove species found at the study sites.

	Avicennia marina	*Bruguiera gymnorrhiza*	*Rhizophora mucronata*	*Ceriops tagal*	*Lumnitzera racemosa*
Sediment conductivity (mS)	18.9 - 46.1	10.2 - 46.0	10.2 - 39.7	34 - 39	34.2 - 39.7
Sediment salinity (PSU)	11.2-29.8	5.7-29.8	5.7-25.3	21.3-24.8	21.4-25.3
Pore water salinity (PSU)	9.5 - 52.1	4.7 - 52.1	4.7 - 34.8	30.6 – 34	18.1 - 35
Redox (mV)	-360.5 to +307.4	-427 to +322.7	-401 to +215.1	+199 to +215.0	+194.4 to +224.2
pH	7.02 -7.6	5.5 - 7.6	6.4 - 8.3	5.5 - 8.3	5.5-7.9

Table 4. Spearman rank order correlations between sediment parameters and species density of South African mangroves. Significant values are in bold.

	Avicennia marina	*Bruguiera gymnorrhiza*	*Rhizophora mucronata*	*Ceriops tagal*	*Lumnitzera racemosa*
Moisture Content	-0.06	**-0.65**	-0.36	-0.50	-0.27
Pore water temperature	0.47	0.29	**0.70**	0.36	0.50
Depth to water table	-0.24	0.37	0.46	**0.62**	0.19

an inverse J-shaped curve in the height distribution of individuals which implies that they were regenerating. Kosi Bay is the only mangrove forest in South Africa where all six species of mangroves occur. The height of adult trees at Kosi Bay was significantly shorter than in other forests, but the number of seedlings was high with the exception of *Lumitzera racemosa* where there were more adults than seedlings in the areas sampled. The height and basal cover of this species were ~2 m and 4.7 $m^2.ha^{-1}$ respectively. The average height of *Ceriops tagal* was less than 2 m and it had a basal cover of 2.3 $m^2.ha^{-1}$, which was similar to stands at Gazi Bay in Kenya (height 2.1-3.8 m, BA 2.7-5.4 $m^2.ha^{-1}$; Bosire *et al.*, 2008). Both these species are widely distributed from East Africa to Australia, but reach their southern distributional limit at Kosi Bay in South Africa. The sandy sediments and lack of nutrients, particularly phosphorus, in this system may be the reason for the short stature of this species (Lin & Sternberg, 2007). There were signs of harvesting of trees for fish traps in Kosi Bay. In particular, branch harvesting of *Lumnitzera racemosa* appeared to be changing the morphology of the plants. It is important that long-term monitoring tracks the state of the mangroves in Kosi Bay as this is the most diverse mangrove estuary in South Africa.

Only *Avicennia marina* and *Bruguiera gymnorrhiza* occurred at St Lucia Estuary and no seedlings or saplings of these species were found. The average pore water salinity at St Lucia was 29 PSU, while the sediment electrical conductivity was 18.9 mS. Naidoo (1990) reported that the optimal growth for *Bruguiera* occurred at 8-26 PSU and that higher salinities increased mortality. Kirui *et al.* (2008) found that the interaction between salinity and light was the main factor limiting the survival of *Bruguiera* saplings at Gazi Bay in Kenya. While these environmental factors may be important, the present lack of *Bruguiera* seedlings and saplings at St Lucia should be investigated further, as there are indications that herbivory by kudu may be causing this. Drought and prolonged closure of the estuary mouth to the sea has also restricted tidal inundation in the mangrove areas.

The largest trees of *Bruguiera gymnorrhiza* and *Rhizophora mucronata* were found at Echwebeni. These mangroves are at risk due to their location in Richards Bay Harbour but their conservation is important as they may be the oldest stand of mangroves in South Africa. Port authorities should implement an ongoing monitoring programme so that adverse changes can be immediately detected. Naidoo and Chirkoot (2004) showed that coal dust reduced mangrove photosynthesis, a problem in Richards Bay. General management issues include the clearing of pollutants (plastic and industrial) and further developments behind the mangroves should be prevented to allow the mangroves space to respond to stresses such as sea level rise.

Avicennia marina, *Bruguiera gymnorrhiza* and *Rhizophora mucronata* occur in Mhlathuze Estuary and mangroves cover the largest area (652 ha) relative to the other estuaries. Mangrove progression rates after creation of this "new" estuary with the construction of its mouth were measured by Bedin (2001) to be 20-55 ha year^{-1} from 1976 to 1982 and 5.4 ha year^{-1} from 1982-1995. The height of the trees measured in this study increased with the age of the sites (2.38 m in the youngest to 14.3 m in the oldest stands). McKee and Faulkner (2000) compared the height, DBH and basal area of different species in different age forests. While younger forests (3-6 years) had a higher density (11 000-41 100 per ha) with a stand height of 1.9-7.5 m, the DBH of older forests (>50 years) was between 94.0-11.4 cm and their stand height was between 7.4 – 22.7 m.

Sediment characteristics affect the growth and population dynamics of mangroves and the exchange of organic materials with the near-shore environment (Ellison & Farnsworth, 1993; Kristensen *et al.*, 2008). Sediment particle size has been correlated with redox potential, pH, organic content and nutrients in coastal sediments as it affects the permeability of the substratum (Wilson *et al.*, 2008). One of the reasons mangrove forests are able to regenerate after disturbance is their ability to retain nutrients in the sediment (Alongi, 2008). Kosi Bay does not have this function due to its sandy sediment composition and it is therefore vulnerable to change. Salinity is known to have a marked effect on the growth and physiology of mangroves. This study showed that *Avicennia marina*, *Bruguiera gymnorrhiza*, *Rhizophora mucronata* were found in a range of salinity from freshwater to saline but never above 52 PSU. Temperatures ranged from 15°C (min) to 25-30°C (max) at St Lucia and Richards Bay (37 years; WeatherSA). Pore water temperatures in this study were always above 20°C and were positively correlated with the density of *Rhizophora mucronata*. In South Africa, *Ceriops tagal* and *Lumitzera racemosa* occur only at Kosi Bay under a narrow range of conditions, but other studies have shown that these species occur in wider environmental conditions (Clarke & Kerrigan, 2000; Ashton & Macintosh, 2002; Muhibbullah *et al.*, 2007; Alongi & Carvalho, 2008; Bosire *et al.*, 2008).

Bruguiera gymnorrhiza occurred in drier habitats and its tree density was negatively correlated with sediment moisture content. The *Bruguiera* habitat is often inundated only by spring tides. Sediment moisture content was highest in estuaries with high silt content; this is due to the higher surface area of finer fractions that retain moisture and nutrients in the sedimentary matrix (Prasad & Ramanathan, 2008). Alongi *et al.* (1998) recorded increased organic matter in the sediment as the age of a mangrove plantation increased in Malaysia. A similar trend was found by McKee and Faulkner (2000) in Florida, USA. At young, restored sites, the organic matter ranged between 10-12%, while in natural stands it was 38-56%. The higher organic content of the sediment associated with older mangrove stands (Site 5) at Mhlathuze Estuary compared to Site 1 was consistent with this trend. The Echwebeni site had the highest sediment organic content as this was the oldest site with the tallest trees of *Bruguiera* and *Rhizophora*.

Avicennia marina and *Bruguiera gymnorrhiza* were found in all estuaries sampled in a wide range of conditions, from highly oxidised sediments (+125 to + 322.7 mV) to those that were very reduced (-360 to -35.8 mV). Variability in the measurement of soil redox has been recorded by many authors and the values recorded here are within the ranges of published data. For example Matthijs *et al.* (1999) measured redox potential along an elevation gradient at Gazi Bay and found that it decreased from +200mV some distance from the mangrove creek to -400 mV at the creek. In the same study, *Rhizophora mucronata* was the only species that seemed to respond to changes in redox potential, as it only occurred in areas where the redox potential was between -200mV and -400 mV. McKee and Faulkner (2000) measured soil redox potential in restored and natural forests of different ages. The values ranged from +426 to -336 mV; restored sites were always lower than natural sites. This was due to greater flooding, less soil aeration and low soil porosity (McKee & Faulkner, 2000). Although low soil redox potential may affect mangrove seedling establishment and growth, our study showed that the highest seedling density for all species occurred where the redox potential of the soil was reduced (-300mV). Middelburg *et al.* (1996) and Muhibbullah *et al.* (2007) measured the pH in mangrove sediments in Gazi Bay, Kenya, in the Sundarbans, which were similar to those reported in this study (Table 4).

The aerial cover of the mangrove forests presented in this paper account for more than 70% of the total mangrove cover in South Africa and represents all six species. These mangroves occur at their latitudinal limits and are therefore susceptible to anthropogenic impacts. Conservation and management of these areas are therefore important. Management plans in these estuaries should take into account anthropogenic impacts such as harvesting, chemical pollution and the freshwater requirements of each estuary, and long-term monitoring should be established to record any changes in species distribution relative to changes in their sediments.

Acknowledgments–The National Research Foundation and the Nelson Mandela Metropolitan University (NMMU) provided funding for this study. Thanks are due to Dr Ricky Taylor, Dr Scotty Kyle, Mr Frans Matembu and all field guards from Ezemvelo KwaZulu-Natal Wildlife as well as Dr Gavin Snow and Sabine Hoppe-Speer from NMMU for assistance in the field and technical advice. The authors would also like to thank an anonymous reviewer for helpful comments.

REFERENCES

Adams JB, Colloty BM, Bate GC (2004) The distribution and state of mangroves along the coast of Transkei, Eastern Cape Province, South Africa. Wetlands Ecology and Management 12: 531-541

Alongi DM, Sasekumar A, Tirendi F, Dixon P (1998) The influence of stand age on benthic decomposition and recycling of organic matter in managed mangrove forests of Malaysia. Journal of Experimental Marine Biology and Ecology 225: 197–218

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

Alongi DM (2008) Mangrove forests: Resilience, protection from tsunamis and responses to global climate change. Estuarine, Coastal Shelf Science 76: 1-13

Alongi DM, de Carvalho NA (2008) The effect of small-scale logging on stand characteristics and soil biogeochemistry in mangrove forests of Timor Leste. Forest Ecology and Management 255: 1359–1366

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

Bedin T (2001) The progression of a mangrove forest over a newly formed delta in the Umhlatuze Estuary, South Africa. South African Journal of Botany 67: 433–438

Begg GW (1978) The Estuaries Of Natal. The Natal Regional and Planning Commission: Durban, South Africa, 657 pp

Black CB (1965) Methods of Soil Analysis. American Society of Agronomy, Inc., Madison, Wisconsin

Bosire JO, Kairo JG, Kazungu J, Koedam N, Dahdouh-Guebas F (2008) Spatial and temporal regeneration dynamics in *Ceriops tagal* (Perr.) C.B. Rob. (Rhizophoraceae) mangrove forests in Kenya. Western Indian Ocean Journal of Marine Science 7: 69-80

Breen CM, Hill BJ (1969) A mass mortality of mangroves in the Kosi Estuary. Transactions of the Royal Society of Southern Africa 38: 285-303

Briggs D (1977) Sources and Methods in Geography. Butterworths, London, UK, 190 pp

Bruton MN (1980) An outline of the ecology of the Mgobezeleni Lake System at Sodwana, with emphasis on the mangrove community. In Bruton MN, Copper KH (eds) Studies on the Ecology of Maputaland. Rhodes University and The Natal Branch of the Wildlife Society of Southern Africa, Durban, pp 382-407

Clarke PJ, Kerrigan RA (2000) Do forest gaps influence the population structure and species composition of mangrove stands in Northern Australia? Biotropica 32: 642-652

Dahdouh-Guebas F, Koedam N (2002) A synthesis of existent and potential mangrove vegetation structure dynamics from Kenyan, Sri Lankan and Mauritanian case studies. Mededelingen der Zitittingen Bulletin Des Seances - Koninklijke Academie Voor Overzeese Wetenschappen 48: 487-511

Dahdouh-Guebas F, Hettiarachchi S, Lo Seen D, Batelaan O, Sooriyarachchi S, Jayatissa LP, Koedam N (2005) Transitions in ancient inland freshwater resource management in Sri Lanka affect biota and human populations in and around coastal lagoons. Current Biology 15: 579–586

Day PR (1965) Particle fractionation and particle-size analysis. P. 545-567. In CA Black et al (ed.) Methods of Soil Analysis, Part 1. Agronomy 9: 545-567

Ellison AM, Farnsworth EJ (1993) Seedling survivorship, growth and response to disturbance in Belizean Mangal. American Journal of Botany 80: 1137-1145

FAO (2003) Status and trends in mangrove area extent worldwide. By Wilkie, M.L. and Fortuna, S. Forest Resources Assessment Working Paper No. 63. Forest Resources Division. FAO, Rome. (Unpublished)

Gee GW, JW Bauder (1986) Particle-size Analysis. In A. L. Page (ed.) Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods. Second Edition, Agronomy Monograph 9, American Society of Agronomy, Madison, WI, pp 383-411

Gilbert AJ, Janssen R (1998) Use of environmental functions to communicate the values of a mangrove ecosystem under different management regimes. Ecological Economics 25: 323–346

Gilman EL, Ellison J, Duke NC, Field C (2008) Threats to mangroves from climate change and adaptation options: A review. Aquatic Botany 89: 237-250

Green AN, Garland GG, Uken R (2006) Geomorphological and managerial implications of fish trapping in the Kosi Bay Estuary, KwaZulu–Natal, South Africa. African Journal of Marine Science 28: 617-624

Kairo JG, Lang'at JKS, 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

Kirui BYK, Huxham M, Kairo J, Skov M (2008) Influence of species richness and environmental context on early survival of replanted mangroves at Gazi Bay, Kenya. Hydrobiologia 603: 171-181

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

Lin Y, da Sternberg SL (2007) Nitrogen and phosphorus dynamics and nutrient resorption of Rhizophora mangle leaves in South Florida, USA. Bulletin of Marine Science 80: 159-169

Lovelock CE, Feller IC, Ellis J, Schwarz AM, Hancock N, Nichols P, Sorrell B (2007) Mangrove growth in New Zealand estuaries: the role of nutrient enrichment at sites with contrasting rates of sedimentation. Oecology 153: 633-41

Marchand C, Baltzer F, Lalleir-Verges E, Alberic P (2004) Pore-water chemistry in mangrove sediments: relationship with species composition and developmental stages (French Guiana). Marine Geology 208: 361-381

Matthijs S, Tack J, van Speybroeck D, Koedam N (1999) Mangrove species zonation and soil redox state, sulphide concentration and salinity in Gazi Bay (Kenya), a preliminary study. Mangroves and Salt Marshes 3: 243-249

McKee KL, Faulkner PL (2000) Restoration of biogeochemical function in mangrove forests. Restoration Ecology 8: 247-259

Middelburg JJ, Nieuwenhuize J, Slim FJ, Ohowa B (1996) Sediment biogeochemistry in an East African mangrove forest (Gazi Bay, Kenya). Biogeochemistry 34: 133-155

Moll EJ, Ward CJ, Steinke TD, Cooper KH (1971) Our mangroves threatened. African Wildlife 25: 103-107

Muhibbullah M, Chowdhury MAT, Sarwar I (2007) Floristic condition and species distribution in Sundarban mangrove forest community, Bangladesh. Journal of Biological Sciences 7: 384-388

Naidoo G (1990) Effects of nitrate, ammonium and salinity on growth of the mangrove *Bruguiera gymnorrhiza* (L.) Lam. Aquatic Botany 38: 209-219

Naidoo G, Chirkoot D (2004) The effects of coal dust on photosynthetic performance of the mangrove, *Avicennia marina* in Richards Bay, South Africa. Environmental Pollution 127: 259-366

Piou C, Feller IC, Berger U, Chi F (2006) Zonation patterns of Belizean offshore mangrove forests 41 years after a catastrophic hurricane. Biotropica 38: 365-374

Prasad MBK, Ramanathan AL (2008) Sedimentary nutrient dynamics in a tropical estuarine mangrove ecosystem. Estuarine, Coastal and Shelf Science 80: 60-66

Rajkaran A (2011). A status assessment of mangroves in South African and utilisation of mangroves at Mngazana Estuary. PhD Thesis. Department of Botany, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa, 140 pp

Rajkaran A, Adams JB, Taylor R (2009) Historic and recent state (2006) of mangroves in small estuaries from Mlalazi to Mtamvuna in Kwazulu-Natal, South Africa. Southern Forests 71: 287-296

Rajkaran A, Adams JB (2010) The implications of harvesting on the population structure and sediment characteristics of the mangroves at Mngazana Estuary, Eastern Cape, South Africa. Wetlands Ecology and Management 18: 79-89

Riddin T (1999) The botanical importance of the Nhlabane Estuary. MSc, Thesis, University of Port Elizabeth, South Africa, 177 pp

Schoonees JS, Theron AK, Bevis D (2006) Shoreline accretion and sand transport at groynes inside the Port of Richards Bay. Coastal Engineering 53: 1045-1058

Sherman RE, Fahey TJ, Martinez P (2001) Hurricane impacts on a mangrove forest in the Dominican Republic: damage patterns and early recovery. Biotropica 33: 393-408

Steinke TD, Ward CJ (1989) Some effects of the cyclones Domoina and Imboa on mangrove communities in the St Lucia Estuary. South African Journal of Botany 55: 340-348

Steinke TD (1999) Mangroves in South African estuaries. In: Allanson BR, Baird D (eds) Estuaries of South Africa. Cambridge University Press, pp 114-140

Taylor M, Ravilious C, Green EP (2003) Mangroves of East Africa. United Nations Education Programme - World Conservation Monitoring Centre. Cambridge, United Kingdom, 24 pp

Taylor RH, Adams JB, Haldorsen S (2008) Primary habitats of the St Lucia Estuarine System, South Africa, and their responses to mouth management: African Journal of Aquatic Science 31: 31-41

The Non-Affiliated Soil Analyses Working Committee (1990). Handbook of Standard Soil testing Methods for Advisory Purposes. Soil Society of South Africa, Pretoria

Walters BB, Rönnbäck P, Kovacs JM, Crona B, Hussain SA, Badola R, Primavera JH, Barbier E, Dahdouh-Guebas F (2008) Ethnobotany, socio-economics and management of mangrove forests: A review. Aquatic Botany 89: 220-236

Ward CJ, Steinke TD (1982) A note on the distribution and approximate areas of mangroves in South Africa. South African Journal of Botany 1: 51-53

Wilson AM, Huettel M, Klein S (2008) Grain size and depositional environment as predictors of permeability in coastal marine sands. Estuarine, Coastal and Shelf Science 80: 193-199

Whitfield AK, (1998) Biology and ecology of fishes in Southern African Estuaries. JLB Smith Institute of Ichthyology, Grahamstown, 223 pp

Wright CI, Lindsay P, Cooper JAG (1997) The effect of sedimentary processes on the ecology of the mangrove-lined Kosi estuary/lake system, South Africa. Mangroves and Saltmarshes 1: 79-94