GIS-based Integration of Interdisciplinary Ecological Data to Detect Land-cover Changes in Creek Mangroves at Gazi Bay, Kenya

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***Abstract*—**Historic environmental, faunal, floral and socioeconomic data of Gazi Bay in coastal Kenya were collated and integrated into a GIS environment and data of impacts due to various factors were then related to remotely sensed data. *Rhizophora mucronata*, a valuable mangrove species, was investigated. Very low values of basal area (7.7 m^2/ha and 4.9 m^2/ha) and complexity indices (1.86 and 1.12) at Makongeni and Kinondo 1, respectively, reflected intense human pressure in these areas. Areas that were easily accessible or close to human settlements appeared more vulnerable. Accrued information from a socioeconomic survey carried out over the same period corroborates the hypothesis that human influence was a major contributor to these changes. Historic aerial photographs together with satellite imagery indicate less than 20% decrease in coverage of *R. mucronata* between 1965 and 1992, but an increase of almost 35% in sand cover over the same period. The approach that was used in this study, one largely unprecedented in the East African region, was useful in drawing the conclusion that human influence was the most probable trigger of the observed changes.

INTRODUCTION

Mangrove ecosystems are economically and ecologically very important, and are commercially exploited worldwide. Well developed mangroves exist in many areas along the East African coast, but consist of only 10 species. Along the Kenyan coast, which stretches over a distance of 570 km, bordering Somalia at 1°40’ S to the North to 4°40’ S at the Tanzanian border (Kokwaro, 1985), extensive mangrove stands are found in Lamu district, the Tana River mouth, near Ngomeni, Mida, Kilifi, Mtwapa, Mombasa, Gazi, Funzi, Vanga and Shimoni (Isaac & Isaac, 1969; Ruwa & Polk, 1986; Dahdouh-Guebas et al., 2000a; Kairo, 2001a).

A major threat to mangroves worldwide is their overexploitation for wood products and the conversion of the mangrove habitats to other uses (Terchunian et al., 1986; Primavera, 1995; Hussein, 1995; Farnsworth & Ellison, 1997; Semesi, 1998, Naylor et al., 2000; Dahdouh-Guebas et al., 2000a; Kairo, 2001a). Other threats include the reduction of freshwater inflow, which leads to an increase in salinity (Tack & Polk, 1999). Excessive freshwater input may also have adverse influences on

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mangroves (Jayatissa et al., 2002). For instance, aerial cover by *Sonneratia caseolaris* (L.) Engler at Kalametiya in Sri Lanka increased by more than 30 times between 1956 and 1997 (Jayatissa et al., 2002). The increase was due to the inception of an upstream irrigation project in 1967 that led to an increase of freshwater inflow to the lagoon. Salinity is often used as a key factor which links the physical environment through the physiology of mangroves to patterns of spatial organization (Snedaker, 1982; Matthijs et al., 1999). The distributions of individual mangrove species may be controlled by the precise interplay of factors such as water level, salinity, pH, sediment flux and oxygen potential, together with interspecific competition and successional factors (Thom, 1984).

An understanding of the parameters controlling the distribution of mangrove species within a given habitat is essential and incorporation of these data to mangrove-related studies is important. Effects of such parameters as land use activities and erosion in the hinterland, pH, salinity, temperature and depth of substrate type are important for designing advisory and protection schemes for the proper interpretation of the results from monitoring programmes (Gang & Agatsiva, 1992).

Frequency of tidal flushing, soil type, soil salinity, drainage, plant and animal interactions were listed as the major factors that appear to determine the survival of individual mangrove species (Kenneally, 1982). Bio-indicators, for instance, phytoplankton, may be used to show the importance of physico-chemical variables. Phytoplankton constitute 95% of the total marine production (Steemann Nielsen, 1975) implying that they form a vital source of energy at the first trophic tier and also serve as a direct source of food to many aquatic animals including mangrove-associated species. Temperature has been shown to be an important factor in controlling the growth of phytoplankton (Goldman, 1977). Kuenzler (1974) argued that salinity is important in reducing competition to mangrove forest development from freshwater and terrestrial vascular plants.

Apart from natural changes in mangrove vegetation, anthropogenic activities such as extraction, pollution and reclamation, have significantly influenced the mangrove vegetation in various parts of the world (Farnsworth & Ellison, 1997). Saenger et al. (1983) attribute the reduction of mangrove forests to less than 50% of the original total cover to anthropogenic pressures.

Since mangrove forests may undergo rapid changes caused by natural and/or anthropogenic effects, availability of reliable data on this ecosystem is crucial to the development of policies and their implementation. Dahdouh-Guebas et al. (2000b) inferred fundamental floristic and structural changes in the mangroves of Galle (Sri Lanka) in a time scale of decades, both when comparing to the past and predicting the future. The mangrove degradation in Gazi Bay, Kenya has been mainly due to overexploitation for building poles and firewood. Kairo et al. (2001b) attributed this to the unsustainable removal of wood products for use in house construction and fuelwood. Some effects of this overexploitation include loss of straight-stemmed trees suitable for building, inadequate regeneration in the clear-cut areas, severe erosion of the coastline, shortage of fuelwood and reduction in fishery productivity. The anthropogenic impact on mangroves in Gazi Bay has been so intensive that there are uncertainties regarding natural succession patterns (Dahdouh-Guebas et al., in press).

Remote sensing offers multitemporal repetitive data for identification and quantification of land surface changes, and therefore, greatly enhances capability of a GIS in updating map information on a regular basis. For ecological studies, it provides a distinct scale advantage over traditional solely ground-based measurements. The technology offers a cost-effective method of extending limited field areas to map large areas of mangroves (Green et al., 2000). In his paper, Dahdouh-Guebas (2002b) reviews the application of these tools in tropical coastal zones, and illustrates their relevance in sustainable development.

The aim of this study was to collate and integrate the existing multitemporal inter-disciplinary data for Gazi from previous studies (e.g., Gallin et al., 1989; Osore, 1992; Kairo, 1995a; Kairo, 1995b; Pratiwi, 1995; Beuls, 1995; Osore et al., 1997; Marguillier et al., 1997; Matthijs et al., 1999; Bosire et al., 2003) in a geographic information system, together with newly collected environmental parameters, in order to explain land-cover changes between 1965 and 1992 as derived from remote-sensed images. The changes in the mangrove areas are discussed in the light of the land-cover changes possibly induced by human intervention or changes in environmental variables, or synergistic combinations of both factors. Separate related studies (e.g. Kokwaro, 1985; Dahdouh-Guebas et al., 2000a) have suggested that human activities are responsible. Our hypothesis is that human intervention is a major contributor to the observed mangrove spatial patterns in Gazi. This paper takes into consideration such information including integrative analysis of remote sensing imagery to corroborate the suppositions of previous studies.

De Vits & Tack (1995) carried out a feasibility study on the use of remote sensing as an information source for environmental accounting of coastal areas in Kenya. Their study emphasised physical approaches in which sources and uses of natural resources were quantified and used to develop measures of environmental change and ecological stress.

Ferguson (1993) documented information on a survey carried out to map the Kenyan mangrove forest through the landscape ecological method with the main objective of delivering necessary information for the formulation of a management plan. The method emphasises the establishment of important links between the resource and its environment, whether natural, such as climate, terrain, soil, etc., or anthropogenic. However, to date no management plan has been drafted for Kenya's mangroves (Kairo & Dahdouh-Guebas, in press).

In this study, the available documented information on the flora, fauna, environmental variables and human impacts in Gazi area were collated into a GIS environment. Earlier related work carried out in the area was aimed at setting up a multitemporal database (De Cauwer, 1996). We used retrospective aerial photographs and maps. In addition, ground truthing data were gathered to establish a correlation between the vegetation and the patterns on aerial photographs, and the spectral characteristics of satellite images, respectively.

MATERIALS AND METHODS

Study area

Gazi Bay is located 50 km South of Mombasa in Kwale district, along the southern Kenya coast (4°25' S and 39°50' E). It covers about 18 km^2, and is protected from the Indian Ocean by the Chale peninsula to the east and fringing coral reefs to the south (Slim & Gwada, 1993). It is a tropical region and monsoon air currents of the Indian Ocean control its climate. The area's temperature varies between 24 and 39 °C. The relative humidity is approximately 95% and total annual rainfall varies between 1,000 and 2,100 mm, in a bimodal pattern. Nine mangrove species occur in Gazi with *Rhizophora mucronata* Lamk and *Ceriops tagal* (Perr.) C. B. Robinson being dominant (Kairo, 2001a).

Following extensive overexploitation of the mangroves of Gazi over a long period, especially for industrial fuelwood and building poles, a pilot reforestation project to rehabilitate degraded mangrove areas, restock denuded mudflats and transform disturbed forests into uniform stands of higher productivity was launched in 1991 (Kairo, 2001a). More than 200,000 trees, comprising mainly of *R. mucronata, C. tagal, Avicennia marina* and *Sonneratia alba* had been planted as monocultures in 12.47 hectares by 1995 (Kairo, 2001a). The subsequent development of restored areas has since been monitored, including studies on floral and faunal secondary succession of the restored areas as well as natural areas (Kairo, 2001a; Bosire et al., 2003). Growth and survival rates obtained after 3 years suggested that the performance of replanted mangroves depended on planting material type, elevation of the forests and the size of saplings during transplanting (Bosire et al., 2003). The denuded sites, such as Makongeni, Kinondo 1 and Kinondo 3 that had been clear-felled in the 1970s and were rehabilitated through the community participatory project in 1994 did not show any natural regeneration after the reforestation experiment (Bosire et al., 2003).

Floristic composition of the Gazi Bay mangroves in 1992 and recent field data show a general zonation with six different monospecific

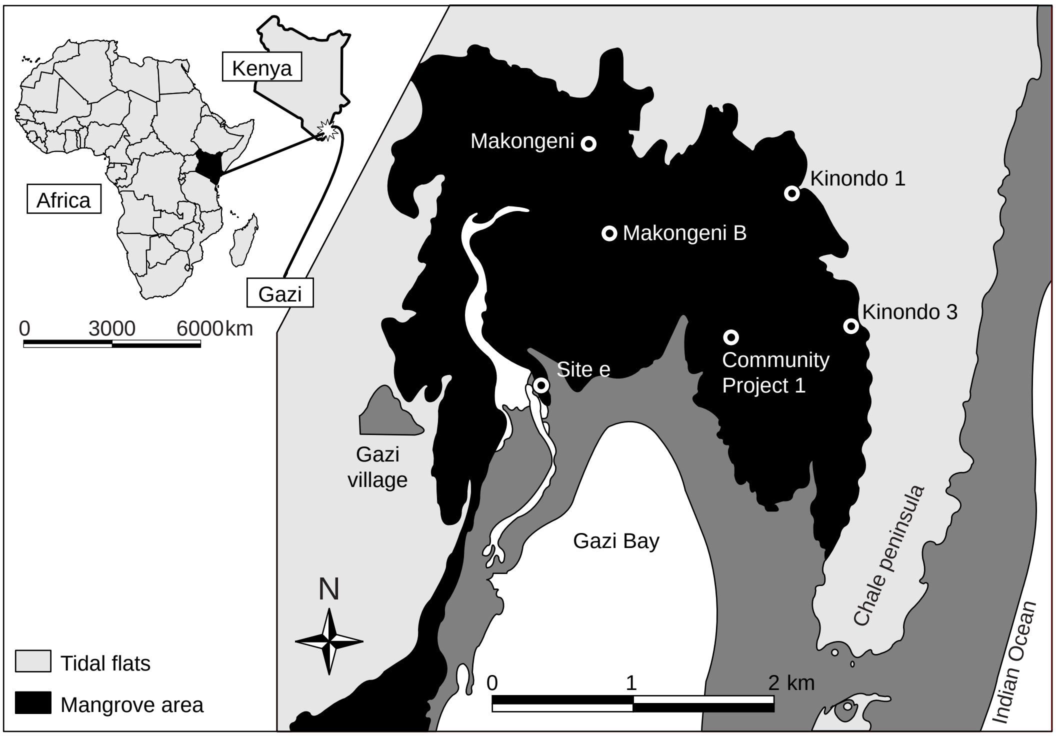

Fig. 1. Map showing study area and the six selected sampling sites, namely Site e, Makongeni, Makongeni B, Community Project 1, Kinondo 1 and Kinondo 3

or mixed mangrove assemblages with *R. mucronata* occurring in most zones (see Fig. 7).

The study area was chosen because much scientific data is available on it, and the mangrove area, despite being relatively small (about 6 km^2), is rich in biodiversity, and both disturbed and undisturbed mangrove sites are available.

Based on the change-detection map for the mangrove in Gazi Bay (1965–1992), six sampling sites were chosen with emphasis on areas occupied by *R. mucronata*. This species was chosen because it is the most abundant as well as highly valued and utilised in Kenya (Kokwaro, 1985, Dahdouh-Guebas et al., 2000a, Obade, 2000 ; Dahdouh-Guebas et al., in press), since it grows long and straight, rendering it suitable for construction applications (Dahdouh-Guebas et al., 2000a; Kairo et al., 2002b). Other considerations that were made for site selection included proximity to human settlements and representative areas of peripheral as well as interior locations. Community Project 1 is a site that was reforested with the participation of the local community to rehabilitate a degraded mangrove stand (Kairo, 1995b). Soil variables and vegetation structure data were collected from 23 August 1999 to 10 October 1999.

Field and Laboratory work

Two quadrats (sample plots) measuring 10 x 10 m were randomly chosen per sampling site (i.e., Site e, Makongeni, Makongeni B, Kinondo 1, Kinondo 3 and Community Project 1) where all the data collection was carried out. The coordinates for all the locations were recorded using a Garmin 80 model Global Positioning System (GPS).

Environmental variables

For salinity, temperature and pH measurements, three holes per quadrat were dug, each of approximately 10 cm depth using a corer with a diameter of 6 cm, to obtain replicate readings for interstitial water. An optical refractometer (Atago brand) was used to determine the salinity, while temperature and pH readings were obtained using a pH meter (WTW pH 320/set-1). All measurements were taken separately and then averaged.

Soil sample variables

The 10-cm deep soil cores from 3 locations within the quadrats mentioned above were divided into 5 approximately equal layers each resulting in 2 sets of replicates per site. These were packed in pre-labelled plastic bags and carried to the KMFRI field station laboratory at Gazi. The samples were oven-dried at 80°C until a constant weight was attained. They were then stored in labelled plastic bags for granulometric analysis conducted at the Royal Belgian Institute of Natural Sciences (KBIN), Brussels. At KBIN, the samples were treated using the method of Wartel et al. (1995) for grain texture analysis. Also, percentage organic matter content per sample was determined.

Vegetation structure

To quantify forest structure, tree height and girth at 130 cm height (G_{130}) were recorded for trees with diameter greater than 2.5 cm in the 10 x 10 m sample plots. A nylon rope was used to measure the G_{130} which was converted to the tree's D_{130} [term according to Brokaw & Thompson (2000), but formerly referred to as diameter at breast height (DBH)] using the formula, $D_{130} = G_{130}/\pi$. A Recta compass with clinometer was used to measure the tree heights in meters. From these data, mean height, the tree basal area and stem density were computed according to Cintrón and Schaeffer-Novelli (1984).

GIS and remote sensing

In order to provide a baseline change at Gazi, SPOT-XS and PAN, JERS-SAR images of 1994 and 1996 were acquired. More details are as shown in Table 1. Aerial photographs for the relevant area were obtained from the Survey of Kenya, the International Institute for Aerospace Survey and Earth Sciences (ITC), and the Department of Resource Survey and Remote Sensing (DRSRS), as shown in Table 2.

The SPOT-XS image of 23/08/94 was geometrically corrected to the topographic map of the Kenya coastline (1:50,000). The other satellite images were registered to this 1994 image. Training samples were selected in areas that were assumed to be the same in 1994 and 1996 thus establishing spectral signatures for the various classes. An unsupervised classification was performed on the SPOT-XS image with the application of the nearest neighbour resampling method. Classification of pixels with similar spectral characteristics representing various land-cover classes was carried out using the cluster module. A maximum likelihood algorithm was used (Richards, 1993). A Boolean-logic technique

Table 2. Information regarding aerial photographs that were used in the study

Area	Year	Scale	Institute
Gazi	1965	1/12500	Survey of Kenya
Gazi	1968	1/50000	Survey of Kenya
Mombasa–Gazi	1969, 1975	1/50000	ITC
Gazi	1992	1/25000	Survey of Kenya

Table 1. Displaying information on satellite systems and sensors that were used

Date	Sensor	Path/row	Time	Area	Scale
07 Mar 1994	+SPOT XS and PAN	146-359	07:57	Gazi	1: 25000
23 Aug 1994	SPOT XS and PAN	146-359	07:52	Gazi, Shimoni	1: 25000
09 Jan 1996	++JERS-SAR	232-308	07:48	Gazi, Vanga	1: 25000

+Système Probatoire pour l'observation de la Terre Multispectrale et Panchromatique
++Japan Environmental Resources Satellite-Synthetic Aperture Radar

(Mattikalli, 1995) was applied to vector layers for automatic analysis of historical land-cover dynamics.

Digital processing for the work was performed using the Arc/Info® version 3.4D for image processing and ArcView version 3.2 for GIS work and display (ESRI 1996). After processing of the images, data were put into ArcView® GIS. A mangrove database map for Gazi, available from the mangrove dataset at the Kenya Marine and Fisheries Research Institute (KMFRI), was used as a background for new data. Other information on previous research work done in Gazi were obtained and put into the GIS in order to incorporate all possible contributions to the vegetation changes observed from the remotely sensed images. These were selected from relevant scientific publications on Gazi Bay (Gallin et al., 1989; Osore, 1992; Kairo, 1995a; Kairo, 1995b; Pratiwi, 1995; Beuls, 1995; Osore et al., 1997; Marguillier et al., 1997; Matthijs et al., 1999; Bosire et al., 2003), together with data obtained from the KMFRI database. The selection criteria for relevant articles were based on the area of study being Gazi, their descriptive values as well as qualitative and quantitative aspects of the data.

The first step taken was to summarise the data obtained from an article taking into account the main study objectives, all the important results and sampling locations including mangrove vegetation types. Scientific data were recorded in a suitable format to be entered later into attribute tables for the GIS database.

Database tables representing the theme's attributes were then created and data were loaded into the database for various themes. All the themes were represented at different levels as displayed in the table of contents in the ArcView programme. Consequently, the GIS database was ready for manipulation, information retrieval, updates and other data analysis.

Statistical analysis

For environmental variables, Kendall tau correlation coefficients (τ) (tested at 5% significance level) were calculated to compare the results from the various sites and to determine the relationships between the D_{130} of trees from the various sites.

Spearman rank correlation coefficients (r_s) were calculated (tested at 5% significance level) to determine the relationships between height and D_{130} at the various sites.

RESULTS

Environmental variables

Available rainfall data indicated that the highest rainfall for the period 1963–1992 occurred in 1982, with a peak of just over 600 mm in May (Fig. 2). Between 1986 and 1992, the area received roughly the same amount of rainfall annually.

The temperature ranged between 24°C and 27°C at all sites. The highest salinity level 38 ‰

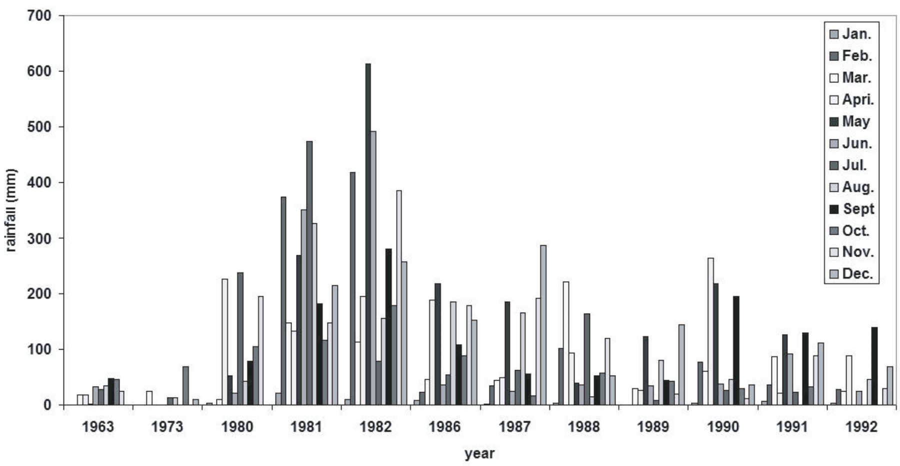

Fig. 2. Monthly rainfall data for Gazi area

was recorded at Kinondo 3. At the other sites, salinity was between 31 and 34 ‰. Both temperature (24°C –26.9 °C) and pH (6.46–6.63), respectively, showed small variations comparatively at all the sites. No significant correlations, at 5% significance level, were found between pH, salinity and temperature values at all mangrove-sampling sites, respectively. This correlation was to ascertain whether or not the environmental variables influenced the mangrove vegetation structure and distribution in the different sites.

Soil samples variables

Amongst the soil samples collected, there was no gravel at any site. For Site e (Fig. 3a), Makongeni (Fig. 3c) and Makongeni B (Fig. 4c), the sand fraction was largest (85%, 65%, and 82%, respectively). Soil samples for Kinondo 1 (Fig. 3e), Kinondo 3 (Fig. 4a), and community project 1 (Fig. 4e) were clay-dominated (56%, 55%, and 62%, respectively). Clay-dominated samples had higher peak values for organic matter content, unlike the sand-dominated samples.

Vegetation structure

For all the sites, the highest frequency occurred for D_{130} class of 3–9 cm (Fig. 5). For the higher classes (above 3–9 cm), there was a general sharp decline in frequency for all the sites. The trends exhibited for the height classes showed a similar pattern, with higher frequencies being observed at the lowest classes. There were large variations in values of basal area between the various sites, though the variations were evidently low for stem

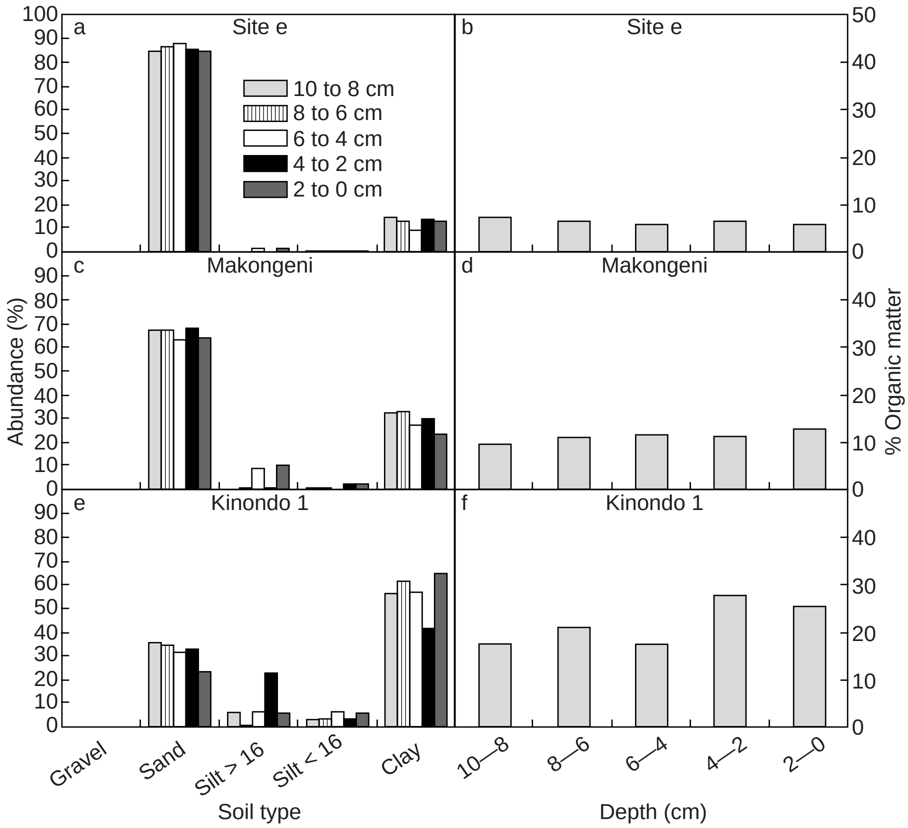

Fig. 3. Grain size distribution (%) of the soil types present at, Site e (a); Makongeni (c) and Kinondo 1 (e): Organic matter abundance at, site e (b); Makongeni (d) and Kinondo 1 (f), with respect to depth. The bars represent percentage composition of soil type abundance and organic matter, respectively.

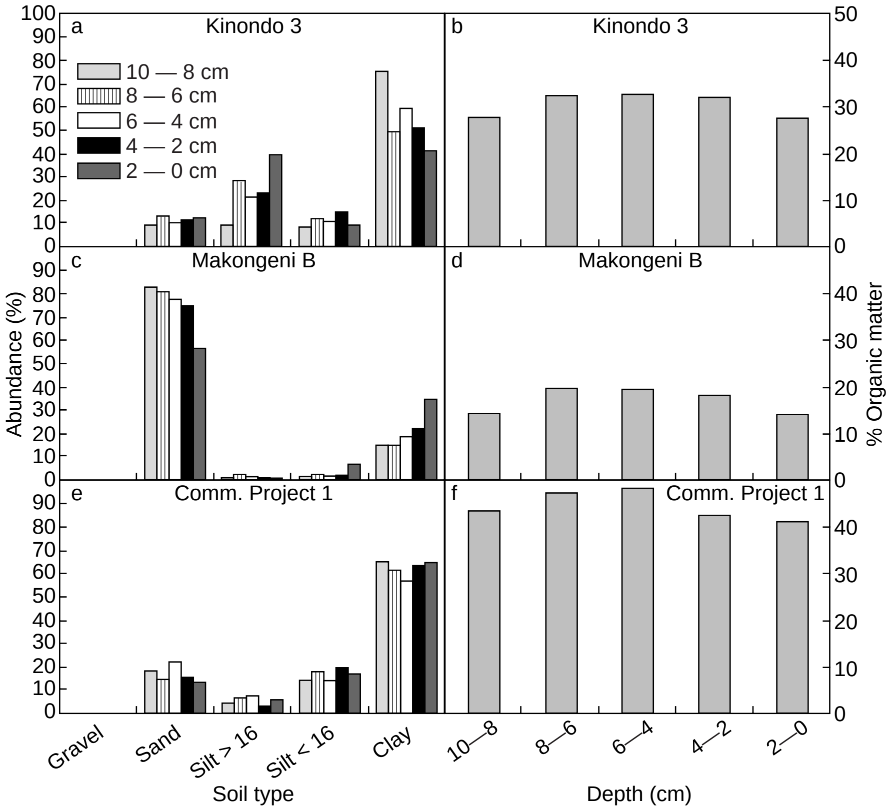

Fig. 4. Grain size distribution (%) of the soil types present at Kinondo 3 (a); Makongeni B (c) and Community Project 1 (e): Organic matter abundance at, Kinondo 3 (b); Makongeni B (d) and Community Project 1 (f), with respect to depth. The bars represent percentage composition of soil type abundance and organic matter, respectively

density and mean height (Table 3). The highest basal area (44.4 m^2/ha) and mean stand height (7.9 m) were recorded at Makongeni B while the lowest basal area was 4.9 m^2/ha at Kinondo 1.

The structural characteristics indicated highest stem density values in the lower diameter classes (D_{130} classes of <3 and 3–9 cm) at all sites and very low values, if any, for the higher diameter classes (Table 4). Compared to the other sites, Makongeni B clearly had the highest stem densities in the higher diameter classes. The highest complexity value for all sites (16.84) was recorded at Makongeni B, while Kinondo 1 registered the lowest complexity index (C.I.) value of 1.12. All correlations (at 5% significance level) were significant between D_{130} and height values for all pairs of variables.

GIS and remote sensing

The area covered by sand increased by approximately 35% between 1965 and 1992 (Figs 6 & 7). The changes were especially pronounced in the Northern part around Makongeni. There were minor changes in the floristic composition with minimal dynamics in zonation and no distinct borders in some instances. However, areas comprising *R. mucronata* or *R. mucronata* and *A. marina* assemblages decreased by less than 20%, and *C. tagal* was noticeable between Makongeni and Makongeni B in 1992 in an area shown to have been occupied previously by *R. mucronata*, *Bruguiera gymnorrhiza*, *Ceriops tagal* and/or *Xylocarpus granatum* in 1965.

The GIS attribute tables provided detailed information, with interlinkages wherever appropriate, of the results obtained from the

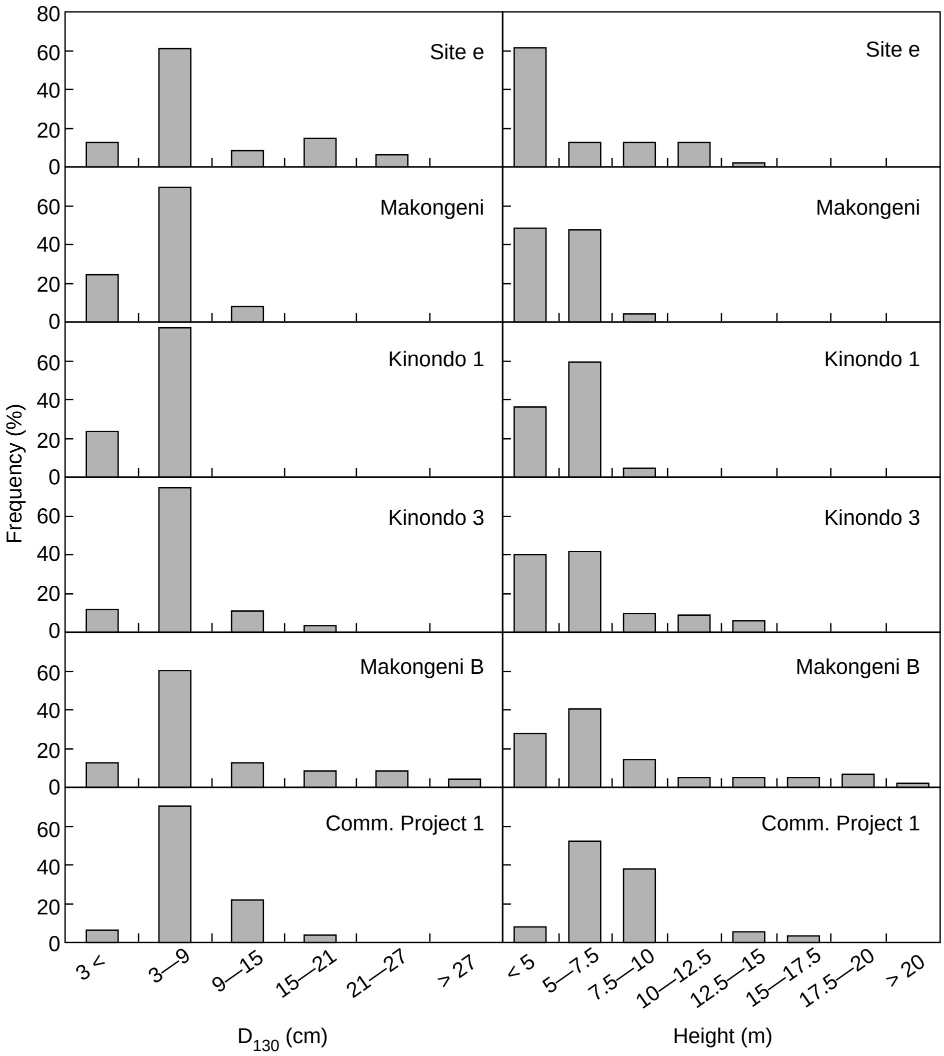

Fig. 5. Frequency of *Rhizophora* trees as a function of D_{130} class and height class at all sites. Each bar represents percentage frequency of mangrove trees in the sampling site

Table 3. Stand table of *Rhizophora mucronata* species of Gazi Bay

Station	Stems/ha (n/ha)	Basal area (m^2/ha)	Mean stand height (m)	Complexity Index⁺
Site e	4300	35	5.8 (± 0.30)	8.73
Makongeni	4650	7.7	5.2 (± 0.10)	1.86
Kinondo 1	4150	4.9	5.5 (± 0.11)	1.12
Kinondo 3	5150	14.3	6.3 (± 0.24)	4.64
Makongeni B	4800	44.4	7.9 (± 0.47)	16.84
Community Project 1	3050	16.3	7.4 (± 0.12)	3.68

⁺Complexity index is the product of number of species, stem density, mean stand height and basal area divided by 10^5 (Holdridge et al., 1971).Values in parentheses represent the standard error.

Table 4. Structural characteristics of various diameter classes for *R. mucronata* of Gazi Bay

	Site e						Makongeni						Kinondo 1					
Diameter class (cm)	<3	3-9	9-15	15-21	21-27	>27	3<	3-9	9-15	15-21	21-27	>27	3<	3-9	9-15	15-21	21-27	>27
Stem density/ha	500	2600	350	600	250	0	1100	3200	350	0	0	0	950	3200	0	0	0	0
Mean height (m)	3.5	4.4	10.1	10.2	9.3	0	4.7	5.1	7.1	0	0	0	4.7	5.8	0	0	0	0
Basal area (m^2/ha)	0.32	3.86	4.25	16.82	9.76	0	0.71	4.11	2.89	0	0	0	0.59	4.27	0	0	0	0

	Kinondo 3						Makongeni B						Community Project 1					
Diameter class (cm)	3<	3-9	9-15	15-21	21-27	>27	3<	3-9	9-15	15-21	21-27	>27	3<	3-9	9-15	15-21	21-27	>27
Stem density/ha	600	3850	550	150	0	0	550	2850	550	350	350	150	200	2500	750	100	0	0
Mean height (m)	4.4	5.8	10.2	11.5	0	0	4.0	6.0	9.1	13.0	18.0	18.5	5.8	6.9	8.6	14.1	0	0
Basal area (m^2/ha)	0.38	5.42	5.45	3.08	0	0	0.33	4.94	5.55	7.81	16.72	9.01	0.13	5.63	8.22	2.42	0	0

various studies conducted in Gazi. It was possible to view relationships and trends, for instance, between the *R. mucronata*, environmental factors and distribution of benthic invertebrates, and so on. Collated information showed no unusual trends with regard to related data from previous work.

DISCUSSION

Environmental variables

The pH values were comparable to 6.74 $\pm$ 0.14 for the *R. mucronata* plot as reported by Bosire et al. (2003). Middelburg et al., (1996) in a study of the same area, obtained pH readings of 5.54 – 7.18. They attributed their findings to the limited buffering capacity of mangrove sediments and intense acidifying processes such as aerobic degradation of organic matter, oxidation of reduced components, ammonium uptake by roots and root respiration. The high readings of salinity observed at Kinondo 1 may be attributed to its location, being the furthest away from any tidal creeks or streams and also being on relatively raised ground (pers. observ.). This consequently leads to poor water exchange and increased soil salinity, since the area does not experience tidal action regularly. Though no significant correlations were found between pH, salinity and temperature values for all the sites, a different vegetation structure was noticeable at each site. Matthijs et al. (1999) found correlations between redox potential (E_h), sulphide concentrations and salinity in relation to *R. mucronata* in a different area of Gazi. They concluded that these may be complimentary, in combination with other unestablished factors, to the spatial distribution and processes of vegetation dynamics. Dahdouh-Guebas et al. (2002a) argued that none of the above environmental factors on the basis of ordination analysis could successfully explain the total variability in the mangrove vegetation data, suggesting that other, more influential factors existed.

The impact of rainfall remains uncertain because rainfall data showed that annual rainfall amounts did not fluctuate significantly especially after 1982. Heavy rains contribute directly to loss of mangrove area, for example, the El Niño rains of 1997/1998 which resulted in heavy sedimentation, killed mature *Rhizophora* trees in Gazi Bay. Heavy damage was also experienced in other areas along the Kenya coast (Kairo, 2001a).

Soil sample variables

Mangrove forests appear to flourish mainly on mud or fine-grained sediments (Odum et al., 1982). Generally, areas that were found near creeks or nearshore had a higher proportion of sand as compared to areas farther away. Site e (Fig. 3a), Makongeni (Fig. 3c) and Makongeni B (Fig. 4c) had sand content between 60% and 90% and were all next to creeks, streams or nearshore. Site e was the most exposed area and thus potentially subjected to the highest energy from tidal action. Whereas tidal action is not a direct requirement for mangrove health according to Odum et al. (1982), it is indirectly important, for instance, because tides bring salt water up the estuaries, permitting mangroves to penetrate inland. Tides also transport nutrients into and export material out of mangrove forests. Various case studies (for example Thom, 1975 and Thom, 1984) highlight the importance of coastal geomorphic processes in the interpretation of temporal variation in mangrove communities. Therefore, as expected, Site e had the highest sand component (ca. 90%). Alongi and Sasekumar (1992) also observed that riverine mangrove systems have fine sands and a thin layer of sediment.

Community Project 1 (Fig. 4e) had the highest silt proportion followed by Kinondo 3 (Fig. 4a) and Kinondo 1 (Fig. 3e), respectively. Silt of grain texture <16 mm is usually important as binding sites for nutrients. An organic layer often covers the surface of sediment particles (Mayer, 1994). This layer may provide a source of nutrients when the organic material is mineralised (Keil et al., 1994). Since sediments dominated by silt or clay particles have a much higher specific area, they are likely to be a much better source of nutrients for mangrove growth. The other areas had negligible silt proportions.

Kinondo 1 (Fig. 3e), Kinondo 3 (Fig. 4a) and Community Project 1 (Fig. 4e) had high clay components (40–75%) and were all found "inland" on the eastern part of Gazi. All the three sampling sites were subjected to lower energy tidal action.

The areas with high clay content, Kinondo 1, Kinondo 3 and Community Project 1 also had a higher organic matter content compared to the sand-dominated areas. Figs 3f, 4b and 4f, show the range of organic matter content to be above 15% and less than 60%, whereas for the remaining, sand-dominated areas, the range was 5 to 20% (Figs 3b, 3d and 4d, respectively). Community Project 1 had the highest content of organic matter, high silt levels and clay-dominated soils. This may explain why the area remained highly productive (Kairo, 2001) compared to the other sites despite being a replanted forest barely 10 years old.

Regeneration of mangroves has been found to be slower on sandy sediment than on clay sediment. Clear-felled areas did not show any natural regeneration (Kairo, 1995b, Bosire et al., 2003; Dahdouh-Guebas et al., in press). Clear-felling of mangroves is thought to greatly impair natural regeneration due to resulting unfavourable site conditions according to Bosire et al. (2003). According to Kairo et al., 2002b, selective removal of small-sized poles by cutters and consequential creation of gaps in the forest canopy stimulates regeneration that approximates selection forest working. However, the regeneration does not necessarily result in the same species being harvested. In Mida creek, they observed that, in a mixed stand of *C. tagal* and *R. mucronata* there was a tendency for natural regeneration to favour *C. tagal*, irrespective of the harvested species. In Gazi, we observed a similar trend. For example, between Makongeni and Makongeni B, *Rhizophora* was replaced by *C. tagal* in the 1992 coverage which may also be partially attributable to the more harsh soil conditions after erosion. Generally, our findings reflected expected occurrences in the various areas depending on adjacency of sampling sites to creeks or further inland locations. From these results, no inferences could be made on the influence on land-cover changes. For the more productive clay areas, accessibility by tree cutters was the major problem and this may have led to a reduction in exploitation.

Vegetation structure

As done for most forest inventories worldwide, besides floristic data and densities, the D_{130} values,

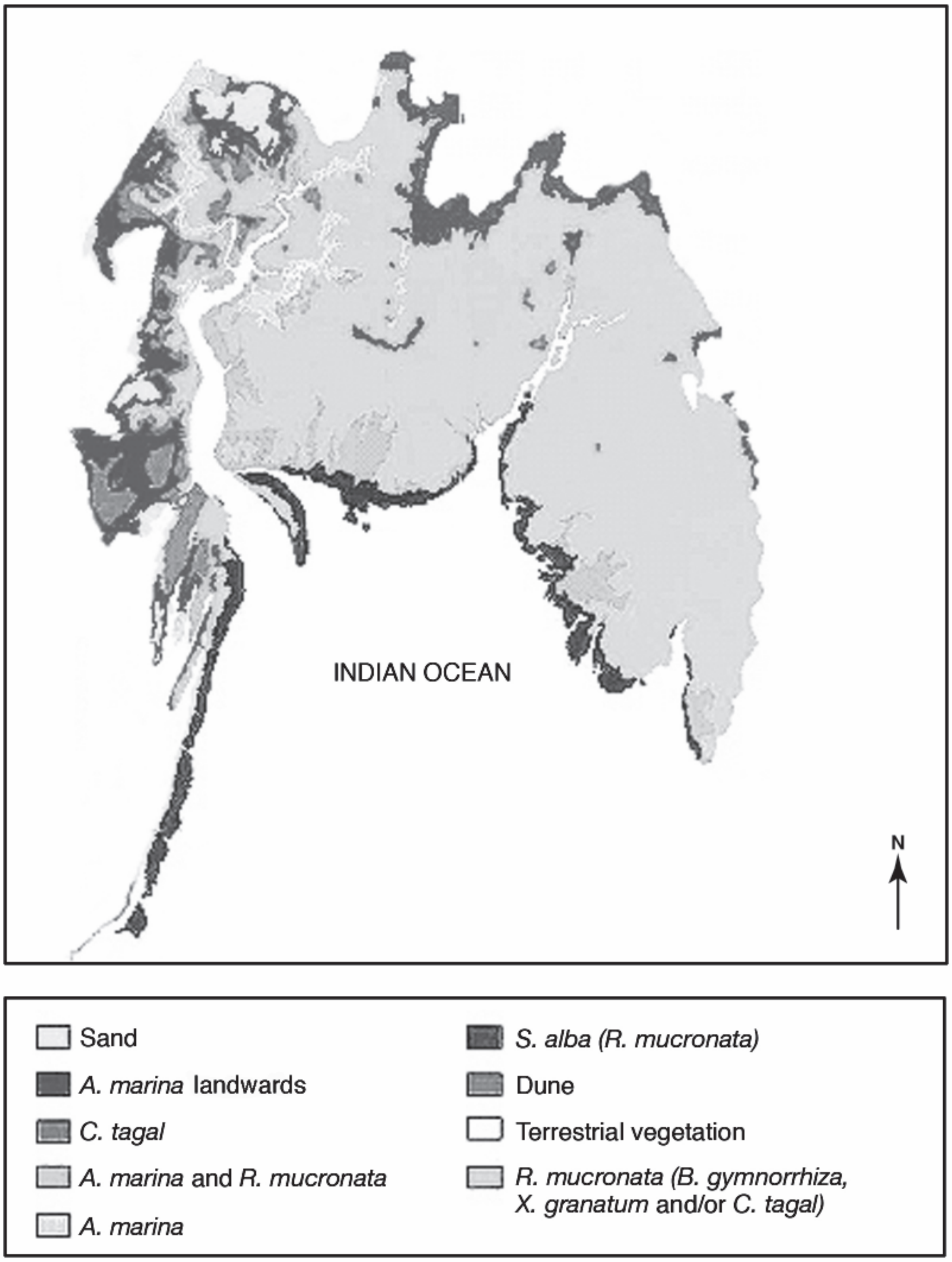

Fig. 6. Floristic composition of the Gazi Bay mangroves in 1965 (Modified from De Cauwer, 1996)

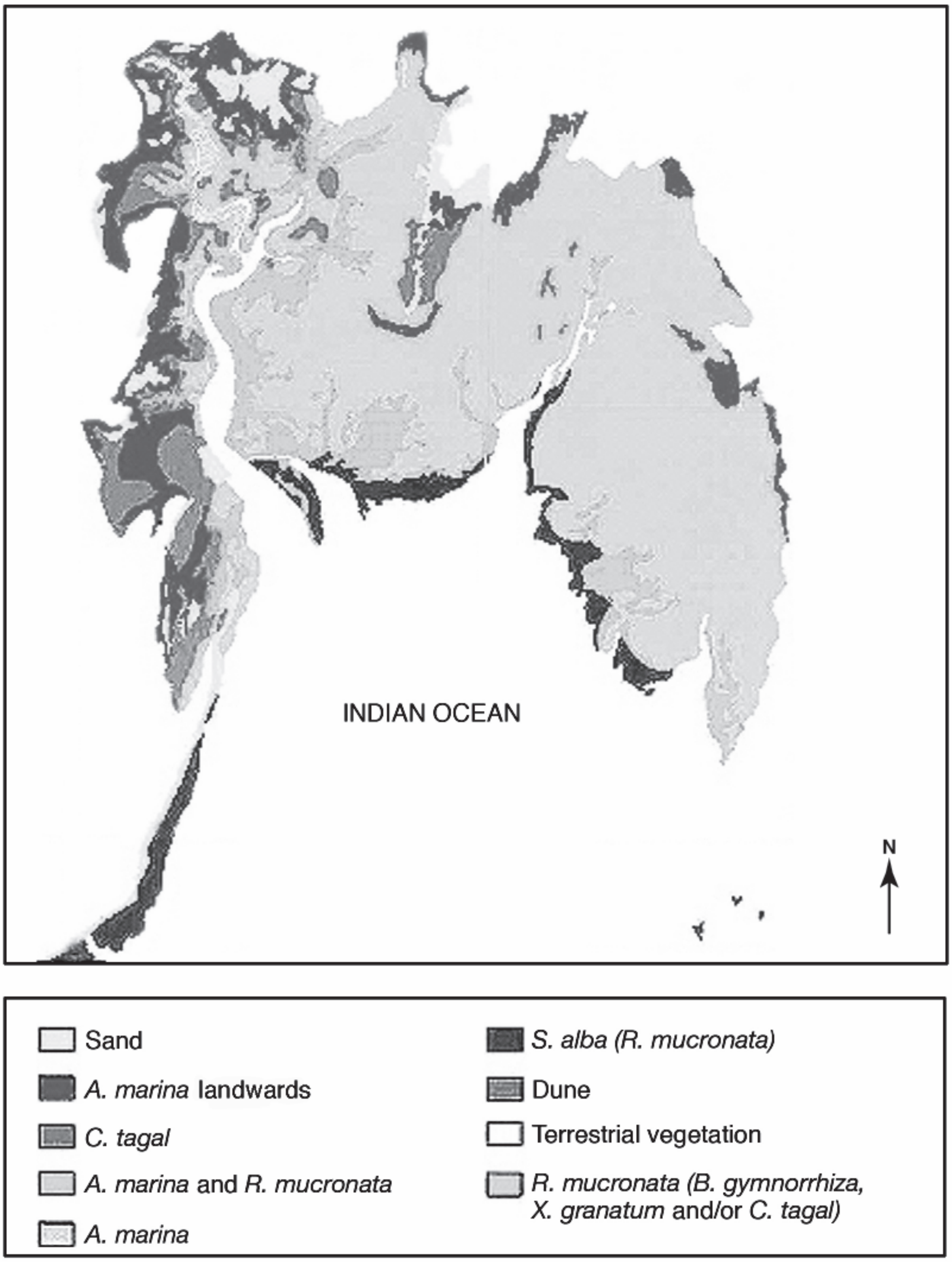

Fig. 7. Floristic composition of the Gazi Bay mangroves in 1992 (Modified from De Cauwer, 1996)

and heights were the main variables measured to determine the tree characteristics for all the study sites.

It was notable that there was a general trend indicating higher frequencies for trees with the lowest values for D_{130} classes (Fig. 5). There was an exponential decrease in frequencies for the subsequent classes. Most of the sampled areas recorded highest frequencies for the lowest tree height classes of <5 and 5–7.5 m combined. The trends are similar to the findings of Dahdouh-Guebas et al. (2002a) who used the Point-Centred Quarter Method of Cottam & Curtis (1956). From field observations, at Makongeni B, there were only few cut trees and those at Community Project 1 were relatively young and largely undisturbed (Kairo, pers. comm.; pers. obs.; Kairo, 2001a). Many tree stumps were evident at Makongeni indicating extensive cutting had taken place in the past. The area is also close to a human settlement. Part of this area was reflected as sand area in the 1992 image (Fig. 7). Kinondo 1 was also easily accessible and was highly exploited. Site e and Makongeni B registered occurrence of trees (Fig. 5) and stem density (Table 4) in the higher D_{130} classes probably due to their location and proximity. Since the logged trees are transported by canoes across the creek from Site e, it was highly unlikely that the cutters would prefer to exploit these trees. Makongeni B was located in the interior parts of the forest hence presenting obvious difficulties in accessibility. The low values of basal area coupled with low values for C.I. at Makongeni and Kinondo 1 also reflected human pressure in these areas. Kairo et al. (2002b) concur that low stand density for large trees is an indication of human-induced pressure in a mangrove forest and the same may apply to Gazi. The high C.I. value registered at Makongeni B was greatly influenced by its high basal area. High C.I. values are indicative of high structural development of a forest.

The stand densities of *Rhizophora* in Gazi varied between 3050 and 5150 stems/ha, respectively. Bosire et al. (2003) obtained stem density values between 2570 and 3330 stems/ha for *R. mucronata* at Gazi. These density values are very high when compared to mangrove forests in other parts of the world, for instance, Ranong in Indonesia, which boasts some of the best-managed mangrove forests in the world, has an average of 812 stems/ha (Aksornkoae, 1993).

D_{130} values of the various sites when paired with their respective tree heights showed significant correlations ($p < 0.05$). Slim & Gwada (1993) found similar correlations linking D_{130} and tree heights at Gazi.

GIS and remote sensing

The reduction of *Rhizophora* area between 1965 and 1992 as observed in the GIS images corresponded to increase of sand area especially around Makongeni and remnants of tree stems that were visible on the ground. The probable reason for the appearance of *C. tagal* in place of *R. mucronata* between Makongeni and Makongeni B could be the changes in the environmental conditions that were more harsh following erosion of the soil cover by extensive and selective cutting of *Rhizophora*. The reforestation with *C. tagal*, which adapt better to harsh conditions, was part of the rehabilitation efforts (Kairo, 1995b) carried out at Gazi after extensive exploitation of [especially] *Rhizophora* for many years especially during the 1970s. Some of the effects of increased sandy area cover is the occurrence of stunted growth for the surviving mangroves that were planted, and this can be seen especially around Makongeni (Obade, pers. obs). The expansion of the sandy area enhances degradation of the *R. mucronata* and it is noticeable that in 1992 *Ceriops* appears in areas previously occupied by *Rhizophora*.

Related methodological studies in other parts of the world include that of Ramachandran et al. (1998), who discussed the changes in the mangrove wetlands in the light of degradation caused by human influence, and emphasised the need for conserving the wetlands. They studied the changes in the mangrove ecosystem between 1990 and 1996 at Muthuphet and Pichavaram, Tamil Nadu and the Andaman and Nicobar islands in India with application of GIS and remote sensing techniques. Their results showed a decrease in total mangrove area in the islands.

CONCLUSIONS

While many studies have been conducted to assess the ecological status and vegetation dynamics of mangrove forests in the past, the importance of this resource has been appreciated only after the effects of its destruction are felt along the coasts where it is found. Various potential influences on the land cover changes were considered and we infer that human impact was probably the most important contributory factor to the observed landscape changes between 1965 and 1992 for Gazi mangroves. A socioeconomic survey corroborated these findings (Obade, 2000; Dahdouh-Guebas et al., in press). The methodology that was used in this study was able to give an insight on the developments at Gazi with due consideration to potential factors.

It would be worthwhile in future to expand this study to cover the entire Kenyan coastline, to document the mangrove status using GIS tools.

Important study topics, such as plant-animal interactions and their effect on the forest structure, and the details of nutrient cycles and food webs have in recent times generated a lot of interest. Available information was collated into a GIS, though research gaps remain to the development of comprehensive relationships. With increased demands and other pressures on coastal resources, resource-use conflicts in coastal regions could result in increased environmental degradation and social inequality. The need to collate the associated information efficiently is thus very important.

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