# APPLICATION OF REMOTE SENSING AND GIS IN THE MANAGEMENT OF MANGROVE FORESTS WITHIN AND ADJACENT TO KIUNGA MARINE PROTECTED AREA, LAMU, KENYA

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**Abstract.** The status of mangroves within and adjacent to Kiunga Marine Protected Area (MPA) were assessed by means of aerial photographs and intensive ground truthing. Vegetation maps (1 : 25,000) were produced on GIS environment making it possible to store, retrieve and analyze various types of information very quickly. The maps together with the digitized information provide important tools to the management of mangroves of Kiunga MPA since various proposed treatments can now be entered and summarized thus providing useful overviews for planning, implementation and monitoring.

The present inventory revealed that the existing mangrove forests within and adjacent to Kiunga MPA have a net standing volume of 2,354,004.85 $m^3$ in 16,035.94 ha. There are eight species of mangrove trees, of which *Rhizophora mucronata* and *Ceriops tagal* are dominant. The standing volume ranges between 6.85 to 710.0 $m^3$ $ha^{-1}$ for stem with diameter above 5.0 cm. The average volume of the entire study area was 145.88 $m^3$ $ha^{-1}$, which corresponds to a stocking rate of 1736 stems per ha. Given its high potential productivity and regeneration, mangroves within and adjacent to Kiunga MPA have excellent prospects for sustainable exploitation.

**Key words:** GIS, Kenya, Kiunga, mangrove management, remote sensing.

## 1. Introduction

Mangrove forests are the dominant ecosystem along the sheltered shoreline of the Kenyan coast. They are a vital resource that serves the inhabitants of coastal areas. Mangroves provide wood products for house construction, firewood and other non-wood forest products such as tannins and medicine (Kokwaro, 1985; Dahdouh-Guebas et al., 2000a). At the ecosystem level, mangroves serve as habitat and breeding areas for many commercially important fish and crustaceans, provide detritus for offshore fisheries, controls coastal erosion as well as maintaining water quality (Davis, 1940; Robertson et al., 1992). A strong correlation has been shown to exist between the presence of mangrove ecosystems and the productivity of fish and marine life in coastal areas (MacNae, 1974; Odum and Heald, 1975; Martosubroto and Naamin, 1977).

Over the years, mangroves of Kenya have been subjected to ever-increasing human population and economic pressure that has led to their degradation (Graham, 1929; Rawlins, 1957; Roberts and Ruara, 1967; FAO, 1993; Dahdouh-Guebas et al., 2000a; Kairo, 1995). The degradation is directly reflected in the increased coastal erosion, shortage of building material and firewood (Dahdouh-Guebas et al., 2000b; Kairo et al., 2001) and reduction in fishery (Tiensogrusmee, 1991). Recent surveys of conservation status of mangroves in Kenya indicate considerable loss of forest resources through over-exploitation in Lamu (Kairo and Kivyatu, 2000), Mida creek (Gang and Agatsiva, 1992) and the south coast area (Ferguson, 1993; Kairo, 2001). Losses of mangrove through oil pollution and aquaculture (Yap and Landoy, 1986) have also been reported. Today, mangrove forests in Kenya are estimated to occupy between 50,000 and 60,000 ha, with Lamu district having 70% of the area (Doute et al., 1981).

The major problem facing the management of mangrove forests in Kenya is the lack of a management plan. Owing to lack of reliable and up-to-date comprehensive vegetation maps, mangrove managers do not have access to information on the present forest condition and also on the changes that have occurred in the forest cover over period of time. Accurate mangrove vegetation maps with details of species distribution and abundance are essential for monitoring forest changes over time, for estimating mangrove production and for investigating linkages with other ecological systems that rely on them either directly or indirectly. A comprehensive database, including the information on distribution and extent on mangrove areas and forest structure is a prerequisite for the development of mangrove management plans and their implementation.

The present study deals with the application of remote sensing and GIS technology in mapping the mangrove forests within and adjacent to Kiunga Marine Protected Area (MPA) in Kenya. Remote sensing and GIS are increasingly used in mangrove forestry worldwide to assist in gathering and analysing images acquired from aircrafts, satellites and even balloons (Aschbacher et al., 1995; Blasco et al., 1998; Spalding et al., 1997; Dahdouh-Guebas et al., 2000b). The notable advantages of using GIS include the ability to update the information rapidly, to undertake comparative analytical work and making this information available as required (Silapathong and Blasco, 1992; Long and Skewes, 1994). GIS in addition to providing efficient data storage and retrieval facilities also offers a cheaper option of monitoring forest conditions over time (Long and Skewes, 1996; Ramachandran et al., 1998). The application of GIS in mangrove forestry in Kenya is almost nil, because of lack of resources and trained personnel to do the work. Results generated from this study could provide an additional opportunity for a better understanding of mangrove forests geared towards their sustainable management. On the technical side, the results could serve as a guideline in choosing the appropriate tools in the development of management plans for the mangrove forests in Kenya.

### 1.1. Description of the study area

Kiunga Marine National Reserve (KMNR) was created in 1979. The total area of the reserve is 25,000 ha. It is situated close to Lamu town in the northern coast of Kenya between geo-coordinates 2°00′S, 41°13′E in the south and 1°37′S′, 41°35′E in the north (Figure 1). The reserve is shallow, and is underlain by limestone of

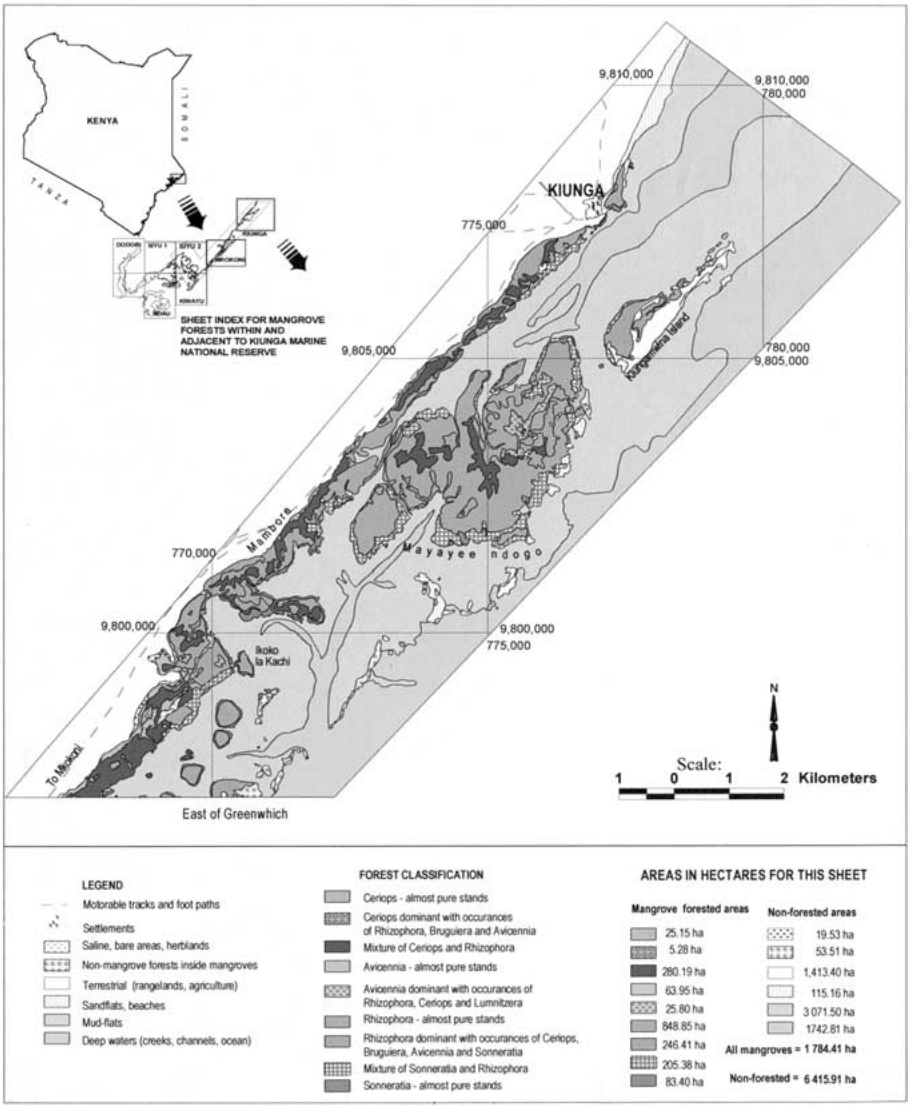


*Figure 1*. Mangrove vegetation map of Kiunga management area in the Northern Swamp forest, KMNR. Detailed characteristics of individual stand attributes could not be displayed here because of scale (see Kairo and Kivyatu, 2000).

Pleistocene age (Oostrom, 1988) which surfaces in some areas as islands. The unique environment of Kiunga MPA and its rich biodiversity is recognized worldwide, and this led to its designation as a Biosphere Reserve in 1980 (WWF, 1996) and later to an ecoregion of global importance in 2000 (WWF, 2001). The reserve contains extensive mangrove areas, breeding populations of turtles and dugong, corals reefs, and shorebird population (UNEP/IUCN, 1988; WWF, 2001).

Biogeographically, KMNR is located in zone 3 (coastal mosaic) of land classification in Kenya (White, 1991). Out of the five geographical regions described by Roberts and Ruara (1967) for Lamu mangroves, KMNR is located in the Northern and North Central Swamp forests (Figure 1). The Kenya Forest Department use these geographical zones in the management of mangroves of Lamu district (FD, 1983).

The climate in KMNR is hot and humid with an average temperature of 27°C. Humidity is high throughout the year, up to 90% during the rainy season. Rainfall is bimodal. The long rain falls from April to June with a peak in May. The short rain falls from September to December. The average annual precipitation is about 500–900 mm (McClanahan, 1988).

The soils of the mangrove areas are predominantly unconsolidated collarine, with poor water holding capacity and extreme alkalinity (Boxen et al., 1987). Sediment deposition is extensive within the sheltered creek waters. Much of the sediments in KMNR could be originating from the adjacent agricultural hinterlands through alluvial deposition (Brakel, 1984).

Fishing and farming are the primary occupation of the people living within and adjacent to Kiunga marine reserve, while mangrove cutting is regarded a secondary occupation (Gubelman and Kavu,1996). Commercial logging of mangroves is permitted in areas adjacent the reserve but is prohibited inside the reserve (Kairo and Kivyatu, 2000). As the population continue to expand and density increasing, the conservation of mangroves within and adjacent to KMNR becomes a challenging task.

## 2. Study approach and methodology

### 2.1. Photo-interpretation and ground truthing

Medium scale (1 : 25,000) black and white panchromatic aerial photographs procured from the Department of Resource Survey and Remote Sensing, Nairobi, were used to derive vegetation maps of mangrove forests within and adjacent to Kiunga MPA. Preliminary photo-interpretation was carried out in the field to correlate image characteristics and ground features. A final interpretation was done using Wild APT Mirror Stereoscope and applying a classification-key developed for the purpose. Tonality (contrast), crown texture, structure, and tree height and relative position on the ground easily distinguish different species of mangroves (Kairo, 2001). Species of *Avicennia marina* (Forsk.) Vierh. have a gray tone and a coarser texture compared to species of *Rhizophora mucronata* Lamk. that appears dark. *Rhizophora* has a small crown diameter than *Avicennia* and *Sonneratia*. On horizontal distribution, *Sonneratia* mostly occupy the seaward side of the intertidal area, while *Avicennia* prefers the land ward side.

The low water line, road network, forest boundary and village location were transferred from the Survey of Kenya toposheets (1 : 50,000) that were used as base maps. Use was made also of mangrove database sourced from the marine databank of the Kenya Marine and Fisheries Research Institute in Mombasa. The data included GIS ArcInfo coverage of mangrove areas for the entire Kenyan coast (Ferguson, 1993). Polygon dimensions were checked for their accuracy. Error analysis showed that the overall digitisation was accurate and the boundary between marked polygons (stand compartments) coincided with the ground-truth data, at least 95% of the time.

Stratification was carried out at two levels:

– *Land use level*: The study site was stratified into forested and non-forested areas. The non-forested areas contained open water, but also included agricultural areas, rangeland and saline bare areas inside mangroves.
– *Operational planning level*: The mangrove-forested areas were further stratified into productive and non-productive forest types supplemented by ground truthing. We define productive forest stand as one having stem density of more than 40% and tree height exceeding 5 m. Each forest type was described by its species composition and was named after the most dominant species. A total of 9 forest types were recognized.

In order to evaluate the growing stock and regeneration status, forest types were divided into density and height classes. In the text, density has subjectively been assessed as being; a (scarce), b (dense), and c (very dense) for stem density of less than 40%, 40–80% and greater than 80%, respectively. Whereas height has subjectively been categorized as; 1 (high), 2 (medium), 3 (low) and 4 (very low) for canopy height greater than 20, 15–20, 5–15 and less than 5.0 m, respectively.

### 2.2. Sampling procedures

Transects were selected and made to run from the sea ward or channel bank inward across the types already marked out on the aerial photographs, the length of each transect depending on the locality and the extend of the types. Sampling units were $10 \times 10\,m^2$ quadrat for adults and $5 \times 5\,m^2$ for juveniles.

Sampling for adult trees was restricted to stems with butt diameter greater than 5.0 cm, since logging of mangrove trees of stem diameter less than 5.0 cm is currently banned in Kenya (FD, 1983). All trees with diameter less than 5.0 cm were therefore sampled as juveniles. Within the quadrat, individual trees were identified and counted. Vegetation measurements included tree height and diameter of the stem at breast height (DBH), from which were derived; tree basal area,

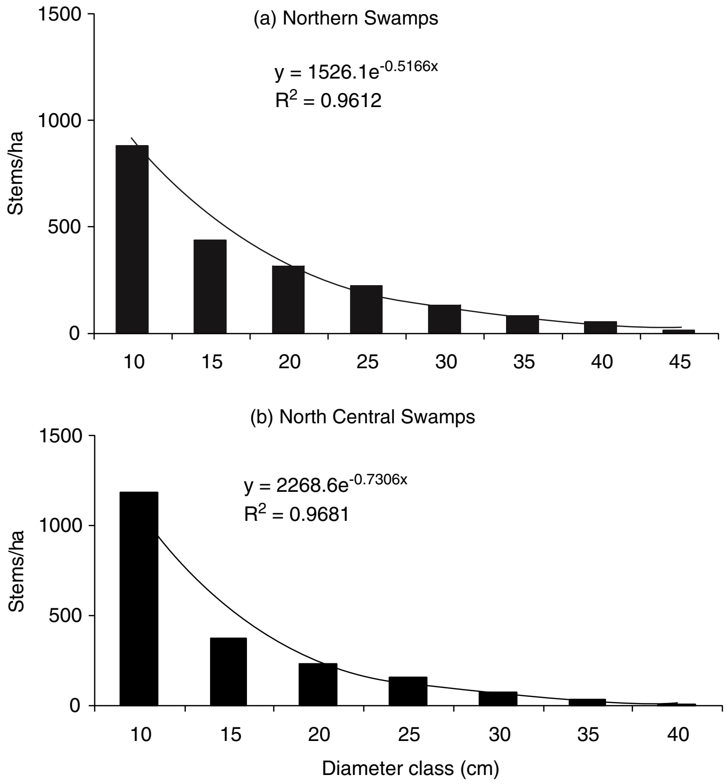


*Figure 2.* Size class distribution of mangroves in Kiunga MPA. (a) Northern Swamps. (b) Northern Central Swamps.

species density and frequency (Mueller-Dombois and Ellenberg, 1974; Cintron and Schaeffer-Novelli, 1984). The importance value (IV) of each species was calculated by summing its relative density, relative frequency and relative dominance (Cintron and Schaeffer-Novelli, 1984). While the vegetation complexity index (CI) for each of the geographical region was obtained as the product of number of species, basal area ($m^2$ per 0.1 ha), maximum tree height (m) and number of stems per 0.1 ha, times $10^{-3}$ in a 0.1-ha plot (Holdridge et al., 1971).

Stand table data were presented graphically as frequency diagrams (Figure 2). Class interval was set at 5.0 cm commencing with class 5–10 cm. For simplicity sake, class intervals have been condensed and only the upper limit in each class is entered. Thus the first class is not entered into $x$-axis as 5–10 cm, but simply as 10 cm.

### 2.3. Volume estimation

In this study the following function was used to estimate standing wood volume:

$$v = (\pi d^2/4) \times h \times f \qquad (1)$$

where, $v$ = volume ($m^3$), $d$ = DBH (cm), $h$ = tree height (m) and $f$ = form factor.

In the present study, a general form factor of 0.7 that was earlier estimated for *Rhizophora mucronata by* Roberts and Ruara (1967) was used to calculate wood volume.

## 3. Results and discussion

### 3.1. Vegetation maps

Six vegetation maps, on a scale of 1 : 25,000, were derived from aerial photographs for the entire mangrove forests within and adjacent to Kiunga MPA. An example of such a vegetation maps for the Northern Swamp forest at Kuinga management unit is given in Figure 2. Detailed description of the mapped community is presented in Tables I and II. Large concentrations of mangroves occur in Ndau and Siyu management areas. *Rhizophora*-type forests occupied 24.14% of the entire forested area of Kiunga MPA, while *Ceriops*-type forests occupied 15.38% of the area. A total forested area of 16,035.94 ha was mapped (Table I). The non-forested areas were mainly mudflats, but also included rangelands and agricultural fields, sand beaches and water-spread areas within and adjacent to the reserve. There were 31 million stems of mangroves in Kiunga MPA with a net standing volume of 2.4 millions $m^3$ (Table II).

Mangrove forests within and adjacent Kiunga MPA have been under uneven cutting pressures and the accessible areas adjacent the reserve have now been largely over-exploited, particularly in Ndau and Siyu 1 management areas. In areas where commercial harvesting is still going on such as Uvondo and Yowea all the market sized poles (butt diameter: 11.5–14.0 cm) have been cleared. *Rhizophora mucronata* and *Ceriops tagal* (Perr.) C.B. Robinson are the most affected species. Only very large trees, the majority *Avicennia marina* and *Sonneratia alba* J. Smith are left behind. This selective logging greatly affects the quality and stability of the remaining future forest (Kairo, 2001).

Near pristine mangrove forests with stand density of over 80% and mean stand height greater than 10 m still occur in some parts of Kiunga MPA (Tables III and IV). The analysis of different compartments show that there is no significance difference ($F_{(1,46)} = 4.052$, $p = 0.259$) in the total compartment size between the two geographical regions ($F_{(1,46)} = 4.052$, $p = 0.259$). There were 8,975.52 ha (55.97%) of high dense forests (c-3) in the entire KMNR with a net stock of 16.4 million stems (equivalent to 1.5 $m^3$ of wood). The high concentration of a-4 and c-4 stands in the North Central forests indicate most probably human pressure though we cannot rule out completely the role of the environmental factors in determining the dwarf stands in this region. Salinity levels on the land ward areas of North Central Swamps recorded 72% on Atago refractometer (Kairo and Kivyatu, 2000).

TABLE I. Area occupied by different mangrove vegetation types in Kiunga MPA.

| Forest type classification | Kiwayu | Ndau | Siyu1 | Siyu2 | Mkokoni | Kiunga | Total | % area |
|---|---|---|---|---|---|---|---|---|
| *Ceriops* type forests | 4.43 | 951.64 | 805.43 | 561.29 | 117.83 | 25.15 | 2465.77 | 15.38 |
| Mixed *Ceriops* types | 0.36 | 228.26 | 56.14 | 99.75 | 55.26 | 5.28 | 445.05 | 2.78 |
| *Ceriops-Rhizophora type* | 0 | 377.83 | 229.79 | 232.10 | 144.81 | 280.19 | 1264.22 | 7.88 |
| *Avicennia* type | 3.43 | 590.80 | 926.78 | 887.49 | 200.71 | 63.95 | 2673.17 | 16.67 |
| Mixed *Avicennia* type | 0 | 219.77 | 115.67 | 199.73 | 0 | 25.80 | 560.97 | 3.50 |
| *Rhizophora* type | 209.19 | 1463.54 | 433.28 | 642.82 | 273.43 | 848.85 | 3871.11 | 24.14 |
| Mixed *Rhizophora* type | 13.87 | 709.59 | 1107.54 | 1052.04 | 517.00 | 246.41 | 3646.45 | 22.74 |
| *Sonneratia-Rhizophora* type | 19.49 | 79.02 | 88.70 | 87.86 | 27.53 | 205.38 | 507.98 | 3.17 |
| *Sonneratia* type | 74.22 | 151.55 | 77.08 | 170.66 | 44.31 | 83.40 | 601.22 | 3.75 |
| Total mangroves | 324.99 | 4772.00 | 3839.92 | 3933.74 | 1440.88 | 1784.41 | 16035.94 | 100 |
| Saline bare areas and herblands | 12.86 | 219.50 | 3405.29 | 1023.71 | 73.43 | 19.53 | 4754.32 | 6.82 |
| Non-mangrove forests inside mangroves | 0 | 408.92 | 388.80 | 193.19 | 204.05 | 53.51 | 1248.47 | 1.79 |
| Agricultural and rangeland within/adjacent mangroves | 201.23 | 4543.86 | 7153.62 | 8012.35 | 1413.40 | 1413.40 | 24951.81 | 35.81 |
| Sand-flats and beaches | 44.93 | 49.84 | 48.80 | 100.74 | 57.34 | 115.16 | 416.81 | 0.60 |
| Mudflats and shallow waters | 1177.62 | 3414.25 | 311.40 | 3548.09 | 557.53 | 3071.50 | 12180.39 | 17.48 |
| Water spread areas (creeks, channel, ocean) | 10230.84 | 8900.21 | 249.12 | 2779.86 | 2232.87 | 1742.81 | 26135.71 | 37.50 |
| Total non-forested areas | 11676.48 | 17636.58 | 11557.03 | 15657.94 | 6743.57 | 6415.91 | 69687.51 | 100 |

TABLE II. Detailed characteristics of mangrove vegetation types in Kiunga MPA.

| Forest types | Number of compartment | Area (ha) | Average canopy height (m) | Crown cover (%) | Tree density (Trees/ha) | Standing volume ($m^3$/ha) | Net stocking | Net volume ($m^3$) |
|---|---|---|---|---|---|---|---|---|
| Mixed *Avicennia* | 53 | 560.97 | 12.5 | 69 | 2148 | 106.78 | 1,167,570 | 65,142.73 |
| *Avicennia* | 632 | 2673.17 | 10.0 | 66 | 2064 | 45.39 | 5,448,090 | 67,730.05 |
| *Ceriops-Rhizophora* | 249 | 1264.22 | 12.5 | 75 | 2072 | 106.58 | 2,635,091 | 132,146.50 |
| *Ceriops* | 548 | 2465.77 | 1.5 | 80 | 2291 | 50.08 | 5,694,540 | 100,193.11 |
| *Rhizophora* | 189 | 3871.11 | 15.0 | 78 | 1532 | 334.36 | 5,910,449 | 1,281,517.25 |
| *Sonneratia-Rhizophora* | 97 | 507.98 | 12.5 | 80 | 2141 | 102.41 | 1,045,622 | 59,480.01 |
| *Sonneratia* | 335 | 601.22 | 12.5 | 73 | 1962 | 78.30 | 1,216,612 | 49,742.12 |
| Mixed *Ceriops* | 180 | 445.05 | 7.5 | 80 | 2306 | 41.36 | 987,889 | 21,597.79 |
| Mixed *Rhizophora* | 268 | 3646.45 | 12.5 | 79 | 1938 | 159.44 | 7,082,465 | 576,455.29 |
| Total | 2,551 | 16,035.94 | — | — | — | — | 31,188,328 | 2,354,004.85 |

TABLE III. Area of different mangrove density and height classes in Kiunga MPA.

| Height and density classes[1] | Kiwayu | Ndau | Siyu1 | Siyu2 | Mkokoni | Kiunga | Total | % |
|---|---|---|---|---|---|---|---|---|
| a-3 | 3.02 | 416.81 | — | 3.29 | 2.35 | 14.49 | 484.96 | 3.0 |
| a-4 | 1.34 | 376.72 | 239.65 | 447.27 | 84.77 | 47.05 | 1196.80 | 7.46 |
| b-3 | 8.90 | 121.66 | 2.9 | 11.56 | 13.70 | 88.09 | 246.81 | 1.54 |
| b-4 | — | 223.18 | 404.53 | 328.90 | 34.12 | 6.79 | 997.52 | 6.22 |
| c-1 | 0.80 | 92.35 | 2.24 | 27.15 | 197.00 | 206.5 | 526.04 | 3.28 |
| c-3 | 305.04 | 2270.70 | 1955.56 | 2196.16 | 870.83 | 1377.23 | 8975.52 | 55.97 |
| c-4 | 5.89 | 1225.58 | 1235.04 | 919.41 | 178.11 | 44.26 | 3608.29 | 22.50 |
| Total | 324.99 | 4772.00 | 3839.92 | 3933.74 | 1380.88 | 1784.41 | 16,035.94 | |

[1] Density classes are as follows: a = <40%, b = 40–80%, c = >80%. Height classes are given as follows: 1 = >20 m, 2 = 15–20 m, 3 = 5–15 m, 4 = <5 m.

TABLE IV. Detailed characteristics of different mangrove density and height classes in Kiunga MPA.

| Height and density classes[1] | No. of compartments | Area (ha) | Average tree density (stems/ha) | Average standing volume ($m^3$/ha) | Net stock | Net standing volume ($m^3$) |
|---|---|---|---|---|---|---|
| a-3 | 33 | 484.96 | 1596.71 | 30.51 | 915,491 | 48,496.88 |
| a-4 | 170 | 1197.80 | 1540.49 | 6.85 | 1,939,510 | 8,533.21 |
| b-3 | 41 | 246.81 | 1509.96 | 58.56 | 427,311 | 28,403.50 |
| b-4 | 261 | 997.52 | 2155.57 | 38.57 | 2,261,795 | 38,414.70 |
| c-1 | 32 | 526.04 | 1013.25 | 710.00 | 936,488 | 632,560.30 |
| c-3 | 1023 | 8975.52 | 2022.10 | 137.64 | 16,354,951 | 1,456,663.11 |
| c-4 | 991 | 3608.29 | 2313.12 | 39.01 | 8,352,782 | 140,933.15 |
| Total | 2551 | 16,035.94 | — | — | 31,188,328 | 2,354,004.85 |

[1] Density classes are as follows: a = <40%, b = 40–80%, c = >80%. Height classes are given as 1 = >20 m, 2 = 15–20 m, 3 = 5–15 m, 4 = <5 m.

### 3.2. Community characteristics

Structural attributes like tree height, basal area, density and species composition that were recorded from sample plots were used to characterize mangrove community of KMNR (Table V). There are eight mangrove species that occur in the study area. Based on the highest IVs, the principal species are *Rhizophora mucronata* (IV = 162.73%), *Ceriops tagal* (IV = 64.44%); and *Sonneratia alba* (IV = 29.58%). Others are *Avicennia marina*, *Bruguiera gymnorrhiza* (L.) Lamk., *Xylocarpus granatum* König, *Xylocarpus moluccensis* (Lamk.) Roem and *Lumnitzera racemosa* Willd. (Table V). The high value of CI in the Northern Swamps CI = 62.81%, indicate especially the high basal area and canopy height of the stands in the Northern Swamp region as compared to the North Central Swamps.

## 4. Conclusions

The stratification of the aerial photographs and the use of GIS make it possible to locate forest stands within and adjacent Kiunga MPA that are productive and

TABLE V. Community characteristics of mangrove forests within and adjacent to Kiunga MPA. All trees with DBH > 5.0 inside 100 $m^2$ were measured.

| Management unit | Species | Density (stems/ha) | Mean height (x ± s.d.) | Basal area ($m^2$/ha) | Relative values (%) | | Density | IV(%)[1] | Complexity index[2] |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Frequency | Dominance | | | |
| Northern Swamps | *A. marina* | 103 | 7.40 ± 4.16 (1–10) | 2.63 | 7.22 | 7.50 | 4.39 | 19.11 | 62.81 |
| | *R. mucronata* | 1613 | 11.40 ± 5.00 (2–27.5) | 36.53 | 63.40 | 77.78 | 68.87 | 210.05 | |
| (Kiunga and Mkokoni) | *C. tagal* | 443 | 5.10 ± 2.67 (1.2–14) | 2.70 | 15.98 | 5.74 | 18.92 | 40.64 | |
| | *S. alba* | 174 | 8.90 ± 3.96 (6–18) | 4.97 | 9.28 | 10.59 | 7.43 | 27.30 | |
| | *B. gymnorhiza* | 10 | 6.50 ± 3.00 (3–10) | 0.14 | 4.12 | 0.30 | 0.43 | 4.85 | |
| North Central Swamps | *A. marina* | 132 | 3.60 ± 1.94 (1.5–13) | 1.15 | 6.37 | 4.77 | 6.68 | 17.82 | 25.14 |
| | *R. mucronata* | 920 | 8.80 ±3.20 (2–18) | 14.20 | 49.98 | 58.97 | 46.47 | 115.41 | |
| | *C. tagal* | 799 | 4.50±1.94 (1–17.5) | 4.18 | 30.49 | 17.38 | 40.37 | 88.24 | |
| (Siyu, Ndau, Kiwayu) | *S. alba* | 110 | 9.06 ± 3.27 (2–17) | 4.28 | 8.49 | 17.81 | 5.54 | 31.85 | |
| | *B. gymnorrhiza* | 17 | 8.2 ± 2.42 (4–13.5) | 0.24 | 4.25 | 0.98 | 0.84 | 6.06 | |
| | *X. granatum* | 2 | 2.67±0.577 (2–3) | 0.004 | 0.43 | 0.02 | 0.11 | 0.56 | |

[1] *Importance Value (IV)* of a given species is the sum of relative frequency, dominance and density.
[2] *Complexity index (CI)* of a stand is calculated as: number of species × basal area ($m^2$/0.1 ha) × tree height (m) × number of stems/0.1 ha × $10^{-3}$ in a 0.1-ha plot.
*Sample size*: Northern Swamps = 3138 stems (in 134 quadrats); North Central Swamps = 2633 stems (in 133 quadrats). Number in parenthesis indicates the range.

those that are unproductive, either because of edaphic factors or because of human extraction pressure. The highly productive stands (classified here as b-1, b-2, b-3, c-1, c-2 and c-3) occupied 9,745.47 ha (Table III), and had an average volume of 302.07 $m^3$ $ha^{-1}$ (Table IV). The area of less productive category (classified as a-2, a-3, b-4 and c-4) was 6,290.47 ha, with an average volume of 28.73 $m^3$ $ha^{-1}$. The net standing volume of mangroves within and adjacent to KMNR was 2.4 million $m^3$ (Table IV). This is considered to be conservative estimate as measured volumes exceeding 700 $m^3$ $ha^{-1}$ was recorded, particularly in the Northern Swamp forests (Table IV).

Figure 2 shows plots of frequency vs. diameter class for stand table data of the mangroves in the Northern and North Central Swamps forest. In the Northern Swamps forests, 881 trees per ha (41.13%) had diameter of 5.0–10.0 cm (Figure 2a). While in the North Central Swamps, 1187 trees/ha (57.20%) had diameter of 5.0–10.0 cm (Figure 2b). The fitted stand curves show that stem density decreased exponentially as the diameter increased. These are typical reversed *'J'* curves expected for forest stands with a wide range of size classes and by inference also age classes.

The potential yield of the future mangrove forest in KMNR can be gauged by an evaluation of current standing volume. The present inventory revealed that the existing mangrove forests within and adjacent to KMNR have a net standing volume of 2,354,004.85 $m^3$. The average stand volume ranges between 6.85 to 710.0 $m^3$ $ha^{-1}$ for stem diameter above 5.0 cm (Table IV). The average volume of the entire study area was 145.88 $m^3$ $ha^{-1}$, which corresponds to a stand density of 1736 stems per ha. This is considered to be high considering that mangroves of KMNR are not virgin forests.

In Matang, Malaysia, the average density for 30-year-old stand of *Rhizophora apiculata* Bl. is 1343 trees/ha with average volume of 153 $m^3$ $ha^{-1}$ (Haron, 1981). In Ranong, where some of the best mangroves in the world are located an average density of 812 trees per ha and volume of 226 $m^3$ $ha^{-1}$ have been reported (Aksornkoae, 1993). Chong (1988) estimated an annual harvest of 1185 $m^3$ $yr^{-1}$ in a 25-years rotation from Terraba-Sierpe of Costa Rica that contained a stocking of 769 trees per ha (or 281 $m^3$ $ha^{-1}$). KMNR has probably the most productive mangrove forests in Kenya. Given its high potential productivity and regeneration, mangroves within and adjacent to KMNR have excellent prospects for sustainable exploitation.

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