Participatory Forestry Improves Mangrove Forest Management in Kenya

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Research

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Abstract

Background: Mangrove forests worldwide are highly valued for their social, ecological and environmental roles. Participatory forestry has been recognized as a tool for improvement of forest conditions. The current study assessed impacts of PFM implementation on structure and regeneration of mangroves at Gazi Bay, Kenya. Forest data was collected along belt transects perpendicular to waterline in both community and state managed blocks.

Results: Basal area and standing density were significantly higher in the co-managed forests (16 m^2 ha^{-1} and 4,341 tree ha^{-1}) as compared to the state managed forests (eastern block 10.3 m^2 ha^{-1} and 2,673 trees ha^{-1}; western block 6.2 m^2 ha^{-1} and 2,436 trees ha^{-1}). There were significantly higher ($p = 0.0068$) densities of quality class poles in co-managed forest block as compared to state-managed eastern and western blocks. Natural regeneration values of 38,822 juveniles ha^{-1} in the co-managed central block and 23,556 and 35,061 juveniles ha^{-1} in the state managed eastern and western blocks respectively are considered adequate to support recovery of the forest. A higher complexity index (CI) recorded in the co-managed mangrove forest compared to the state managed eastern and western blocks is particularly due to improved stand density, tree height, and biomass resulting from increased surveillance and protection by the community. The results have wide implications in the management of mangroves for community and biodiversity benefits and climate change mitigation.

Conclusion: The results support community participation for improved management of mangrove forests and are in conformity with sectoral policies on natural resources management in Kenya.

Background

Since the 1970s, there have been discernible shifts in forest management in tropical countries from a top-down to an ostensibly more inclusive participatory forest management (PFM) regimes (Arts et al. 2016). The shift towards participatory forestry is based on the assumption that involvement of local community would provide incentives for sustainable forest management, enhanced livelihoods through increased social and financial benefits and reduced levels of deforestation (Tadesse et al. 2016; Kairu et al. 2017). Consequently, PFM has been promoted and implemented in many developing countries as a mechanism for improving both forest conservation and development. However, critics point out that PFM approach could harm or protect the environment, present opportunities or restrictions to local communities, depending on the prevailing conditions and the way resources and rights are devolved from central government to middle and local management levels (Nathan and Boon 2012; Mutune et al. 2017). Thus, while there is increased emphasis on the use of PFM to conserve forests and improve livelihoods, its effectiveness remains poorly understood.

A growing body of literature exists on impacts of PFM on forest status and conditions (e.g. Arts and De Koning 2017). In Ethiopia, for instance, improved forest structure and development was observed in community managed forests as compared to those managed by the state (Tadesse et al. 2016). A recent meta-analysis of tropical forests governance by Porter-Bolland et al. (2011) showed that community-managed forests had lower rates of deforestation than state-protected equivalents. Similarly, Hayes and Persha (2010) established that when communities set their own, there was a positive outcome on forest condition in Honduras, Nicaragua, and Tanzania. A comparative study on the impacts of community rights on forest cover in Bolivia and Peru also revealed that under PFM, forest structure exhibited more stable conditions (Wright et al. 2016). Positive impact of PFM have been associated with the extent to which community enjoys the rights to forest resources (Schlager and Ostrom 1992; Larson and Dahal 2012) and possible benefits that community was deriving from the forests (Matiku et al. 2013; Mutune and Lund 2016).

However, PFM is far from being the panacea for improved forest management. Roy et al. (2013) reported regular and illegal deforestation in Indian and Nepalese forests under co-management. In Kenya, Chomba et al. (2015) highlighted how PFM made some local communities more vulnerable, due to forest access taxations by the government, insufficient power transfer to the community forest associations (CFAs) and the problems of elite capture. There is also evidence that bureaucratic rules and lack of autonomy in decision-making restricted community use and conservation of the forest resources in Southern Thailand (Sudtongkong and Webb 2008), East Africa and South East Asia (Persha et al. 2011) thus affecting forest conditions. In Kenya, Kimutai and Watanabe (2016) reported that forest cover declined under participatory management due to lack of funding to support conservation activities. Similarly, Russell et al. (2017) reported a declining trend in standing density, forest cover, and biomass in Mt. Elgon forest, after the forest was put under participatory management in Kenya. The decline was associated with illegal logging occurring due to unsustainable participatory approaches, characterized by low support from the government line agencies.

Results of PFM approaches have shown mixed successes when applied specifically to mangrove forests. In Bangladesh’s Sundarbans, community based mangrove rehabilitation was initiated as a means of improving forest management in the area (Islam and Gnauck 2009). However, forest depletion continues with recent work attributing these failures to the absence of effective community partnerships (Roy and Gow 2015). The limited examples of successful PFM involving mangroves points to poor enforcement of forest rules involving mangroves (Walters 2004) as well as the little attention of mangrove ecosystem in forest policy implementations (Walters 2004; Mwangi et al. 2017; Feka 2015; Ishtiaque and Chhetri 2016; Roy et al. 2013). Despite evidence that the participatory forestry can improve forest conditions (Umemiya et al. 2010), to our knowledge there are no empirical studies linking PFM with improved mangrove management in Kenya as the majority of such studies have focussed on terrestrial forests (Mogoi et al. 2012; Chomba et al. 2015; Mutune and Lund 2016; Mutune et al. 2017). Research on mangrove forests in Kenya, have tended to focus on their functional ecology (Tamooh et al. 2008; Bosire et al. 2008), mangrove resources utilizations (Dahdouh-Guebas et al. 2000), silviculture of species (Kairo et al. 2001; 2008; 2009), and ecosystem valuation (Huxham et al. 2015). The current study aims to contribute to the understanding of how community participation impacts on structural development of mangrove forests in Kenya.

Materials And Methods

The study area

The study focused on the mangroves of Gazi Bay located in south coast of Kenya in Kwale County (4°25’S and 39°50’E; Fig. 1). The Bay has two main creeks – eastern (Kinondo) and western creeks. Two seasonal rivers – Kidogoweni to the northwest and Mkurumudji to the southwest of the bay drains into the Bay. This is in addition to seepage points (Signa et al. 2017) that provide the Bay with freshwater input. According to Koppen climate classification, the climate of Gazi Bay may be classified as tropical wet/dry that is ideal for supporting mangrove growth. The climate is heavily influenced South East monsoon winds (Kuzi), which are associated with heavy rains and blows from March to August. This is followed by the North East monsoons (Kazkazi) that blow from November to March; and are characterized by dry weather. Annual total rainfall in Gazi ranges from 1000 mm to 1,600 mm. Temperatures ranges from 22 to 34 ^{O}C during North Easterly Monsoon, and from 19 to 29 ^{O}C during the South Easterly Monsoon seasons (UNEP 1998). Humidity is high, and averages 80 % all year round (Kitheka 1996).

Mangrove in Gazi

There are 703 ha of mangrove forests in Gazi Bay. The nine mangroves species documented in the Western Indian Ocean (WIO) region occur in the Bay (Neukermans et al. 2008). The most dominant species are *Rhizophora mucronata* and *Ceriops tagal* that occupies more than 80% of forest formation. These forests have historically been harvested for building materials and firewood. However, in the 1970s, heavy exploitation of mangrove wood for industrial energy left large contiguous blank areas devoid of natural regeneration (Dahdouh-Guebas et al. 2004; Kirui et al. 2013). A joint mangrove management program involving trading of carbon credits was initiated in Gazi Bay in 2013 (Huff and Tonui 2017). This carbon offset scheme involving communities, forest agency and donors is mostly located in the central block of Bay where intensified surveillance and mangrove monitoring is carried out.

Study design

To investigate the impact of participatory forestry on mangrove forest structure, three forest blocks in Gazi were sampled – the eastern, central and western blocks (Table 1, Fig. 1). The *eastern block* stretches from Chale Island to eastern creek and measures approximately 225 ha. This management block is located 3-5 km from Makongeni village (Fig. 1) and has no direct freshwater influence (Signa et al. 2017). The eastern block is largely managed by Kenya Forest Service (KFS), a state forest agency in charge of forests in Kenya, and there is minimal community involvement. KFS authorizes selective logging of mangroves in the eastern block through issuance of harvesting permits for commercial and subsistence uses.

The *western block* covers 145 ha of mangroves and is bordered by Gazi village to the West, river Kidogoweni to the North and Mkurumudji in the South. Mangroves in this block are under the state management and are heavily influenced by human settlement in Gazi village that frequent the forest for wood and non-wood resources. Further, there is direct influence by freshwater input from the seasonal Kidogoweni and Mkurumudzi rivers. Inflowing fresh water into the Bay mixes with the sea-water creating a salinity range of 2.0 % during rainy seasons and 37.5 % in dry season (Kitheka 1996).

Central block has an estimated coverage of 333 ha; and is positioned between the eastern (Kinondo) and western creeks of the Bay. Mangroves in the central block have been managed by local community since 2013 through an approved forest management agreement (FMA) with the government. Conservation activities carried out in this block include replanting of degraded mangrove areas, increased forest surveillance and monitoring. These activities generate verifiable emission reductions (VERs) that are then traded into the voluntary carbon market. Income from carbon trading amounting to ca. US$ 15,000/year is locally used in provision of fresh water, enhancing education, and forest conservation (Wylie et al. 2016).

Assessment of forest structure

In each management block, belt transects were set at 250 m intervals and running perpendicular to the water line. Standard plots of 10 x10 m were randomly established along the transects. All trees inside the quadrants with stem diameter ≥2.5 cm were identified, counted and GPS co-ordinates noted. The following vegetation structural measurements were taken – tree height (m) and stem diameter (dbh) measured at 1.3 m above the ground (D130). From these data, species importance value (IV) (%), stand density (stems ha^{-1}), basal area (m^2 ha^{-1}) and biomass (t ha^{-1}) were derived following the procedures described in Kairo et al. (2002a). A total of 33 transects and 173 quadrats across the three blocks were studied (Table 1).

Generalized allometric equations (Komiyama et al. 2015) were used in estimating stand biomass of mangroves. The equations were in the form:

$$B_{ag} = 0.251 \rho D^{2.46} \quad (1)$$

Where: B_{ag}= Biomass above-ground (t ha^{-1}), ρ = specific wood density (g cm^{-3}) and D = D130.

Localized specific wood densities for common mangrove species in WIO region were used (Bosire et al. 2012). Standing biomass was compared across the management blocks using the 2013 baseline by KMFRI Gazi station for the carbon offset project. Data was checked for normality before subjecting it to the Analysis of Variance.

According to Kairo et al. (2008) it takes 12 years for mangroves in Gazi to achieve an average tree height and dbh of 8.4 ± 1.1 m (range: 3.0–11.0 m) and 6.2 ± 1.87 cm (range: 2.5– 12.4 cm) respectively. Maximum annual increment (MAI) in biomass for the principal mangrove species in Gazi bay was estimated as *R. mucronata* (4.05 t ha^{-1} y^{-1}), *Avicennia marina* (1.46 t ha^{-1} y^{-1}), *Sonneratia alba* (1.34 t ha^{-1}

y^{-1}) and *C. tagal* (0.46 t ha^{-1} y^{-1}). This data was used to compare structural development of mangroves in the co-managed block using 2013 as baseline. Complexity index (Holdridge et al. 1971), which uses the variables of tree density (stems ha^{-1}), basal area (m^2 ha^{-1}), species number, and tree height (m) was used to determine the forest structure in each of the forest block.

Natural regeneration

Natural regeneration pattern was assessed in a 5 by 5 m^2 subplots nested within the larger 10 by 10 m plots. All juveniles inside the subplots were identified and arbitrarily assigned height classes using FAO guidelines whose application can be found in Kairo et al. (2002a). Seedlings with height below 40 cm were grouped as regeneration class 1 (RCI) while saplings with a height of 40 cm - 150 cm were grouped as RCII. Small trees of height larger than 150 cm but less than 300 cm were classified under RCIII.

Forest quality

To evaluate the quality of the forest, trees in each 10 by 10 m plots were assigned quality classes. Class I poles constituted trees with long lead stems suitable for building. Class II constituted bent poles that require few modifications when building. Class III poles were made up of crooked poles unsuitable for building (Kairo et al. 2008) thus excluded by cutters.

Future forest

Future forest was estimated using De Liocourt's model (1898) as describe in Clutter et al. (1983). Based on the model, the ratio, between the tree densities in consecutive dbh classes (designated as *q*) is almost constant for a balanced uneven-aged forest characterized by continuous recruitment by natural regeneration (Clutter et al. 1983). Future forest structure was estimated by fitting the model to the stock densities obtained in this study as applied in Clutter et al. (1983).

Results

Structure of mangroves in Gazi Bay

Nine mangrove species were encountered in Gazi bay. In terms of importance values (IV), the principal species in the Bay is *R. mucronata* with an IV of more than 100% in all the forest blocks. Other important species are *B. gymnorrhiza,* (IV = 80.2) and C. *tagal* (IV = 75.9) in central blocks and *A. marina* (IV = 68.5) in western block (Table 2).

Species zonation

Like most areas in WIO region, mangrove forest in Gazi Bay portrays horizontal distribution of species. The seaward area is occupied by either *Sonneratia alba* or *Rhizophora mucronata* (Fig. 2). This is followed by a mixed zone of *R. mucronata*, *C. tagal* and *Bruguiera gymnorrhiza*, in the middle zone; and zones of *A. marina* and *C. tagal* on the landward side. *Xylocarpus granatum*, *X. moluccensis*, *Heritiera* *littoralis* and *Lumnitzera racemosa* occur on the landward margins or on the fringes of rivers. *Avicennia marina* exhibits a “double zonation” with its presence in the “landward and seaward zones” (Dahdouh-Guebas et al. 2004).

Height-diameter scatter grams of mangroves in the eastern, western and central blocks are given in Fig. 3. All the forest blocks were dominated by small sized trees, mostly with dbh ≤ 6cm and height ≤ 7m. There was no significant difference in height (p = 0.27) and stem diameter (p = 0.12) between central block and state managed eastern and western blocks. The stocking density of trees with a dbh of 2.5 – 6.0 cm (*pau)* and 6 – 9 cm (*mazio)* was higher than trees with dbh ≥ 14 cm in all the forest blocks. Only 2.4 %, 7.8 % and 5.1 % of trees had a dbh ≥ 14 cm in the central, eastern and western blocks respectively. The higher percentage of large diameter trees in the state managed forest can be attributed to the old growth trees. The stocking rate of community managed central block, 4,341 trees ha^{-1} with basal area of 16 m^2 ha^{-1} was higher than densities and basal areas in eastern (2673 trees ha^{-1}; 10.3 m^2 ha^{-1}) and western (2,436 trees ha^{-1}, 6.2 m^2 ha^{-1}) blocks respectively (Table 3 and 5). There was a significantly higher stem density ($F_{(2, 170)}$ = 22.09, p = 0.0001) and basal area ($F_{(2, 15)}$ =4.71, p=0.026) in central block compared to the eastern and western blocks.

Standing biomass

Table 4 shows vegetation attributes for the lower dbh trees, 2.5 – 9.0 cm and for the entire forest blocks. The average stand biomass in western, central and eastern blocks were 130.8 ± 120.7 t ha^{-1} (range 12.8 – 472.3), 170.3 ± 134 t ha^{-1} (range 0.4 - 571) to 190.7 ±138.9 t ha^{-1} (range 21.1 – 792) respectively. Biomass values in the lower size classes (2.5 – 9.0 cm) were significantly higher in the community managed central block that had a mean value of 3.8 ± 1.1 t ha^{-1} (range: 2.6 - 6.1). In the state managed forests, the eastern block had a biomass of 1.4 ± 0.5 t ha^{-1} (range 0.8 - 2.3) while western block had an average biomass of 1.3 ± 0.7 t ha^{-1} (range 0.5 - 2.6) (Table 4). A comparison of the mean biomass values of the dbh class 2.5 – 9.0 cm in the three forest blocks using a one-way ANOVA test revealed a significant difference ($F_{(2, 36)}$ = 41.4, p < 0.001) among the forest blocks. Mean separation using Tukey’s test revealed that co-managed central block had a significantly higher biomass compared to both the eastern and western blocks whose difference was non-significant.

Forest regeneration

There were differences in natural regeneration densities and juvenile sizes among the management blocks (Fig. 4). Total juvenile density was 23,555.6 juveniles ha^{-1} (range: 525 to 11,181); 38,822.6 juveniles ha^{-1} (range 700 to 21,577), and 35,061.1 juveniles ha^{-1} (range 250 to 7,626.6), for eastern, central and western blocks respectively. There was no significant difference between regeneration densities among the three forest blocks. However, central block had a higher density of established regeneration (RCII and RCIII) of 12,313 juveniles ha^{-1}, compared to 8,377 and 6,606 juveniles ha^{-1} in the eastern and western blocks respectively. High densities of large sized saplings in the central block contributed to the high stocking density realized in the co-managed block.

Forest quality

The density of quality class poles (i.e. quality class 1) was significantly higher ($F_{(2, 6)} = 67.1$, $p < 0.001$) in co-managed than in state managed blocks. For instance, there were 1,274 stems ha^{-1} of Class 1 poles in central block compared to the 397 and 265 stems ha^{-1} that were observed in eastern and western blocks respectively. Forests in the western and eastern blocks were over-stocked with truncated *Avicenna marina* and old growth *Rhizophora mucronata* trees of mostly quality class 3 that is undesirable for building and construction industries. Generally, poles with stem diameter less than 13 cm are the most harvested for commercial and subsistence use (Kairo et al. 2008).

Complexity Index

For all size classes, complexity indices (CI) were higher in community-managed central than in state managed blocks (Table 5). Trees in the 2.5 – 6.0 cm size classes recorded a CI of 2.7, 0.5 and 0.4 in central, eastern and western blocks respectively.

Discussion

The study assessed conditions of mangrove forests co-managed with the community versus those solely managed by the state agency. The assessed forest attributes included forest structure in terms of stand density, basal area, biomass and natural regeneration.

Stocking rates

The stocking rate was significantly higher in community managed central block compared to the state managed western and eastern blocks (Table 5). Central forest is particularly stocked with *pau-boriti* sized poles (diameter range: 2.5-13.0 cm) that are nearly depleted in the state managed stands. *Pau – boriti* are the most merchantable pole class and often harvested for building and construction industry (Bosire et al. 2012). Enhanced community scout patrols and surveillance has led to improved management of mangrove in the area as witnessed by higher complexity indices in the central block compared to other blocks (Table 5).

The government signed a forest management agreement with Gazi community to manage the mangroves in the central block of the Bay in 2013. The agreement defines *dos* and *don'ts* inside the co-managed forest area. For instance, harvesting of poles inside the co-managed area is strictly prohibited. However, non-consumptive utilization of the forest products and services such as honey collection, fishing and ecotourism activities are encouraged (GoK 2017). In the case of Gazi, the community utilizes the co-managed area for a carbon-offsetting scheme – Mikoko Pamoja. Sales of carbon credits from the community forest have served as a strong incentive of promoting mangrove rehabilitation, surveillance and monitoring. The outcome of this has been the enhanced stocking density, natural regeneration, biomass, forest quality and complexity index observed in the central block compared to state management blocks (Table 5). A similar study in Philippines observed an enhanced forest structure and regeneration in mangrove forests co-managed with the community (Walters 2005).

Prolonged logging of the *pau-boriti* sized poles (dbh: 2.5 – 13.0 cm) in state managed western and eastern blocks of Gazi mangroves has led to near depletion of the desired product from the forests. Similar conclusions were made in Mida creek (Kairo et al. 2002a) and Kiunga, Lamu (Kairo et al. 2002b) in Kenya where selective logging converted the forest from superior stands with desired products to inferior forest devoid of *pau, mazio* and *boriti* sized poles. In Malaysia, India and Indonesia where commercial logging of mangrove forests has been practiced over many decades, prolonged logging has contributed to loss of forest productivity (Wilkie 2007).

Natural regeneration

FAO has proposed juvenile density of 2500 mangrove saplings ha^{-1} randomly distributed as adequate to support natural regeneration of the forest (FAO 1994; Kairo et al. 2002a). Based on FAO's recommendation, the three forest blocks in Gazi had adequate natural regeneration. The density of established regeneration (RCII and RCIII) of 12,313 juveniles ha^{-1} in co-managed block was high as compared to values of 8,377 and 6,606 juveniles ha^{-1} recorded in state managed eastern and western blocks respectively. A high concentration of established juveniles in co-managed forest signifies higher transition rate from juveniles to mature trees in co-managed forests compared to state managed forest. When mangrove forests are protected from overexploitation and degradation, the substrate become stable allowing saplings and propagules to establish making natural regeneration possible (Kairo et al. 2001). In co-managed block of Gazi, a high regeneration can be attributed to silvicultural activities like replanting and pruning and improved surveillance provided by community user group in collaboration with KFS (Huff and Tonui 2017). The observed ratio of RCI: RCII: RCIII of 2:2:1, 1:2:1 and 8:4:1 for central, eastern and western block respectively is within the sustainable stocking ratio of 6:3:1 proposed by FAO.

Forest quality

Straightness of trees is a relative measure of a quality forest. Class 1 and 2 poles are highly preferred in the market than the crooked class 3 poles. Significantly higher densities of class 1 poles in co-managed forests (1,274 trees ha^{-1}) than in state managed western (265 trees ha^{-1}) and eastern (397 stems ha^{-1}) blocks is an indication of effective protection against illegal logging provided by the community. Carbon financing has enabled the Gazi community to hire scouts for surveillance of the forest against intruders. Improved forest conditions emanating from community conservation efforts have been reported also in Bolivia (Wright et al. 2016), Philippines (Camacho et al. 2011), and Tanzania (Blomley et al. 2008). In Bolivia for instance, communities are involved in monitoring and enforcement of forest rules, guided by a formal agreement between the state and local community (Wright et al. 2016).

Above ground biomass

The biomass of tree with butt diameter ≤ 9.0cm was significantly higher ($p < 0.05$) in co-managed central block (biomass 3.8 t ha^{-1}) than in the Eastern (1.4 t ha^{-1}) and Western (1.3 t ha^{-1}) blocks. In the case of central block, the community has used carbon financing to promote recovery of the forest, as indicated by high regeneration densities, and biomass increment. The community group enjoys autonomy in developing bylaws and decision making relating to their silvicultural activities and allocation of income to social improvement projects of their choice in the village (Huff and Tonui 2017). According Hayes and Persha (2010), ownership rights, autonomy in decision making relating to the forest management and benefits from forest income motivates the community in controlling forest extraction allowing the forest to grow and accumulate carbon.

The old growth trees that existed before the signing of forest management agreement in Gazi in 2013, influenced the overall stand biomass in central (170.3 t ha^{-1}) as well as in eastern (190.7 t ha^{-1}) and western (130.8 t ha^{-1}) blocks (Table 4). Large trees with butt diameter > 20cm are usually not preferred by the mangrove markets in Kenya and are thus avoided by cutters. Biomass values reported in Gazi compares well with the above ground mangrove biomass reported in Kiunga Marine Park, Kenya (199.6 t ha^{-1}) (Cohen et al. 2013). However, the values are significantly higher ($p<0.05$) than the standing biomass of mangroves in North Sulawesi, Indonesia (61.4 t ha^{-1}), and Sarawak, Malaysia (116.8 t ha^{-1}) (Murdiyarso et al. 2009; Chandra et al. 2011). Old growth mangroves forests in Bahile, Philippines, and Cameroon recorded standing biomass of 561.2 t ha^{-1} and 504.5 t ha^{-1} respectively (Abino et al. 2014; Ajonina et al. 2014). Like in tropical rainforests, high biomass values are reported for tropical mangroves with high influence of fresh water (Kathiresan and Bingham 2001; Tomlinson 2016).

When compared with the 2013 baseline data, standing biomass in the co-managed block increased from 42.9 t ha^{-1} to 170.3 t ha^{-1} from 2013 to 2017; translating to annual biomass increment of 31.9 t ha^{-1} y^{-1}. This biomass increase as a result of community interventions is what is converted to biomass carbon and traded as carbon credits. Annual sales from co-managed mangroves in Gazi has been estimated at 2,255 t CO_2-eq. earning the community a direct income of about US$15,000/annum (Wylie et al. 2016). The community uses part of the carbon financing to restore degraded mangrove areas in the Bay; while the balance is used to support priority community projects in water and sanitation, education and health (Wylie et al. 2016). Incentivizing forest conservation activities is a triple win to climate regulations, biodiversity conservation, and community benefits (Huff and Tonui 2017).

The nature of future forests in Gazi

The current stocking rates of mangroves in Gazi can be used to predict the nature of future forests. Based on De Liocourt's predictive model, un-even aged forest produces a reverse *j* curve, when the ratio between successive diameter classes, *q* ratio, is constant. A constant *q* only occurs in a balanced forest stand, with normal diameter distributions capable of producing sustainable yields (Meyer 1952; Govedar et al. 2018). The *q* ratios obtained in the current study were not constant in all the three forest blocks. The exponential curves failed to precisely fit into the actual data obtained for dbh classes 6.1 – 9.0 cm (*mazio*) and 9.1 – 13.0 cm (*boriti*) in central and eastern blocks (Fig. 5). The depletion of stock densities in these dbh classes can be attributed to unsustainable logging of those sizes whose demand is high in local markets (Dahdouh-Guebas et al. 2000). However, the high density of trees with girth of ≤ 6 cm in co-managed block is an indication of the conservation efforts by community groups since establishment of co-management regime. If current participatory activities continue, the normal stem density shown by the exponential curve would be achieved since the small trees (dbh < 6 cm) will grow to fill up the deficits in 6.1 – 9.0 cm (*mazio*) and 9.1 – 13.0 cm (*boriti*) classes thus stabilizing the forest. Using harvesting scheme to control extraction would prevent excessive removal of *mazio* sized poles and eventually allow restoration of depleted diameter classes in state managed blocks. Bundotich et al. (2009) in the mangroves forest of Ngomeni and Mohamed et al. (2009) in Tudor creek mangroves made similar observations where some diameter classes had lower tree densities than normal. This was attributed to selective cutting and an extraction regime that lacked a harvesting plan, resulting in over exploitation of specific diameter classes. The near perfect stock densities observed in western block can be attributed to the presence of a large number of *A. marina* species, a species that is less preferred in local market and community for building and firewood.

Conclusion

This study assessed the impacts of participatory forestry on mangrove forest structure in Kwale County of Kenya. The results revealed that joint management between community and government had improved the structure of mangrove forests in Gazi Bay. The stand density, basal area, biomass and forest quality were significantly higher in co-managed forest as compared to state managed forests. The density of merchantable *pau - boriti* sized poles (butt diameter 2.5 to 13.0 cm) were particularly high in co-managed central block due to community interventions including enhanced surveillance and patrols by community scouts. In addition, community receive direct cash payment for the sale of carbon credits from avoided deforestation of mangroves in the central block (Wylie et al. 2016). According to Schlager and Ostrom (1992) community rights to forest resources has a positive impact on participatory forestry. The improved forest structure is also linked to support by national government, donor support and international partnerships that have worked to sustain the carbon offset facility in the community-managed forest in Gazi. On the contrary, the near *open access* status of the state managed eastern and western blocks had promoted illegal logging due to poor surveillance and patrols. Policy recommendation from the study is that joint mangrove forest management with the community should be promoted in order to improve forest conditions, create wealth and conserve biodiversity in the country, in line with the national mangrove ecosystem management plan (GoK 2017).

List Of Abbreviations

PFM- Participatory forest management

CI - Complexity index

CFA - Community Forest Associations

FMA – Forest Management Agreements

FAO - Food and Agriculture Organization

DBH – Diameter at breast height

GoK – Government of Kenya

RC – Regeneration class

I.V. – Importance Value

WIO - Western Indian Ocean

KFS - Kenya Forest Service

KMFRI - Kenya Marine Fisheries and Research Institute

UNEP - United Nations Environmental Program

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and material

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests

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Authors' contributions

AK and JK designed the project and developed data collection and analysis methods. All the authors contributed equally in the writing and editing of the manuscript. All authors read and approved the final manuscript.

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Tables

Table 1. Sampling intensity of mangroves in Gazi bay.

Block	Area (ha)	No. of Transect	No. of quadrats
Eastern	225	11	51
Central	333	13	83
Western	145	9	39

Table 2
Importance values of mangroves in Gazi

		Relative values (%)			
Eastern	Species	Density	Frequency	Dominance	IV
	A. marina	3.9	8.3	14.4	26.6
	B. gymnorrhiza	7.9	21.1	10.0	39.0
	C. tagal	14.3	14.7	5.9	34.8
	R. mucronata	70.6	45.0	63.3	178.8
	S. alba	1.4	6.4	4.6	12.4
	X. granatum	1.5	4.6	1.8	7.9
Western	*A. marina*	21.5	25.3	21.7	68.5
	B. gymnorrhiza	2.9	8.9	4.6	16.4
	C. tagal	31.1	22.8	14.2	68
	H. littoralis	1.7	2.5	3.4	7.6
	L. racemosa	3.2	2.5	1.9	7.6
	R. mucronata	36.5	30.4	51.5	118.5
	X. granatum	2.3	3.8	1.2	7.3
	S. alba	1.2	3.8	1.6	6.5
Central	*A. marina*	3.0	5.3	10.7	19.0
	B. gymnorrhiza	26.9	24.7	28.6	80.2
	C. tagal	32.8	29.7	13.4	75.9
	R. mucronata	34.6	34.1	41.4	110.0
	S. alba	0.5	1.0	2.8	4.3
	X. granatum	2.3	5.3	3.1	10.6

Table 3
Stand table data for mangroves in different management blocks (values in bracket represent percentages).

	Utilization classes						
Management block	2.5-6.0	6.1-9.0	9.1–13.0	13.1–20.0	20.1–35.0	> 35.0	Total Density
	(Pau/Fito)	(Mazio)	(Boriti)	(Nguzo)	(Banaa 1)	(Banaa 2)	
Western	1480	451	231	172	95	8	2437
(State managed)	(60.7)	(18.5)	(9.5)	(7.1)	(3.9)	(0.3)	
Eastern	1602	318	233	214	292	14	2673
(State managed)	(59.6)	(11.9)	(8.7)	(8.0)	(10.9)	(0.5)	
Central	3223	532	262	215	92	17	4341
(Co-managed)	(74.3)	(12.3)	(6.0)	(5.0)	(2.1)	(0.4)	

Table 4
Mangrove attributes for dbh 2.5–9.0 cm versus entire stand (dbh ≥ 2.5) in the three blocks.

Vegetation attributes	**Basal area (m^2 ha^{-1})**		**Stem density ha^{-1}**		**Biomass (t ha^{-1})**	
Dbh range (cm)	2.5–9.0	≥ 2.5	2.5–9.0	≥ 2.5	2.5–9.0	≥ 2.5
Central	2.35	16	1878	4341	3.8	170.3
Eastern	0.85	10.3	960	2673	1.4	190.7
Western	0.6	6.2	966	2435	1.3	130.8

Table 5
Structural attributes of mangroves in Gazi bay

		Diameter class					
Management block	Attributes	2.5-6.0	6.1-9.0	9.1–13.0	13.1–20.0	20.1–35	> 35
Western							
	No. of species	8	8	7	7	4	1
	Stem density ha^{-1}	1479.5	451.3	230.8	171.8	94.9	7.7
	Average height (m)	4.3	5.6	7.3	9.0	11.5	19.3
	Basal area (m^2 ha^{-1})	0.8	0.8	0.8	1.4	1.6	0.8
	Complexity index	0.4	0.2	0.1	0.2	0.1	0.0
Eastern							
	No. of species	6.0	6.0	6.0	6.0	6.0	3.0
	Stem density ha^{-1}	1602.0	317.6	233.3	213.7	151.0	13.7
	Average height (m)	5.3	6.7	7.9	9.3	11.5	14.8
	Basal area (m^2 ha^{-1})	1.0	0.7	1.1	2.3	4.2	1.0
	Complexity index	0.5	0.1	0.1	0.3	0.4	0.01
Central							
	No. of species	6.0	6.0	6.0	6.0	6.0	5.0
	Stem density ha^{-1}	3223.1	532.1	261.5	215.4	92.3	16.7
	Average height (m)	4.8	6.1	6.9	7.7	9.8	14.2
	Basal area (m^2 ha^{-1})	2.9	1.8	2.0	3.5	3.9	2.1
	Complexity index	2.7	0.4	0.2	0.4	0.2	0.02

Figures

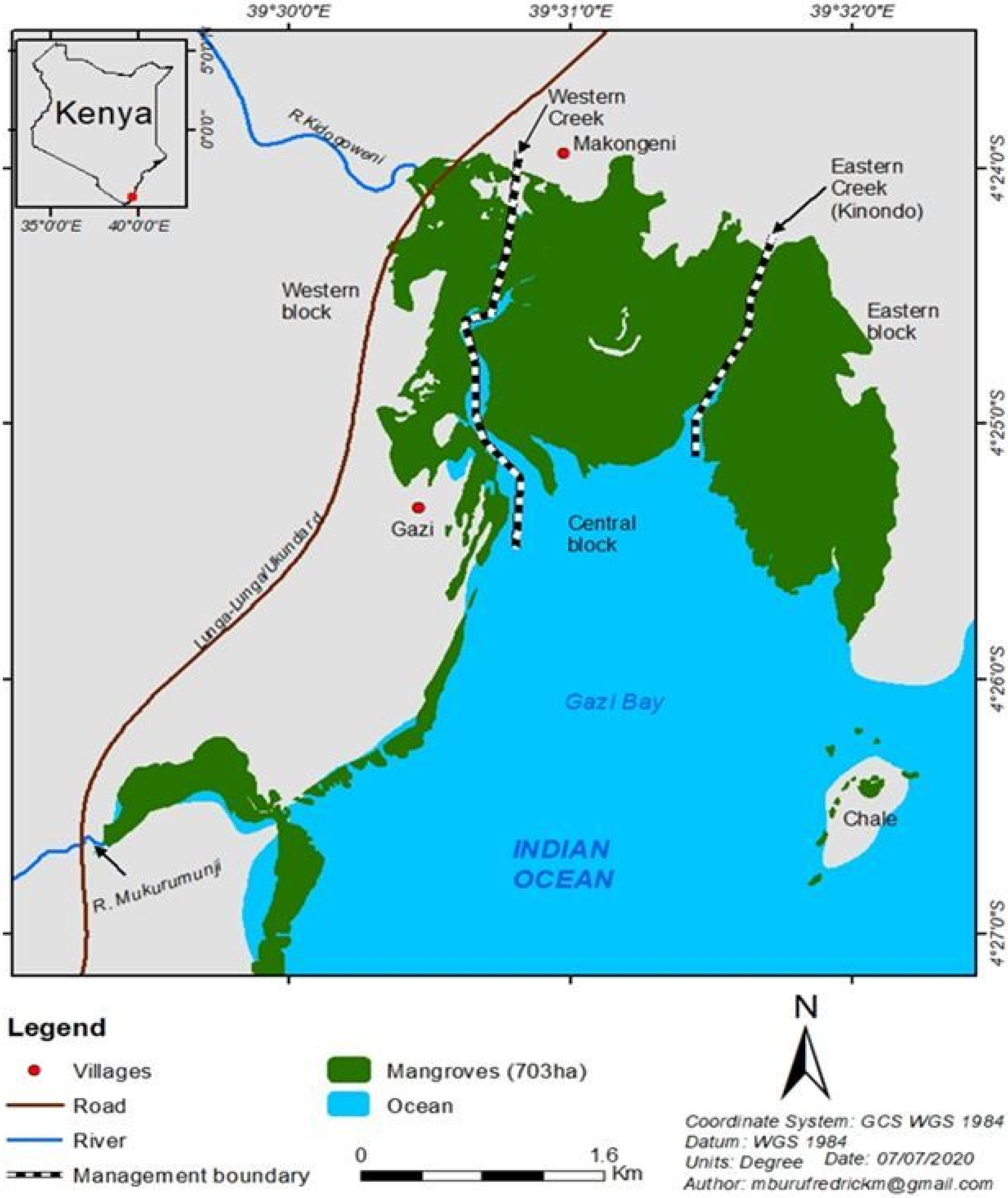

Figure 1

Mangroves of Gazi bay showing the three management blocks – Eastern, Central and Western.

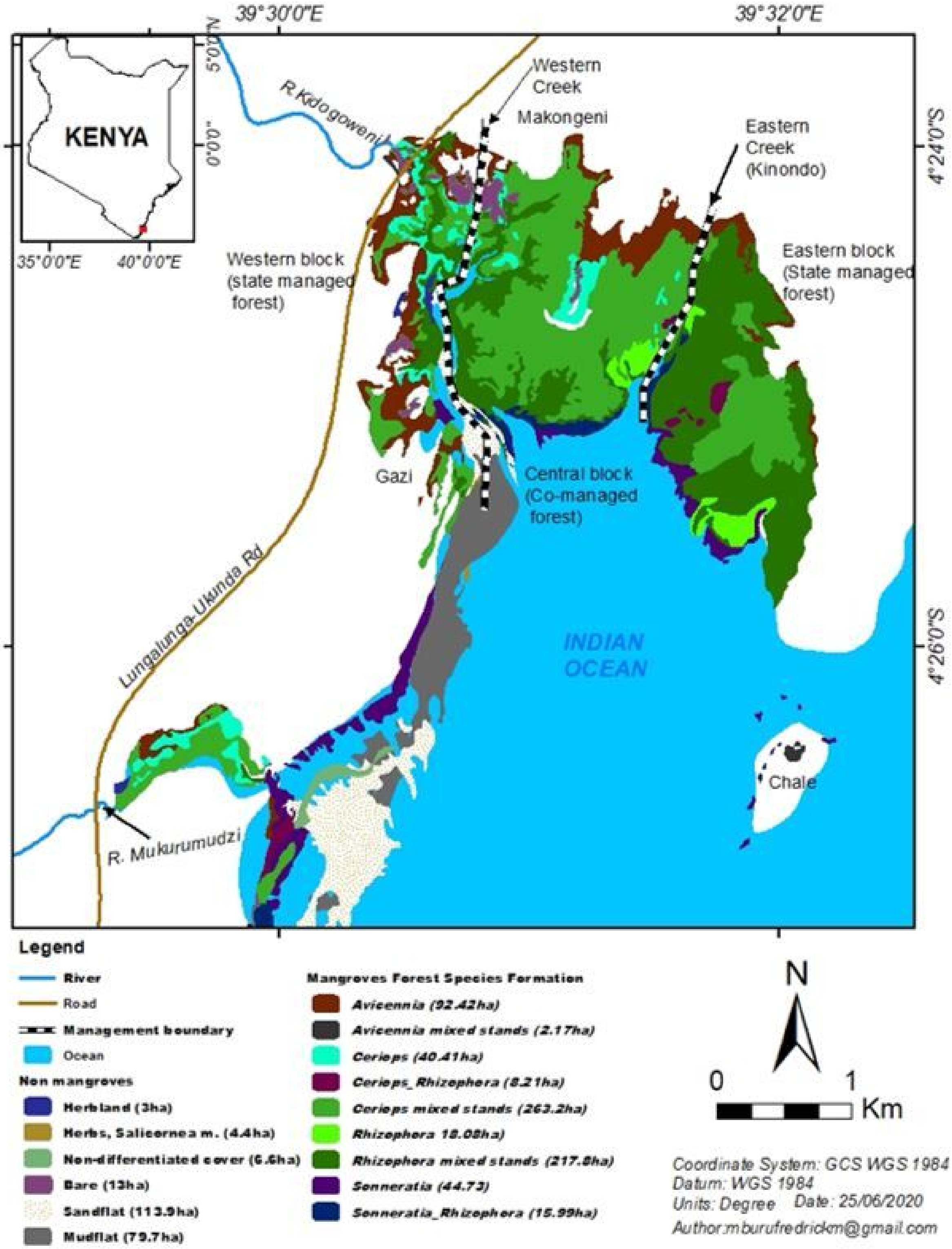

Figure 2

Map of Gazi Bay showing mangrove species zonation in the management blocks.

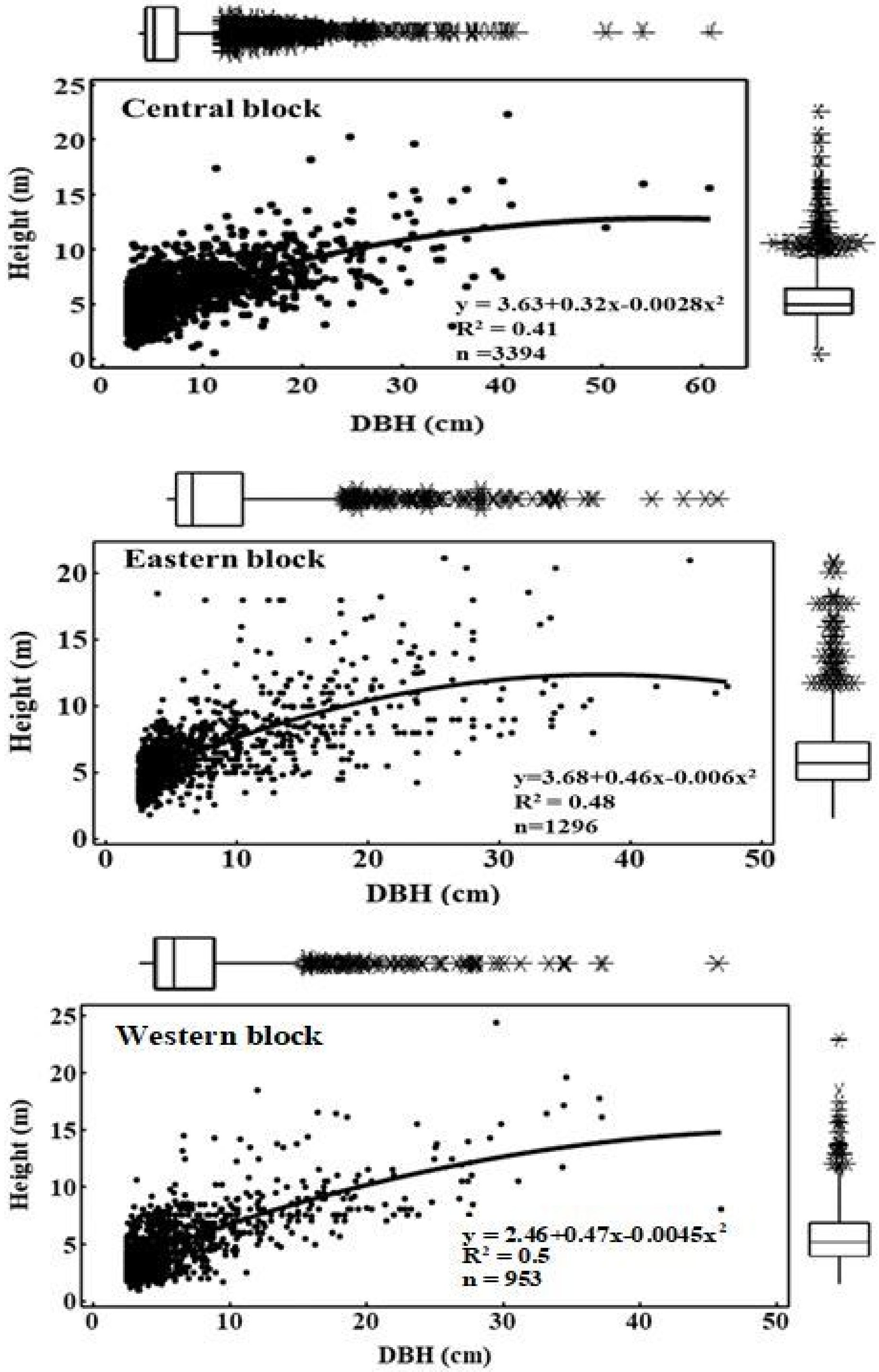

Figure 3

Height-diameter scatter grams of mangroves in Gazi.

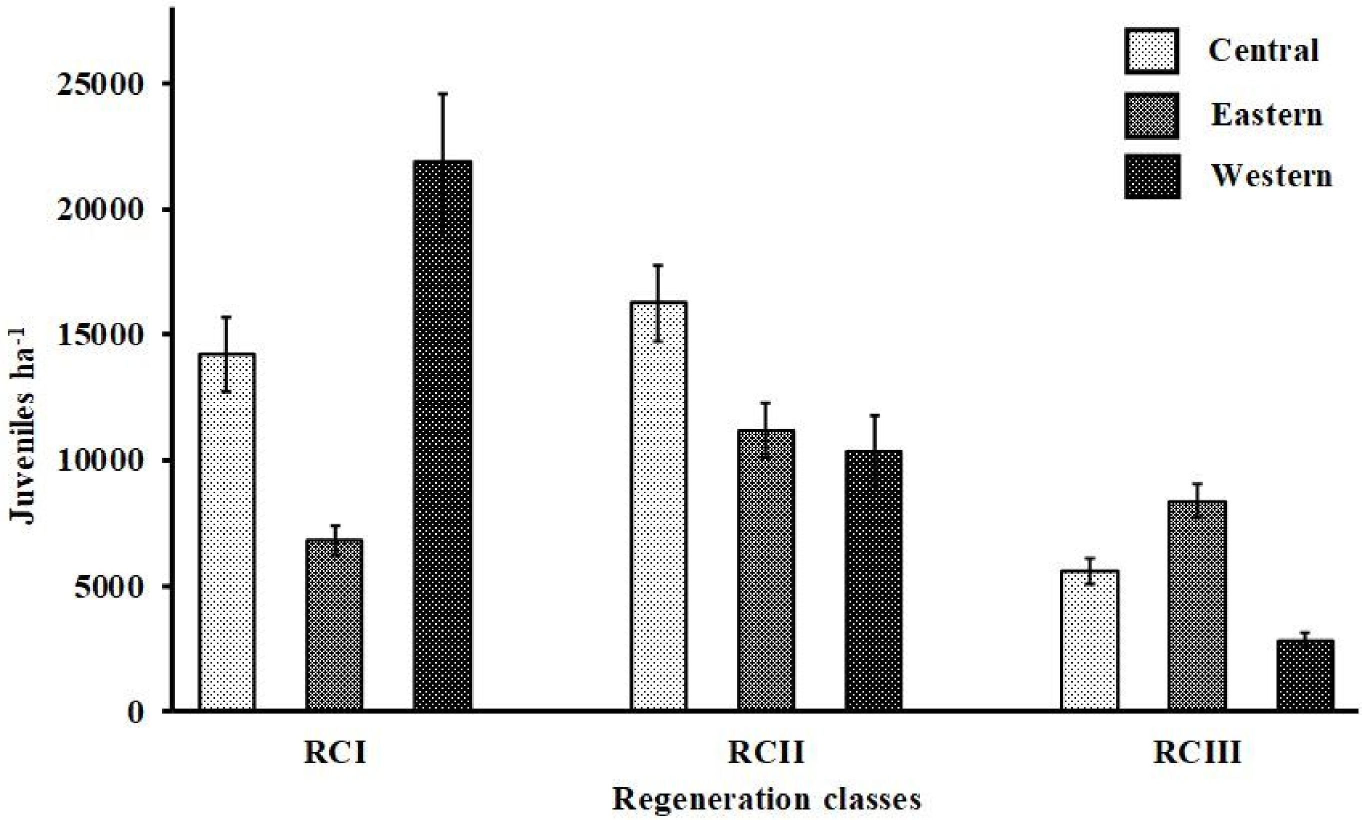

Figure 4

Natural regeneration pattern of mangroves in the three management blocks of Gazi bay

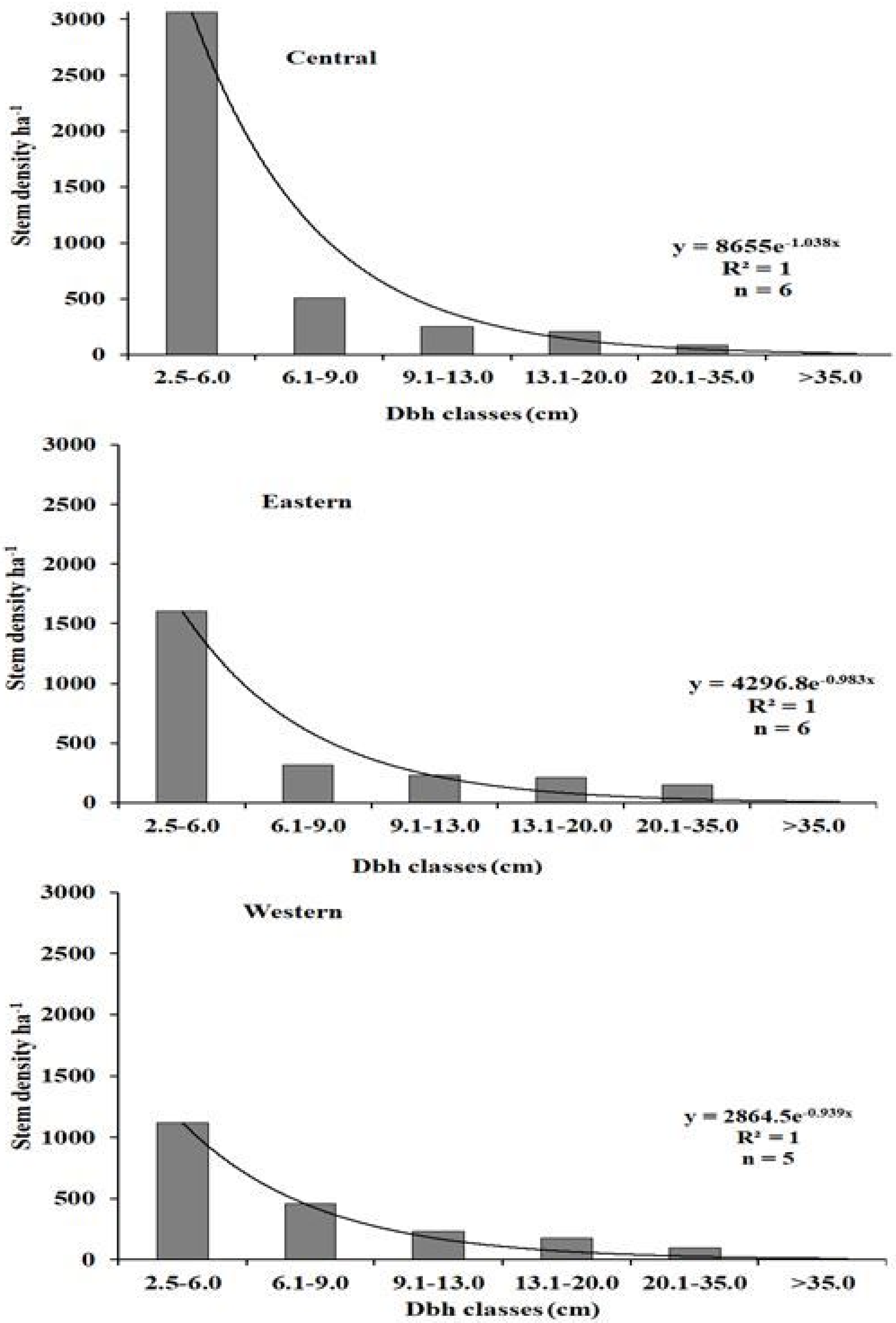

Figure 5

Size class frequency distribution. The bar graph shows the observed densities of trees with diameter equal or greater than 2.5 cm in mangrove forests blocks of Gazi Bay. The solid line represents an approximation of normal diameter distribution using De Liocourt's exponential model. The exponential equation (2) above is of the form Y=ke-ax (Clutter et al. 1983).