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ORIGINAL PAPER

Status, structure and environmental variations in semi-arid mangroves of India

G. A. Thivakaran[1] · Seema B. Sharma[2] · Abhiroop Chowdhury[1,3] · Arumugam Murugan[4]

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Abstract The semi-arid mangroves of the Gulf of Kachchh, the largest ecosystems on the west coast of India, are poorly studied in terms of vegetation structure and environmental parameters in spite of their conservation significance. Therefore, it is necessary to document the structural features of these mangroves in view of ongoing coastal industrial development. Mangrove forest structure in 10 locations on the northern and southern coasts of the Gulf of Kachchh were assessed using the line intercept transect method. Descriptions included density of young and mature age classes, tree heights, diameters at breast height (DBH) and aboveground biomass, along with seven significant environmental variables. Mature tree densities ranged from 350 to 1567 ind. ha^{-1}, while average height and girth at breast height ranged from 1.0 to 6.8 m and 3.0 to 137.0 cm, respectively. The majority of trees (55.6%) were in $\leq$ 1.8 m height class followed by a 1.9 to 2.4 m class (25.1%). DBH was most often in class 2 cm or lower than that. Among the canopy index classes, more trees were recorded in class $\leq$ 2 cm. The regeneration density was greater than the recruitment class. This study indicates that the poor structural attributes of *Avicennia marina* Vierth. var. *acutissima* Stapf and Mold dominated mangroves are largely due to aridity induced by scarce and erratic rainfall and high soil and water salinities. The results should be valuable in conserving and sustainably managing these mangroves in the face of developmental activities.

Keywords Mangroves · Vegetation structure · Abiotic factors · Biodiversity · Forest management · Aboveground biomass · Conservation

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Corresponding editor: Yu Lei.

✉ Seema B. Sharma
seemabhargavsharma@gmail.com

1 Coastal and Marine Ecology Division, Gujarat Institute of Desert Ecology, Bhuj, Gujarat, India

2 Department of Earth and Environmental Sciences, KSKV Kachchh University, Mundra Road, Bhuj, Gujarat, India

3 Department of Chemistry, Manipal University Jaipur, Dehmi Kalan, Jaipur-Ajmer Express Way, Jaipur, Rajasthan 303007, India

4 Central Marine Fisheries Research Institute, Mandapam Regional Centre, Marine Fisheries P.O, Mandapam Campus, Ramanathapuram, Tamil Nadu 623 520, India

Introduction

Mangrove structural analysis is an important tool to understanding stand dynamics and is useful in the management of mangrove ecosystems (Adams et al. 2004). Knowledge of mangrove structure helps create an awareness of their status and future stand dynamics (Dahdouh-Guebas et al. 2002). A sound understanding of mangrove dynamics helps managers to determine the appropriate remedial measures to negate the impacts of development. Due to the importance of mangroves, their structure has gained attention worldwide (Fromard et al. 1998; Chen and Twilley 1999; Dahdouh-Guebas and Koedam 2001; Kairo et al. 2002; Satyanarayana et al. 2002; Adams et al. 2004; Coronado-Molina et al. 2004; Chowdhury et al. 2016; Sharma et al. 2016). The objectives of this study are to evaluate the structural attributes of the Gulf of Kachchh mangrove ecosystems and their governing environmental variables in order to promote their conservation. This will help us gain a better understanding of their dynamics.

Mangroves of Gujarat state are located in arid to semi-arid climates over 1140 km^2, making them the largest mangrove ecosystems on the west coast of India (FSI 2017). Mangrove forests of the Gulf of Kachchh cover approximately 986 km^2 in the state of Gujarat and are dominated by *Avicennia marina* (Forsk.) Vierth. var. *acutissima* Stapf and Mold formations with the sporadic occurrence of eight other mangrove species (ICMAM 2004; GEC and BISAG 2008). Despite the designation of the southern coast of Gulf of Kachchh as a Marine National Park in 1982, recent development activities have stressed these mangroves. Industrial development is impacting these mangrove ecosystems by altering edaphic conditions. Systematic studies of the Gulf of Kachchh mangroves are limited (Chavan 1985; Untawale and Wafar1988; Singh 2000; Nayak and Anjali 2001; Thivakaran et al. 2003; Saravanakumar et al. 2009; Patel et al. 2010). Most of the earlier studies have dealt with the coverage and distribution of mangroves by remote sensing (Nayak et al. 1992; Bahuguna and Nayak1996). However, few studies have focused on stand dynamics and structural variations along the coastline. Reliable information about vegetation structure and governing abiotic properties are a necessity for conservation efforts (Selvam 2003; Chowdhury and Maiti 2016a, b, c). Rapid industrialization in this region harboring extensive mangrove formations requires active management and a sound understanding of mangrove structural and demographic characteristics. As noted by Soares and Schaeffer-Novelli (2005), Donato et al. (2011) and Alongi et al. (2016), studying mangrove forest structural variables, including biomass, could address globally significant issues (Sharma and Gobi 2016) such as carbon sequestration and climate change. In addition, their dynamics could also be better understood. Although many descriptive works dealing with the ecology of Indian mangroves have been carried out (Satyanarayana et al. 2002; Thivakaran et al. 2003), structural attributes of the Gulf of Kachchh mangrove formations need to be studied in detail, particularly with ongoing industrial development and the conservation significance of these ecosystems. This study provides a demographic insight of the Gulf of Kachchh mangroves by analyzing their vegetation structure to aid in the conservation efforts.

Materials and methods

Study area

The Gulf of Kachchh (22°15′ to 23°40′N; 68°20′ to 70°40′E) in the northwestern part of India covers some 7350 km^2 (Chauhan et al. 2006). The networks of creeks and mudflats and differential macro-tidal levels ranging from 3.5 to 6.7 m, creates several hydrographic peculiarities (Vethamony et al. 2004). The Gulf has more than 40 islands of different sizes, each harbouring important ecosystems such as coral reefs and mangroves with a rich associated fauna and flora (Babu et al. 2005). Only a few seasonal rivers empty freshwater into the Gulf, influencing its biological, physical and chemical characteristics during the monsoon months of June–September. The Gulf of Kachchh is semi-arid with higher mean annual rainfall in the southern coast (565 mm) cf. the northern coast (348 mm). The Gulf area therefore experiences a negative water balance due to the lack of perennial river discharge.

In spite of its rich mangroves and coral formations, in the last two decades the Gulf coastal belt has been subjected to aggressive industrial development such as petrochemical installations, oil refineries and port facilities due to its strategic location and proximity to Middle East countries. Dredging in these ports dislodges enormous quantities of bottom sediments, leading to severe mangrove degradation (ICMAM 2004).

Seven study locations on the southern coast, (Positra, Ashapura, Kalubar, Narara, Chhad, Jodia-Variyali, and Jodia-Dora) and three locations on the northern coast (Kandla, Mundra and Kharo) were selected based on mangrove distribution (Fig. 1). The southern coastline is muddy, interspersed with rocky, sandy intertidal belts. Kalubar is the largest island with many mangrove- lined creek systems and coral formations. Coastal stretches of Jodia-Variali and Jodia-Dora are straight and exposed to open waters of Gulf of Kachchh. The three study locations on the north coast are along minor and major creek systems. Kandla and Mundra sites at the end of the Gulf are characterized by highly muddy shores facing severe threats from heavy port-related activities. Pristine mangrove stands in Kharo in northwestern Kachchh near the international border with Pakistan, have limited anthropogenic activities due to security reasons. The grey mangrove, *A. marina*, is the dominant species in all the stands studied, with the sporadic occurrence of other species, especially *Rhizophora mucronata* Lam. and *Ceriops tagal* (Pers.) C.B. Rob. One species observed as a few individual plants outside the study locations was *Aegiceras corniculatum* (L.) Blanco at Kandia, thought to be locally extinct.

Mangroves

Gulf of Kachchh mangroves are overwash fringe formations (Ewel et al. 1998) occurring in tide-dominated high salinity regimes and lacking riverine inflow. Vegetation characteristics in the selected locations were studied using the line intercept transect method (Kershaw 1973; Mueller-

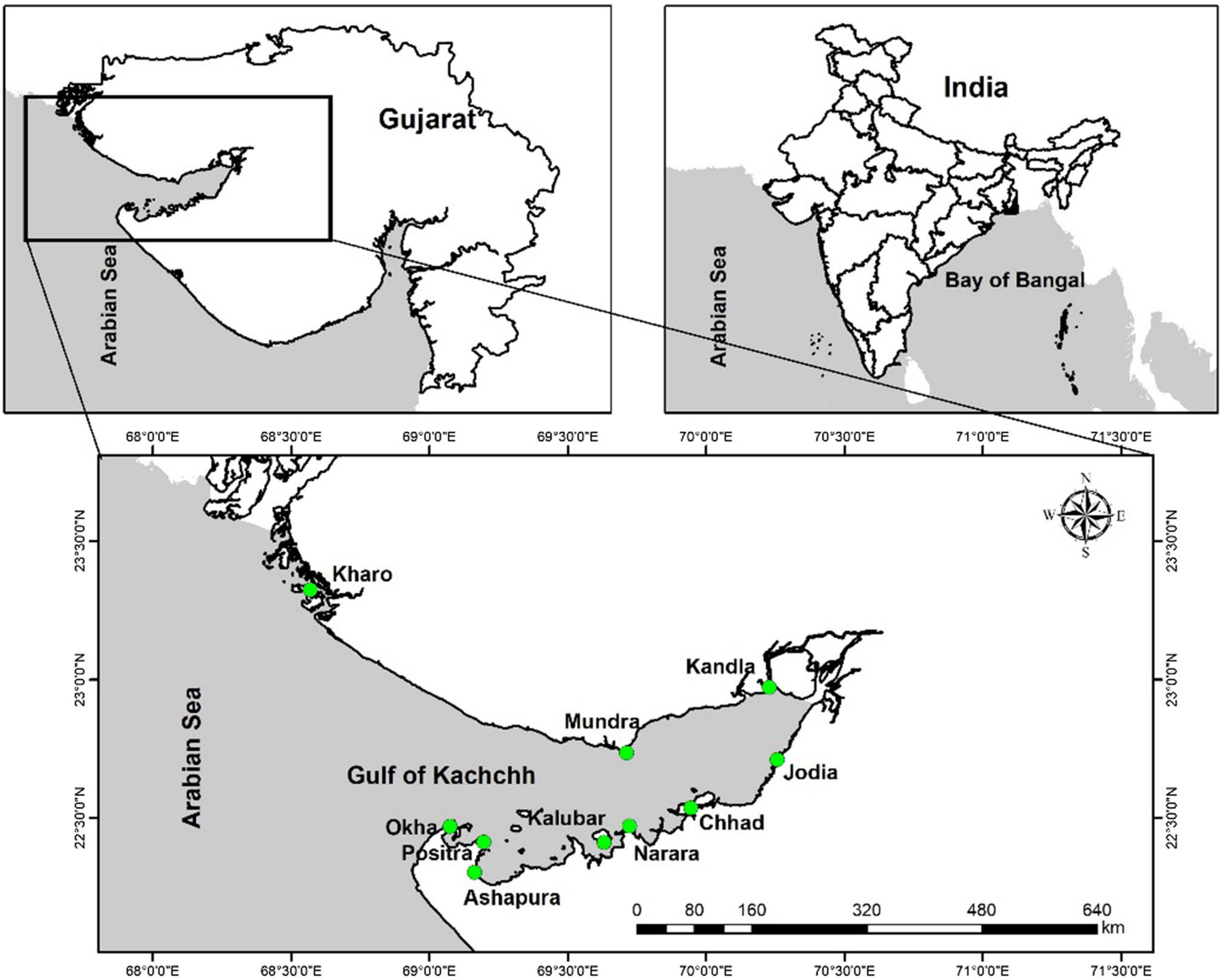

Fig. 1 Study stations in the Gulf of Kachchh, Gujarat, India

Dombois and Ellenberg 1974) from November 2006 to March 2007. In the ten different stands along the coastal stretch of 756 km, 60 transects were established with 162 quadrats covering 4351 trees.

The number of transects in each location varied from 3 to 13 in order to accurately represent the particular stand. The length of each transect and distance between quadrats in each transect was based on the width of the mangrove stand as measured by GPS from low to high tide levels. In each plot, the number of trees, tree height and girth at breast height (GBH) were measured using ranging rods and measuring tapes. GBH readings were converted to DBH by dividing by 3.14. The DBH of all trees $\geq$ 1 m were measured. In case of a branching stem at a specific height, the procedure suggested by English et al. (1997) was followed. Canopy length and width, measured with graduated poles, were multiplied to calculate canopy index (CI). Within each 10 $\times$ 10 m plot, 1 $\times$ 1 m and 2 $\times$ 2 m subplots were laid randomly to determine regeneration and recruitment classes. Seedlings $\leq$ 50 cm tall were considered regeneration, while the recruitment class was well-established saplings $\geq$ 50 cm in height. The density of mature, regeneration and recruitment material for each location was expressed as a number per hectare. Tree height, DBH and CI data were segregated into size classes to study the frequency of occurrence of *A. marina*, *Ceriops tagal* and *Rhizophora mucronata.* Bray–Curtis cluster analysis (SPSS 14), which expresses similarity or dissimilarity between different groups in the form of a dendrogram, was used to test the ecological distance between different locations.

For calculating the aboveground biomass (AGB), the general allometric equation ($B = 0.251\ \rho\ (D^{2.46})$ of Komiyama et al. (2005) was used as it employs DBH as the predictive variable which can be measured more accurately than height. Linear regression plots were constructed for all sites and species to verify the strength of the relationship

R^2 between the dependent variable AGB and the independent variable DBH. Biomass for the three species and for the whole plot was calculated and expressed as mg ha^{-1}.

Abiotic parameters

Important abiotic parameters that play a significant role in shaping the mangrove vegetation structure were analysed. These were studied during the dry winter season of November 2006 to March 2007. Creek water salinity (ppt, parts per thousand) was measured during low tides with a pre-calibrated refractometer (Master 3 M, Aatago, Japan). Porewater samples for salinity and pH were collected with a siphon and syringe, and soil samples were collected for soil texture studies. These samples were collected in triplicate at three tidal levels at a depth of 20 cm. Hydrogen ion concentration (pH) was estimated in situ using a pre-calibrated pH pen (Model 331, Hanna, Italy). Samples for texture analysis were oven-dried and mechanically sieved for sand (0.125–0.250 mm); silt (0.0039–0.0625 mm); and clay (0.00098–0.0039 mm). Samples for dissolved oxygen (DO) were collected in biological oxygen demand bottles and a modified Winkler's titrimetric method (APHA 1998) was used to estimate dissolved oxygen. Total suspended solids (TSS) were estimated by filtering 1-L of water sample through a glass micro fibre filter and the results were expressed as mg L^{-1}. Surface water temperature was measured using a calibrated thermometer (sensitivity ± 0.1 °C). Turbidity of suspended particles was measured in a calibrated nephelometer (Model 331, Hanna, Italy) and the results expressed in nephelometer turbidity units (NTU).

Results

Mature tree density and composition

The grey mangrove, *A. marina,* is the principle mangrove species in the Gulf of Kachchh, forming pure stands in seven out of the ten locations studied. *Rhizophora mucronata* and *Ceriops tagal* were found only at the Chhad and Kalubar sites in the southern coast and at Mundra on the northern coast. For *A. marina,* the highest density of 3308 ha^{-1} was recorded at Mundra while the lowest 1462 ha^{-1} was at Kalubar (Table 1). The densities of *C. tagal* and *R. mucronata* were highest at Kalubar with 292.0 and 223.0 ha^{-1}, respectively. At the Chhad site, *C. tagal* was a mere 7.5% of the total density, while at the Kalubar site, *R. mucronata* and *C. tagal* were 11.3% and 14.8%, respectively. At the Mundra site, *R. mucronata* contributed less than 1.0% to the total density, while *C. tagal* was 6.0%. *A. marina* had the highest relative density of 96.4% followed by *C. tagal* (2.5%) and *R. mucronata* (1.1%) (Fig. 2).

Mature tree height

The average tree height values ranged from 1.0 to 6.8 m in different locations, with the highest variation at Kalubar and the lowest at Jodia-Dora (Table 1). Mean tree height was 2.2 ± 0.6 m and 2.1 ± 1.1 m for *C. tagal* and *A. marina,* respectively, at Kalubar. The mean tree height of *C. tagal* was larger at Chhad and Kalubar, while it was shorter at Mundra.

Segregation of tree heights into 0.6 m frequency classes showed that more trees (55.6%) were ≤ 1.8 m followed by 25% of the trees in the 1.9–2.4 m class. There were few (1.0%) trees 4.3–4.8 m (Fig. 3).

Diameter at breast height (DBH)

DBH ranged from 0.3 to 43.6 cm, and mean values were 7.0 cm (± 2.8) and 21.1 cm (± 0.2) at Mundra and Kalubar, respectively (Table 1). Stands at Kalubar, Mundra and Chhad had larger DBH ranges while *R. mucronata* and *C. tagal* stands showed less variation. Among DBH classes, 25% of the trees 3.1–4.5 cm were predominant followed by 20% of the trees in the 1.6–3.0 cm class (Fig. 4). In all study locations, trees ≥ 16.5 cm were fewest whereas in Positra, Narara, Chhad, Kalubar and Mundra stands it was more in number. For *A. marina*, all 13 girth classes were represented at Chhad, Mundra and Kharo locations but not in the Kandla and Jodia-Dora ecosystems.

Canopy indices

Canopy index values were higher for *A. marina* mangroves than for *C. tagal* and *R. mucronata.* Among canopy classes, 54.3% of the trees were in the frequency class of ≤ 2. Other higher frequency classes (8–9, 9–10 and 10–11) were least represented among all the sites, whereas lower 2–4 classes were well-represented (Fig. 5). Site locations such as Positra, Ashapura and Narara had 12 out of 13 frequency classes.

A Bray–Curtis coefficient (Bray and Curtis1957) was used to produce a hierarchical cluster for 10 study locations using tree density, DBH and height as variables (Fig. 6). Four groups were identified at a scale of 1–10 (Fig. 6), apparently due to similar structural characters as a function of their geographical proximity and similar environments. The first cluster, Narara, Positra and Chhad is located on the western part of the southern shore, whereas the second cluster, represented by a single location, Kalubar, is an island ecosystem where maximum average tree heights and

Table 1 Structural characteristics of Gulf of Kachchh Mangroves

Stations	Density (ind. ha^{-1})	Tree Height (m)			DBH (cm)			AGB (t ha^{-1})	Canopy index		
		Min.	Max.	Mean	Min.	Max.	Mean		Min.	Max.	Mean
Positra—*A. marina*	1567	1	4.6	1.9 (± 0.66)	0.96	26.43	5.29 (± 3.74)	36.3 (r^2 = 0.745; N-171)	1.2	105	7.69 (± 12.21)
Ashapura—*A. marina*	2742	0.76	5.04	1.87 (± 0.75)	1.27	20.38	5.57 (± 3.39)	80.4 (r^2 = 0.839; N-329)	1	103	3.76 (± 7.63)
Narara—*A. marina*	2107	1	12	1.8 (± 0.74)	0.41	26.11	5.14 (± 2.85)	105.3 (r^2 = 0.715; N-569)	3	43.2	2.7 (± 3.36)
Chhad—*A. marina*	1633	1	4.7	1.58 (± 0.63)	1.21	35.35	6.57 (± 4.36)	52.44 (r^2 = 0.688; N-298)	2.2	25	2.45 (± 3.01)
Chhad—*C. tagal*	133	1.1	2.3	1.72 (± 0.28)	1.59	5.1	2.87 (± 0.75)	0.352 (r^2 = 0.92; N-22)	1.2	5	1.56 (± 1.12)
Chhad-total	1766	1	4.7	1.59 (± 0.61)	1.21	35.35	6.28(± 4.31)	52.79 (r^2 = 0.73; N-320)	1	25	2.38 (± 2.92)
Kalubar—*A. marina*	1454	1	6.8	2.13 (± 1.08)	0.96	43.63	6.71 (± 5.18)	70.83 (r^2 = 0.71; N-289)	1	64	4.27 (± 7.12)
Kalubar—*R. mucronata*	223	1.1	3	1.31 (± 0.39)	0.86	6.05	2.28 (± 1.34)	0.276 (r^2 = 0.87; N-29)	1.5	2.25	0.54 (± 0.6)
Kalubar—*C. tagal*	292	1.1	3.2	2.18 (± 0.56)	1.59	7.01	4.14 (± 1.6)	2.37 (r^2 = 0.95; N-37)	2.25	5	2.14 (± 1.2)
Kalubar-total	1969	1	6.8	2.28 (± 1.1)	0.85	43.63	6.17 (± 5.12)	73.51 (r^2 = 0.67; N-256)	1	64	3.6 (± 6.36)
Jodia-Variyali—*A. marina*	2513	1	3.25	1.66 (± 0.39)	1.27	15.92	4.27 (± 2.42)	24.1 (r^2 = 0.86; N-201)	4	5.41	2.32 (± 1.12)
Jodia-Dhoro—*A. marina*	2178	1	2.1	1.3 (± 0.22)	1.59	9.87	3.32 (± 1.33)	10.1 (r^2 = 0.88; N-196)	1.2	105	4.17 (± 8.44)
Kandla—*A.marina*	2243	1	3.1	1.61 (± 0.5)	0.96	7.96	4.51 (± 1.37)	30.3 (r^2 = 0.93; N-314)	2.8	22.5	1.63 (± 1.7)
Mundra—*A.marina*	3308	1	6.7	2.15 (± 0.77)	0.31	36.66	6.2 (± 4.36)	96.75 (r^2 = 0.71; N-1191)	6.25	80	3.34 (± 5.03)
Mundra—*R. mucronata*	33	1.1	2.2	1.57 (± 0.31)	0.95	3.82	2.31 (± 0.89)	0.618 (r^2 = 0.94; N-12)	1.1	1.5	0.96 (± 0.52)
Mundra—*C. tagal*	166	1	3.2	1.6 (± 0.5)	1.27	4.46	2.22 (± 0.89)	4.52 (r^2 = 0.93; N-60)	1	4	0.84 (± 0.8)
Mundra— total	3608	1	6.7	2.12 (± 0.77)	0.31	35.66	5.98 (± 4.34)	101.89 (r^2 = 0.70; N-1263)	1	80	3.20 (± 4.92)
Kharo-*A.marina*	2877	0	4.5	2.07 (± 0.66)	1.27	25.48	6.61 (± 3.71)	216.8 (r^2 = 0.77; N-633)	1	27.5	4.04 (± 4.19)

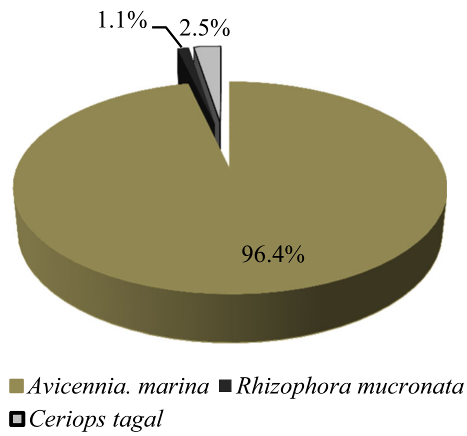

Fig. 2 The relative density (%) of the mangrove species at the Gulf of Kachchh, India

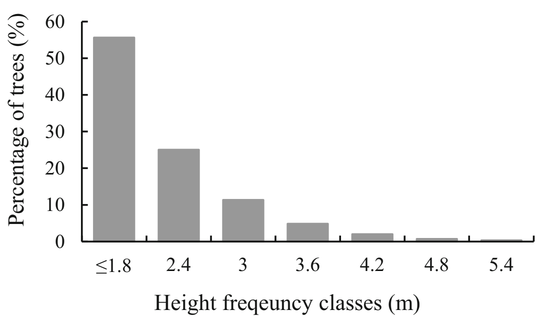

Fig. 3 Percentage of trees in different height frequency classes (m) in Gulf of Kachchh Mangroves

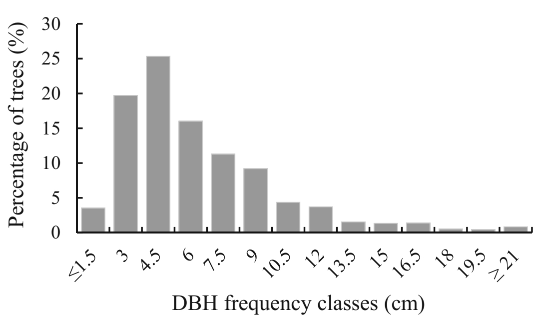

Fig. 4 Percentage of trees in different DBH frequency classes (cm) in Gulf of Kachchh mangroves

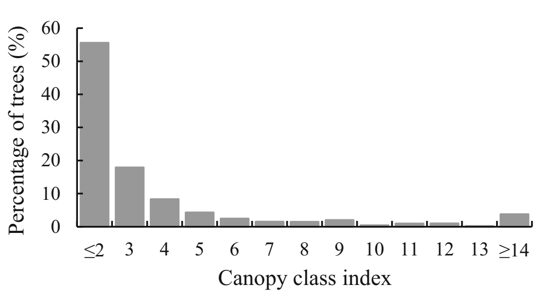

Fig. 5 Percentage of trees in different canopy index frequency classes in Gulf of Kachchh Mangroves

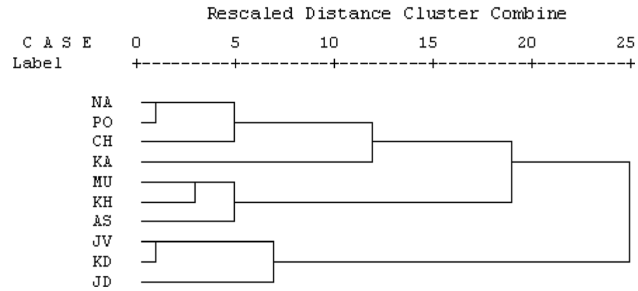

Fig. 6 Dendrogram for 10 stations using average linkage (between groups) *PO* Positra; *AS* Ashapura; *NA* Narara; *CH* Chhad; *KA* Kalubar; *JV* Jodia Variali; *JD* Jodia Dhora; *KD* Kandla; *MU* Mundra; *KH* Kharo

high floral diversity and density were recorded. The third cluster, Mundra, Kharo and Ashapura, share similar vegetation attributes and the fourth, Jodia-Variyali, Kandla and Jodia-Dora, is located on the inner gulf and is characterized by the lowest floral density.

Aboveground biomass (AGB)

The grey mangrove ecosystem had the highest aboveground biomass in all locations, followed by *C. tagal* and *R. mucronata*. The highest values were in the Kharo site (216.8 mg ha^{-1}) followed by the Narara (105.3 mg ha^{-1}) and Mundra (101.9 mg ha^{-1}) sites. The strongest regression co-efficient (R^2) between biomass and DBH was at the Chhad (*C. tagal*; $R^2 = 0.92$, $p < 0.001$), Mundra (*C. tagal*; $R^2 = 0.93$, $p < 0.001$) and Kandla sites (*A. marina*; $R^2 = 0.93$, $p < 0.001$). The relationship between DBH and biomass for the three species followed a second order polynomial trend (non-linear) as evident in Fig. 7a–c. R^2 values were highest for *C. tagal* ($R^2 = 0.999$), followed by *R. mucronata* ($R^2 = 0.999$), and *A. marina* (0.994) (Fig. 7a–c).

Younger classes

Regeneration in all locations was higher than recruitment; based on location, the average regeneration density ranged from 21,111 ind. ha^{-1} at Kandla to 550,733 ind. ha^{-1} at Jodia-Variyali (Table 2). Regeneration was high in Jodia-Dora (295,911 ind. ha^{-1}) and Ashapura (AS) stands (293,892 ind. ha^{-1}). The ratio between regeneration and recruitment categories was lower in Chhad (1:1.5), Kandla (1:2.3) and Kharo stands (1:5), indicating a high entrance of regeneration into the recruitment category. At the Ashapura, Jodia-Variyali and Positra sites, the regeneration to recruitment ratio was higher, implying poor entrance of this class into the mature category (Table 2). A ratio of 1:2 and 1:2.5 was calculated between recruitment and mature

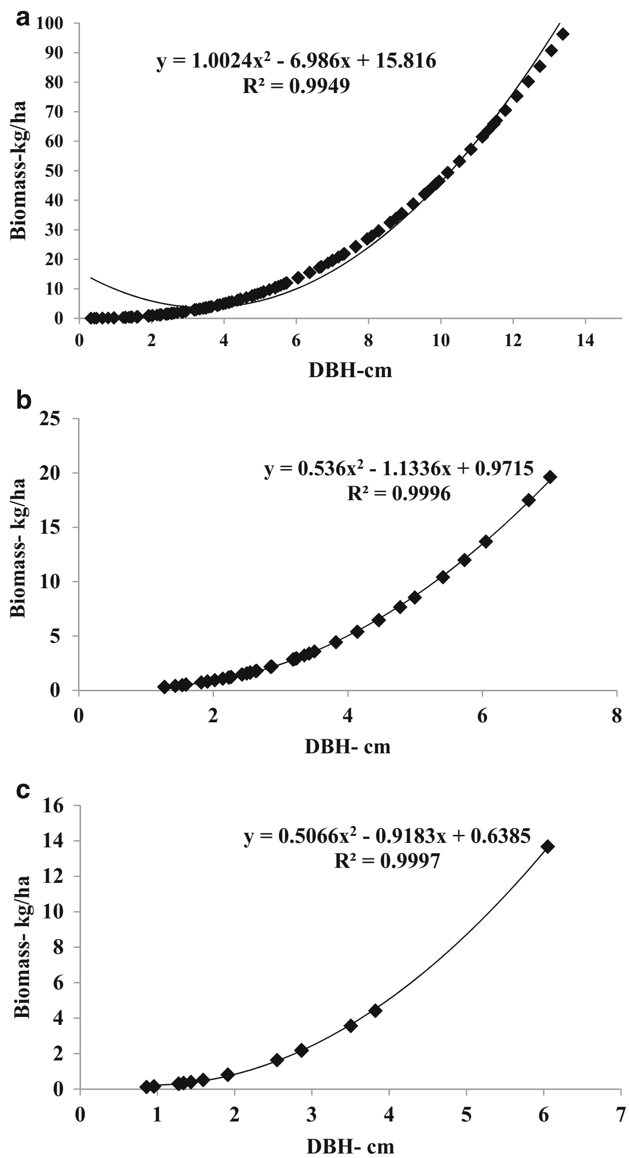

Fig. 7 **a** Second order polynomial relationship between DBH and biomass for *A. marina*; **b** Second order polynomial relationship between DBH and biomass for *C. tagal*; **c** Second order polynomial relationship between DBH and biomass for *R. mucronata*

tree categories at Ashapura and Mundra sites, indicating good sapling recruitment.

Abiotic factors

Mangrove creek water and porewater salinity significantly influenced floral diversity, growth, and height. Creek water salinity in the southern coastal locations ranged from 34 to 41 ppt (parts per thousand), with an average of 36.7 ppt which was marginally higher than the average 38.7 ppt at northern locations. The average porewater salinity values of the three quadrats of each transect increased in upper tidal reaches (Table 3). The lowest and highest porewater salinities were at Jodia-Dora and Chhad, recording 51.0 and 40.7 ppt, respectively. Creek water pH ranged from 7.2 to 8.0 at Chhad and Kharo, respectively (Table 3). The mean in all locations was 7.5. However, porewater pH was acidic, ranging from 6.5 to 6.9. Creek water temperatures ranged from 22.0 to 28.4 °C with an average of 25.0 °C, whereas, soil temperatures ranged from 25.0 to 29.0 °C with a mean of 27.6 °C (Table 3).

Turbidity at Kharo was 52 NTU and 162 NTU at Kandla, showing fairly high fluctuations among the locations (Table 3). Suspended solids fluctuated significantly among locations with a minimum level of 52 mg L^{-1} at Mundra and a maximum 168 mg L^{-1} at Jodia-Dora. Dissolved oxygen saturation in the waters of mangrove creeks was generally low, with minimum and maximum levels of 2.9 and 4.5 mg L^{-1} at Ashapura and Kharo, with an overall mean of 3.7 mg L^{-1}. Analysis of sediments for the four fractions (silt, fine and coarse clay, sand) did not reveal any major variations. Only silt and fine clay constituents were dominant in all locations (Table 4).

Discussion

This study shows that structural characters and diversity of the Gulf of Kachchh mangroves are less comparable with other mangrove formations on the Indian subcontinent, such as the Pitchavaram (Kathiresan et al. 1994), the Sundarbans (Saha and Choudhury 1995; Chowdhury et al. 2016) and Kakinada Bay (Satyanarayana et al. 2002), due to their aridity and harsh environmental conditions. Structure of the Gulf of Kachchh mangroves seems to be governed largely by regimes of low, highly variable rainfall and high evaporation as a function of aridity. The importance of various physical and climatic factors in relation to salinity in determining the vegetation structure of mangroves is well-demonstrated (Bunt et al. 1982; Ball 1988; Ball and Pidsley 1988; Duke 1992; Ukpong 1997; Chowdhury et al. 2016).

These mangroves are dominated by *A. marina* or grey mangrove, the second most dominant mangrove genus worldwide, and are particularly prevalent in harsh climatic conditions (Duke 2001). The arid conditions and erratic rainfall of the Gulf of Kachchh confirms the observation by Blasco (1975) that Gujarat mangroves are floristically poor and semi-arid. In all the stands studied, trees on the waterfront were considerably taller, and a gradual reduction in height could be discerned towards high tide levels due to differing inundation patterns. Although eight true mangrove species have been reported earlier from the Gulf, only *A. marina* was dominant in the locations studied. This may be due to the well-established, extraordinary

Table 2 Regeneration and recruitment densities (ind. ha^{-1}) and their ratio to mature Tree Density in Gulf of Kachchh mangroves

Stations	Mature trees (ind. ha^{-1})	Recruitment (ind. ha^{-1})	Regeneration (ind. ha^{-1})	Ratio 1: 2	Ratio 2: 3
Positra	1567	7964	194,811	1:5.1	1:24.4
Ashapura	2742	5415	293,892	1:1.9	1:54.2
Narara	2107	19,074	253,704	1:9.1	1:13.3
Chhad	1766	14,667	23,000	1:8.3	1:1.5
Kalubar	1969	18,542	190,000	1:9.4	1:10.2
Jodia-Variyali	2513	25,275	550,733	1:10.1	1:21.7
Jodia-Dhoro	2178	10,833	295,911	1:4.9	1:27.3
Kandla	2243	9306	21,111	1:4.1	1:2.2
Mundra	3507	8846	68,718	1:2.5	1:7.7
Kharo	2877	9583	47,500	1:3.3	1:4.9

Table 3 Mean Values of selected environmental Parameters in Study stations of Gulf of Kachchh

Stations	Creek water		Pore water salinity (ppt)				Pore water pH				Temp. (°C)		Dis.O_2 (mg L^{-1})	NTU	TSS (mg L^{-1})
	Salinity	pH	LTL	MTL	HTL	Avg.	LTL	MTL	HTL	Avg.	Creek water	Soil			
Positra	35.5	7.5	46	49	52	49	6.4	6.5	6.7	6.5	28.4	29	3.9	99.5	99
Ashapura	34	7.3	39	46	51.8	45.6	6.8	6.5	6.4	6.6	24.5	28	2.9	96	125
Narara	35.5	7.6	38.2	40.1	47.8	42	6.7	6.9	6.9	6.8	22	27	4.1	158.2	125
Chhad	34	7.2	35	43	44	40.7	6.4	6.5	6.9	6.6	22	29	3.1	98.5	124
Kalubar	38	7.3	42	51	56	49.7	6.5	6.7	6.9	6.7	25.5	25	4.1	87.2	93.5
Jodia-Variali	41	7.2	43	52	55	50	6.7	6.7	6.8	6.7	26.5	27	3.8	126	134
Jodia-Dhoro	39	7.4	44	53	56	51	6.8	6.9	6.9	6.9	25.5	26.5	4.2	159	168
Kandla	39	7.2	44	49	50	47.6	6.4	6.6	6.5	6.5	27	29	3.2	162	102
Mundra	38	7.9	41	43	49	44.3	7.1	6.9	6.8	6.9	26	28	3.9	99	52
Kharo	39	8	42	44	46	44	6.8	6.7	6.8	6.7	23	26	4.5	52	66

HTL high tide line, *MTL* mid tide line, *LTL* low tide line, *ppt* parts per thousand

ecological plasticity of *A. marina* to thrive in harsh environmental conditions like those of the Gulf of Kachchh (Downton 1982; Clough 1984; MacNae 1986; Shalom-Gordon and Dubinsky 1993; Ye et al. 2005; Jayatissa et al. 2008). Patel et al. (2010) demonstrated the germination ability and high salt tolerance of *A. marina* in Gujarat mangroves. Khan and Aziz (2001) showed that *A. marina*, *R. mucronata* and *C. tagal* have higher tolerance to salinity than other species, and thus have wide distribution in Karachi mangroves of Pakistan, which has close geographical proximity to the Gulf of Kachchh. In their study, *A. marina* was also the tallest of the three species under higher salinity conditions, supporting the results in this study.

Mangrove stand density and species composition are influenced by many factors, including salinity regime, seasonality of rainfall, tidal inundation, freshwater inflow, micro-level topography, sediment composition and community structure. Higher entrance of a recruitment class into the mature tree category leads to the latter's higher density at Mundra (3308 ind. ha) and Ashapura (2742 ind. ha) sites, which had low ratios of recruitment to mature tree densities. Along with factors such as tidal inundation and rainfall, upstream freshwater runoff is vital in determining floristic diversity in mangroves (Venkatesan 1966; Blasco and Aizpuru 1997; Naskar and Mandal 1999). Besides the inherent aridity of the region, the development of numerous water harvesting structures in the upland areas has curtailed downstream runoff to coastal waters, resulting in poor mangrove species diversity.

Close positive relationships among younger age classes and mature age classes, as observed by Dahdouh-Guebas et al. (2004) in Kenyan and Sri Lankan mangroves, could be observed in this study as well, which may be due to the inherent nature of the grey mangrove species to spread propagules widely. In addition, conducive canopy gaps and

Table 4 Sediment grain size in the study stations of Gulf of Kachchh

Stations	Silt (%)	Clay (%)		Sand (%)
		Fine	Course	
Positra	39.42	31.89	17.2	11.5
Ashapura	19.49	35.21	24.1	21.25
Narara	24.45	45.87	19.26	10.75
Chhad	39.41	25.88	20.11	14.66
Kalubar	39.12	34.87	18.45	7.62
Jodia-Variali	24.93	43.95	20.25	11.24
Jodia-Dhoro	16.25	30.12	32.47	21.25
Kandla	21.65	34.02	28.44	15.36
Mundra	24.89	29.77	25.39	19.92
Kharo	23.77	43.87	19.21	13.15

Values (%) are average of three samples

tidal reach, (by way of propagule dispersal), may also influence the establishment of a regeneration class and their successful entry into recruitment and mature tree categories. Higher densities of younger age classes as recorded at Ashapura and Narara could be due to such conducive factors prevailing in these stands.

Low biomass values in Kalubar, Chhad and Mundra sites could be due to aridity and subsequent hypersaline conditions (Fromard et al. 1998; Komiyama et al. 2008). Even though low latitude tropical countries have higher aboveground biomass in general (Komiyama et al. 2008), values in this study are comparatively lower than those reported for other Asian stands. Arid and semi-arid mangroves worldwide have poor structural attributes as reported for Mexico (Lizarraga et al. 2004), the Caribbean (Cintron et al. 1978) and on the east African coast (Walter and Steiner 1936). With a mean tree height (1.8 m) and mean DBH (4.8 cm), the Gulf of Kachchh mangroves could be classified as structurally inferior as per the classification of Pellegrini et al. (2009).The single species nature of the stands also suggests inferiority since the growth is less than that of the mixed stands (Das et al. 1997).

As a large contiguous formation, the Gulf of Kachchh mangroves are unique from the deltaic (Sundarbans), riverine (Godavari–Krishna) and island (Andamans) formations of the Indian subcontinent in terms of structural attributes such as poor floral diversity and rich faunal association. Given the low annual mean rainfall of 565 mm, the height range of 1.0–6.8 m is normal, although it is not comparable with high rainfall areas of the east coast of India where trees as tall as 10.0 m have been recorded (Blasco 1975). Usually mangrove forests in regions with less than 1500 mm rain have a height range of 1.0–6.0 m (Duke et al. 1998). At Ashapura, Kalubar and Mundra, all height classes are well-represented in contrast to stands at Kandla, Jodia-Dora and Jodia-Variyali which showed anomalous height class distribution lacking many successive classes. Kandla mangroves especially face severe development-related threats, which results in drastic cover reduction and altered physical and chemical properties of the creeks (ICMAM 2004; Shirodkar et al. 2010). Stands at Jodia-Doria and Jodia-Variyali sites appear stunted as higher DBH classes coupled with short height classes were recorded, possibly due to high porewater salinity on these sites (Table 3). Height class distribution of *C. tagal* was moderately better than *R. mucronata* as more trees were evenly distributed in different frequency classes (Fig. 2). Their DBH frequency was also less and did not exceed the initial three frequency classes, showing that these two species were not stressed and are rejuvenating in the stands studied. Wider representation of different DBH and height classes at Ashapura, Kalubar and Mundra sites indicate that their stands are regenerating while this is not true for Kandla, Jodia-Dora and Jodia-Variyali stands where DBH and height frequency classes were poorly represented. Use of girth and height frequency classes to construct past dynamics of the mangrove stands was demonstrated in Kenyan and Sri Lankan mangroves (Dahdouh-Guebas et al. 2002). Similarly, in this study, variations in girth and height frequency classes at Ashapura, Kalubar and Mundra sites indicate their young and dynamic state contrary to Kandla, Jodia-Dora and Jodia-Variyali stands where increased porewater salinity might influence the overall mangrove structure.

This study, as a first attempt to delineate the structural characteristics of Gulf of Kachchh mangroves, indicates that this ecosystem is structurally inferior to other deltaic mangroves of India. The prevailing environmental variables such as salinity, rainfall regimes and the concomitant aridity play a pivotal role in governing structural variation. The on-going industrial development in the northern and southern shores of the Gulf of Kachchh is of concern for the future of this ecosystem. The congregation of twenty medium and major ports which handle ~ 60% of the country's crude oil requirements, and allied coastal development in close proximity calls for strong management measures to conserve these mangroves. This initial primary information on the Gulf of Kachchh mangroves should assist forest managers for the sustainable management of these ecosystems.

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