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REPORT

Climate change-induced salinity variation impacts on a stenoecious mangrove species in the Indian Sundarbans

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Abstract The alterations in the salinity profile are an indirect, but potentially sensitive, indicator for detecting changes in precipitation, evaporation, river run-off, glacier retreat, and ice melt. These changes have a high impact on the growth of coastal plant species, such as mangroves. Here, we present estimates of the variability of salinity and the biomass of a stenoecious mangrove species (*Heritiera fomes*, commonly referred to as Sundari) in the aquatic subsystem of the lower Gangetic delta based on a dataset from 2004 to 2015. We highlight the impact of salinity alteration on the change in aboveground biomass of this endangered species that, due to different salinity profile in the western and central sectors of the lower Gangetic plain, shows an increase only in the former sector, where the salinity is dropping and low growth in the latter, where the salinity is increasing.

Keywords Aboveground biomass · Climate change · Gangetic plain · Glacier melting · *Heritiera fomes* · Salinity

INTRODUCTION

The patterns of salinity change can be used to infer changes in the Earth's hydrological cycle over the oceans, seas, estuaries and bays (Wong et al. 1999; Curry et al. 2003), and are an important complement to atmospheric measurements (Bindoff et al. 2007). Estimates of changes in the freshwater content of the global ocean have suggested that the global ocean is freshening (Antonov et al. 2002). The estuaries adjacent to the oceans have also been affected in terms of salinity, but for the lower Gangetic delta system, a unique situation has been observed owing to connection of the Ganga–Bhagirathi–Hooghly River system in the western sector with the Himalayan glaciers (Banerjee 2013). The Farakka barrage discharge in this sector built to increase the draft of the aquatic subsystem for navigational purpose also exerts a regulatory influence on salinity. The discharge of freshwater by this barrage on regular basis results in the freshening of the system (Banerjee 2013). On the contrary, the central part of the deltaic lobe has lost its connection with the river system (fed by Himalayan glaciers) since late fifteenth century through heavy siltation, and the rivers and estuaries are mostly tide fed showing an increasing trend in salinity (Chakrabarti 1998). The footprints of global warming is thus perceived in two contrasting ways in two sectors of the deltaic complex: freshening of the estuaries of western sector (Hooghly and Muriganga) due to melting of the Himalayan glaciers, and increased barrage discharge and salinification of the central sector (Matla and Thakuran) estuaries due to expansion of adjacent oceanic water (Mitra et al. 2009). The Bay of Bengal and its adjacent estuaries are one of the less studied regions of the world ocean, while being one of the most exploited water bodies to benefit a sizeable fraction of the world population (Holmgren 1994).

Mangroves are the most widespread tree communities of the Gangetic delta, and their physiology is considerably influenced by surface water salinity (Zaman et al. 2014). Therefore, salinity alteration is clearly visualized in the mangrove community by way of differential growth of aboveground biomass (AGB) of sensitive species (Komiyama et al. 2008).

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Long-term monitoring of hydrographical observations in the lower Gangetic delta region in north-western Bay of Bengal clearly indicates that the water temperature in this part of the world oceans has risen at the rate of ~0.5 °C per decade (Sengupta et al. 2013; Mitra and Zaman 2015). This rate is much higher than the globally observed warming rate of ~0.06 °C per decade (Solomon 2007), but cannot evidently influence species growth in a local scale. However, contrasting geophysical set up of the western and central sectors has resulted in the variation of salinity profile of the lower Gangetic system. The increased melting of Himalayan ice along with barrage discharge has impacted the salinity to decrease at the mouth of the River Ganga–Bhagirathi–Hooghly system, in the western sector of the deltaic complex where it meets the Bay of Bengal (Banerjee 2013). The Farakka barrage discharge contributes substantially to dilute the salinity of the lower Gangetic region, but it is difficult to segregate the noise caused by human-induced factors (such as barrage discharge) at this stage. A decadal surveys (1999–2008) on water discharge from Farakka dam revealed an average discharge of $(3.7 \pm 1.15) \times 10^3\ m^3\ s^{-1}$ (Rudra 1996). Higher discharge values were observed during the monsoon with an average of $(3.81 \pm 1.23) \times 10^3\ m^3\ s^{-1}$, and the maximum of the order $4524\ m^3\ s^{-1}$ during freshet (September). Considerably lower discharge values were recorded during pre-monsoon with an average of $(1.18 \pm 0.08) \times 10^3\ m^3\ s^{-1}$, and the minimum of the order $846\ m^3\ s^{-1}$ during May. During post-monsoon discharge, values were moderate with an average of $(1.98 \pm 0.97) \times 10^3\ m^3\ s^{-1}$ as recorded by earlier studies (Rudra 1996).

On the other hand, for the central sector, the increase of ~6 psu over three decades in salinity, ~2 psu per decade (Mitra et al. 2009), is much higher than that documented (Solomon 2007) for the average in the Indian Ocean (0.01–0.02 psu per decade). In a separate study, Curry et al. (2003) found that the increase in salinity over the last 40 years in tropical Atlantic was on the order of 0.4–0.5 psu. This is a rate of 0.125 psu per decade, which is an order of magnitude less than that observed in the study area.

These evidences show that the estuarine complex at the apex Bay of Bengal is a hot-spot for global warming, and has the potential to act as a natural laboratory where impact of climate change could be tested on mangrove vegetation in short-term (over a decade) scale. The presence of rich mangrove vegetation (34 true mangrove species according to Mitra and Pal 2002) and stenoecious species, such as *Heritiera fomes*, in the deltaic lobe commonly referred to as Indian Sundarbans has imparted special significance to the this area because of the possibility to test the impact of salinity alteration due to climate change.

Here, we analysed the effect of changes in salinity on the AGB change of the freshwater-tolerant mangrove species *Heritiera fomes* (Family: Malvaceae, locally called Sundari). This species is locally common and abundant in some parts of its range such as the Sundarbans and in Bangladesh, but has a limited overall distribution. In Bangladesh and India, this species is rapidly declining (Chaudhuri and Choudhury 1994). This species is found in the upstream estuarine zone in the high intertidal region. It prefers freshwater, and is fast-growing in low-saline environments. It occurs in stands and grows up to 25 m. It is the only *Heritiera* species that produces pneumatophores. This species is a valuable commercial species for timber and is planted in commercial plantations (fuelwood and construction), but it is preferred for timber extraction in the wild. There has been an estimated population decline from 50 to 80 % in the majority of its range (Malaysia) based on decline of mangrove area due to coastal development and extraction since the 1950s, primarily due to the clearing of mangroves for rice farming, shrimp aquaculture and coastal development (Chaudhuri and Choudhury 1994). No additional data are available to estimate decline over three generation lengths (120 years). This species is listed as Endangered (Chaudhuri and Choudhury 1994). However, populations in India and Bangladesh are rapidly declining and may qualify for Critically Endangered at a regional level.

We collected 11 years (2004–2015) of in situ salinity data and other physiologically important parameters (such as water nitrate, phosphate and temperature) from two Indian sectors (Western and Central) of the Gangetic delta complex and Sundarbans in order to identify long-term trends in salinity and to compare them with mangrove AGB. In each sector, we selected three sampling stations to monitor the aboveground biomass annual change (ΔAGB) of *Heritiera fomes* (and other most common species as an ancillary data) from 2004 to 2015.

MATERIALS AND METHODS

Study area

Data analysed in this study were sampled in six stations (between 21°26′–22°13′N and 87°56′–89°09′E): 3 in the western and 3 in the central sectors of the Ganges River (Supplementary Table S1) from 2004 to 2015.

The Ganges River is shared by China, Nepal, India and Bangladesh. The river has great importance for the socio-economy of the co-basin countries. It is estimated that about 410×10^6 people are directly or indirectly dependent on the Ganges River (Mirza 1997).

The River Ganges is, thus a trans-boundary river of Asia which flows through India and Bangladesh Sundarbans, a mangrove-dominated delta complex in the inshore region of the Bay of Bengal. At the apex of this bay, a delta has been formed which is recognized as one of the most diversified and productive ecosystems of the tropics and is referred to as the Indian Sundarbans. The deltaic complex has an area of 9.630 km^2 and houses about 102 islands. The western and central Sectors of Indian Sundarbans (Fig. 1) have pronounced salinity variation.

The hyposaline environment of western Indian Sundarbans may be attributed to Farakka barrage discharge situated in the upstream region of Ganga–Bhagirathi–Hooghly river system. The central sector represents a hypersaline environment due to complete obstruction of the fresh water flow from the upstream region owing to Bidyadhari siltation since the late fifteenth century. Local people extraction of timber and logging procedures did not differ between the two sectors (Mitra and Pal 2002).

Aboveground biomass sampling

AGB refers to sum total of aboveground stem biomass (AGSB), aboveground branch biomass (AGBB) and aboveground leaf biomass (AGLB), which have been estimated year by year (from 2004 to 2015) as per the standard procedure:

Aboveground stem biomass (AGSB) estimation

The stem volume of 5 individuals of the species in 15 randomly distributed plots (dimension = $10 \times 10\ m = 100\ m^2$, then multiplied with a factor of 10^2 to express it in tonnes ha^{-1}) per each station ($n = 75$) was estimated using the Newton's formula:

$$V = h/6\ (A_b + 4A_m + A_t),$$

where V is the volume (in m^3), h is the height measured with laser beam (BOSCH DLE 70 Professional model) and A_b, A_m and A_t are the areas at base, middle and top, respectively. Specific gravity (G) of the wood was estimated taking the stem cores by boring 7.5 cm deep with mechanized corer. This was converted into stem biomass (B_S) as per the expression $B_S = GV$. The stem biomass of individual tree was finally multiplied with the number of individuals of the species in 15 selected plots. This exercise was carried out for all the six stations distributed in the two surveyed sectors of the Indian Sundarbans.

Aboveground branch biomass (AGBB) estimation

These branches were categorized on the basis of basal diameter into three groups, viz. <6, 6–10 and >10 cm. The total number of branches, irrespective of size, was counted on each of the sample trees. The leaves on the branches were removed by hand. The branches were oven dried at 70 °C overnight in hot air oven in order to remove moisture content if any present in the branches. Dry weight of two branches from each size group was recorded separately using the following standard equation:

$$B_{db} = n_1 bw_1 + n_2 bw_2 + n_3 bw_3 = \Sigma n_i bw_i,$$

where B_{db} is the dry branch biomass per tree, n_i is the number of branches in the ith branch group, b_{wi} is the

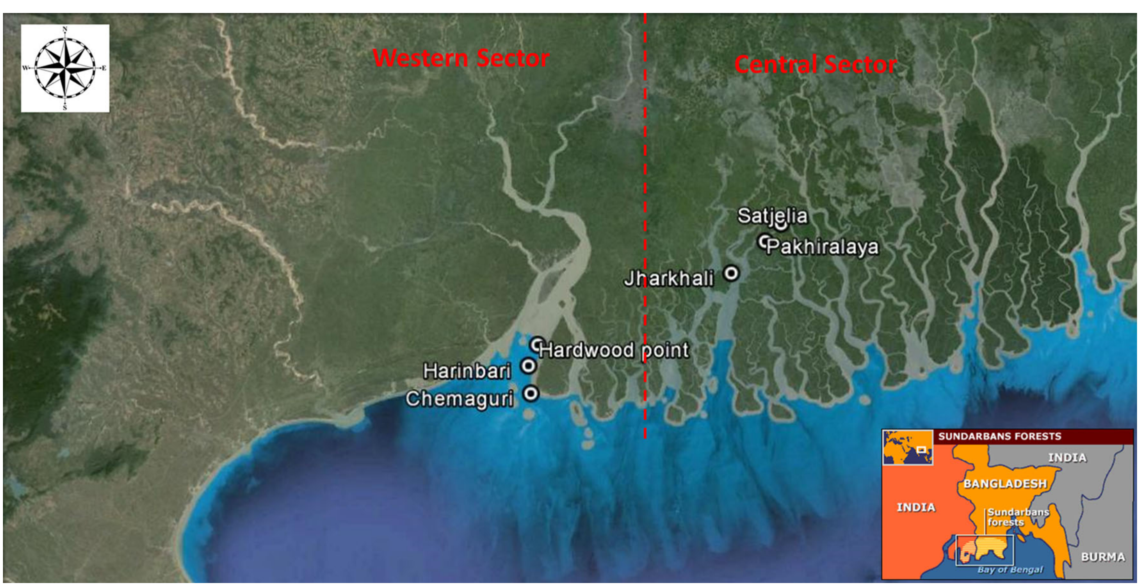

Fig. 1 Study sites in the Indian Sundarbans. The three western stations and the three central stations, all in India, are shown divided by an *imaginary red line* on the map (coordinates are provided in Table S1)

average weight of branches in the ith group and $i = 1, 2, 3,\ldots,n$ are the branch groups. The branch biomass of individual tree was finally multiplied with the number of trees of the species in all the 15 plots for each station.

Aboveground leaf biomass (AGLB) estimation

One tree per each plot was randomly considered for estimation. All leaves from six branches (two of each size group) of individual trees of each species were removed and oven dried at 70 °C, and dry weight (species wise) was estimated. The leaf biomass of each tree was then calculated by multiplying the average biomass of the leaves per branch with the number of branches in that tree. Finally, the dry leaf biomass (for each station) was estimated with the following equation:

$$L_{db} = n_1 Lw_1 N_1 + n_2 Lw_2 N_2 + \cdots + n_i Lw_i N_i,$$

where L_{db} is the dry leaf biomass of selected mangrove species per plot, $n_1 \ldots n_i$ are the number of branches of each tree of the species, $Lw_1 \ldots Lw_i$ are the average dry weight of leaves removed from the branches and $N_1 \ldots N_i$ are the number of trees of the species in the plots.

"Other species" AGB estimation

During the same time span of the study, the AGB of the three most common species (*Avicennia alba*, *Avicennia marina* and *Excoecaria agallocha*), within each study site, was estimated (Supplementary Fig. S1), as an ancillary data, by the same methods described above. Then, the annual biomass change of the three species was summed and referred as "Other species AGB". The mean total annual AGB for "Other species" of Western sector was 149.13 ± 25.87 t ha^{-1} (range: 100.41 ± 14.32–185.25 ± 21.16), while the mean total annual AGB for "Other species" of central sector was 172.30 ± 18.11 t ha^{-1} (range: 117.53 ± 13.81–215.71 ± 19.42). Differently from the growth of *H. forms*, the AGB trends of these three most common species (a proxy of the whole mangrove forest) show no discrepancy between, and a constant increase in both, the two sectors (Supplementary Fig. S1).

Phosphate, nitrate and temperature sampling

For each observational station, triplicate water samples were collected from the surface (depth range = 0–25 cm) at a distance of 50 m of each other and analysed for the following parameters: nitrate (NO_3-N), phosphate (PO_4-P) and temperature. A Celsius thermometer was used to measure the surface water temperature. NO_3-N and PO_4-P were analysed as per the procedure stated in Strickland and Parsons (1972) and APHA (2001).

Statistical analysis

Because our data came from time series, to evaluate the significance of the differences between the two sectors, we calculated a pairwise non-parametric statistics, such as Wilcoxon–Mann–Whitney (WMW) signed-rank test (Hettmansperger and McKean 1998).

Then, we calculated the Spearman's rank correlation coefficient, which is a non-parametric good indicator of the significance level of a tendency in a time series (Daniel 1990).

We performed linear regression and residuals analysis, and then we checked for (temporal) autocorrelation of residuals (Tuljapurkar and Haridas 2006).

RESULTS

Prior to analyse the influence of our target parameter (salinity) on *H. formes*, we analysed whether there was a significant correlation between other physiologically important parameters (phosphate P, nitrate N and temperature T) and the AGB change of this species. We plotted P, N and T in time (Fig. 2). This figure shows no evident increasing–decreasing trend, apart from a moderate rise of nitrate level in both sectors. To check the significance of any potential relation, we performed a Spearman's rho correlation test. None of the coefficients correlate significantly with AGB in both sectors (W: P-AGB $t = 0$, $p = 1$; C: P-AGB $t = 1.1$, $p = 0.29$; W: N-AGB $t = 0.7$, $p = 0.5$; C: N-AGB $t = 2.02$, $p = 0.07$; W: T-AGB $t = 0.97$, $p = 0.36$; C: T-AGB $t = 1.67$, $p = 0.13$).

Then, we plotted AGB of *H. fomes* and salinity trends in time (Fig. 3). Differences in AGB ($U_{12,12} = 78$; $p < 0.01$) and salinity ($U_{12,12} = 69$; $p < 0.01$) between western and central sectors were both statistically significant.

Spearman's rho correlation coefficients for AGB and salinity of western and central sectors were -0.92 and 0.85, respectively. Scatterplots show the correlation between ABG and salinity in both sectors (Fig. 4), and underline the fact that AGB and salinity in the western sector are inversely proportional and highly correlated.

Linear regression analysis showed that AGB of *H. fomes* and salinity relationship, in both sector, is highly significant (W: $t = -7.59$, $p < 0.01$; C: $t = 5.17$, $p < 0.01$). Residuals analyses showed no evident trend.

We also tested the temporal autocorrelation of the regression residuals, and we detected that both ACF and PACF were within the lower and uppers confidence levels (at 95 %).

DISCUSSION

In this study, we showed the impact of salinity alteration on the change in AGB of the endangered and stenoecious

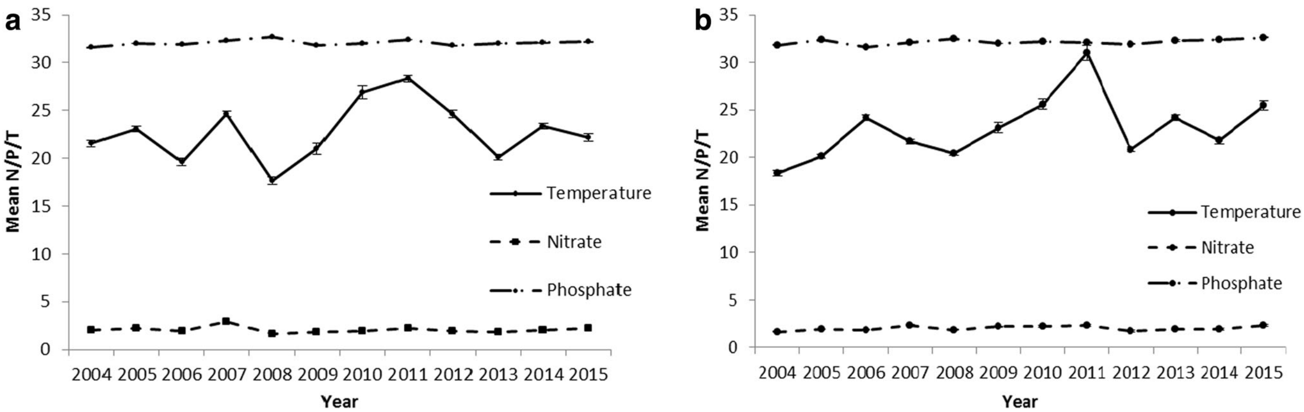

Fig. 2 Temporal variations of phosphate (P, in μg l^{-1}), nitrate (N, in μg l^{-1}) and temperature (T, in °C) in the central and western sectors of the lower Gangetic delta (annual mean values ± SD bars)

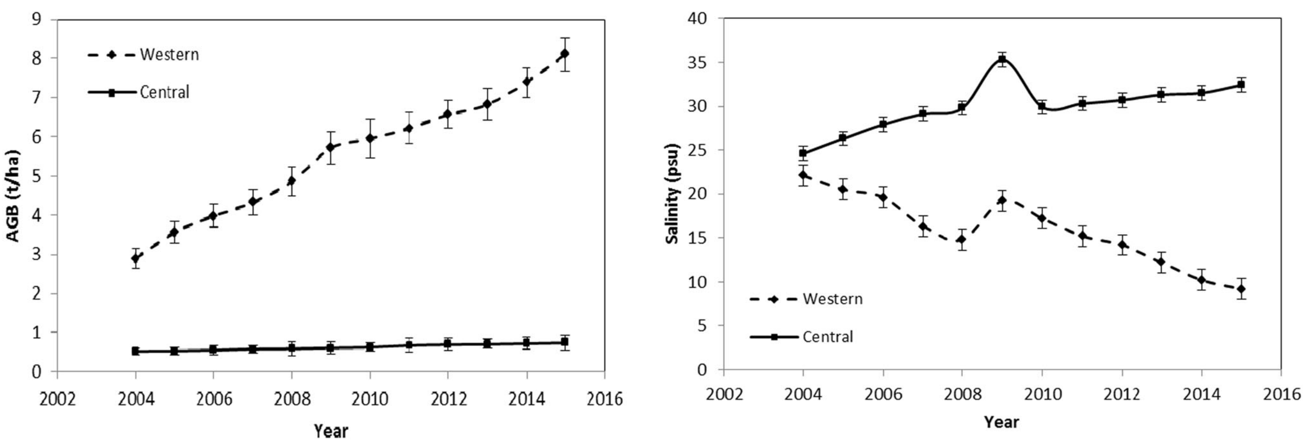

Fig. 3 Temporal variations of surface water salinity and aboveground biomass in the central and western sectors of the lower Gangetic delta (annual mean values in psu ± SD and tonnes ha^{-1} ± SD, respectively)

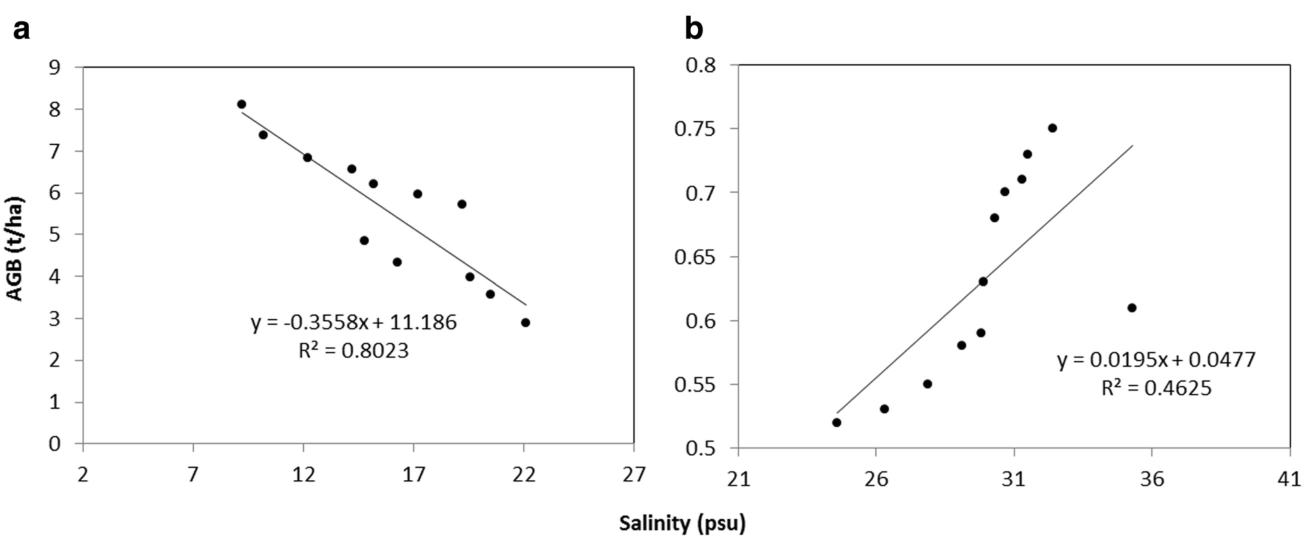

Fig. 4 Aboveground biomass values (ordinate) plotted against salinity levels (abscissae) in the western (**a**) and central (**b**) sectors of the lower Gangetic delta

mangrove species *Heritiera fomes* (commonly referred as "Sundari"). In the past, the species was abundant in the lower Gangetic delta, but due to different salinity profile in the western and central sectors, its populations currently show signs of differential growth. In the western sector, the change of the AGB is much higher than the central one (Fig. 2), and this seems due to the different trends of salinity, which increased in the central sector and decreased in the western one. No other relevant factor (such as nutrient level and water temperature changes) was significantly related to the differential growth trends of the two sectors.

On the global scale, coherent trends of salinity have been observed and are characterized by global freshening in sub-polar latitudes and a salinification of the shallower parts of the tropical and subtropical oceans (Bindoff et al. 2007). Freshening is pronounced in the Pacific, while increasing salinities prevail over most of the Atlantic and Indian Oceans (Wong et al. 1999). Alteration in salinity profile is highly region-specific, and is a function of geophysical set up, current pattern and climatic conditions of the area (Curry et al. 2003).

Different causes (discharge, precipitation, run-off) increase the dilution factor of the Hooghly estuary in the western part of Indian Sundarbans—a condition for the better growth of the fresh water-loving *Heritiera fomes* biomass. On the contrary, the Matla estuary, in the central sector of the Gangetic delta, does not receive the freshwater discharge on account of siltation of the Bidyadhari River, which may be the cause for stunted growth and extinction of the species in an environment of increasing salinity.

Although the water temperature increase is uniform in both the sectors, there could be two reasons why the mangrove populations of some species, such as *Heritiera fomes*, are not responding uniformly to salinity variation in the Indian Sundarbans (Mitra et al. 2009). The first, and less likely, is that natural and anthropogenic aerosols are not well mixed geographically and could have a substantial effect on regional warming rates, which subsequently affect salinity through a variable rate of evaporation. The second reason is that the western sector of the Sundarbans delta receives the fresh water input of Himalayan glaciers via the Farakka barrage discharge, which is undergoing a rapid recession, at the rate of 23 m year^{-1} (Hasnain 1999, 2000, 2002). This is adding fresh water and increasing the dilution factor in the Hooghly estuary in the west. On the contrary, the increase in salinity in the central sector (by 3–5 psu over a period of 29 years) is due to heavy siltation of the Bidyadhari channel since late fifteenth century that obstructs the supply of fresh water in the region. Therefore, the lower growth rate of *Heritiera fomes* in this sector appears as an acid test for the rising salinity.

Mangroves are basically evergreen sclerophyllous, broad-leaved trees with aerial root like pneumatophore or stilt root and viviparously germinated seedlings (Linden and Jernelöv 1980) with a preference for brackish water habitat with a salinity range from 5 to 20 psu (Mitra et al. 2004), and along protected sedimentary shores preferably in tidal lagoons, embayments and estuaries (MacNae 1968). The plants are halophytes that are well adapted to salt water and fluctuation of tide level (Karim 1988). Even germination of seeds of some halophytes is dependent on a certain level of salinity, and there is an optimum salinity range for maximum growth of different mangrove species (Hoque et al. 2006). A few mangrove species, such as *Heritiera fomes* and *Nypa fruticans*, prefer high dilution of the brackish water system for a better growth and survival. Despite a limitation on the AGB growth on the other mangrove species considered is not evident, the relatively higher increase of the AGB of *Heritiera fomes* in the western sector, with respect to that of the central one, confirms the freshening and salinification of the western and central parts of the lower Gangetic delta region, respectively.

Even though numerous studies on tropical plant biomass have been carried out in the last years (Valentini et al. 2014; Battipaglia et al. 2015; Cazzolla Gatti et al. 2015; Avitabile et al. 2016; Vaglio Laurin et al. 2016) and some have focused on mangroves wood production, forest conservation and ecosystem management (Putz and Chan 1986; Tamai et al. 1986; Komiyama et al. 1987; Clough and Scott 1989; Chaudhuri and Choudhury 1994; McKee 1995; Ong et al. 1995; Mitra and Pal 2002; Cazzolla Gatti 2016), this study represents the first evidence showing the impact of salinity changes due to a combination of climatic and other anthropogenic changes on a mangrove species in the Indian Sundarbans.

CONCLUSION

Our study clearly demonstrates the response of a stenoecious mangrove species to a changing salinity that may serve as an indicator for climate change-related studies. Similar works in Bangladesh also revealed adverse impact of salinity on *Heritiera fomes* (Hoque et al. 2006). The species was rare in strong salinity zones, whereas its presence was abundant in the moderate and the low salinity zones of the Sundarbans forest of Bangladesh. Death of the species was also reported due to top dying disease which was frequently observed beside the river or the canals where inundation by the saline water is much and has water logging problem. Rahman (1994) showed that the top dying symptom was seen in areas where most of the pneumatophores have been partially buried.

Furthermore, our study clearly depicts that AGB change of *H. fomes* can be used as a proxy to evaluate climate change-induced salinity alteration in the lower Gangetic delta complex and, potentially, in other similar ecosystems that host such stenoecious species.

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