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Research Paper

How Mangroves Respond to Hypersaline Condition? Preparedness for Predicted Sea Level Rise

Marine Science

KEYWORDS :

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ABSTRACT

Climate change has several components of varied nature and scale that influences the coastal vegetation. For mangroves, however, the most relevant components include changes in sea level, high water events, storminess, precipitation, temperature, atmospheric CO2 concentration, ocean circulation patterns, health of functionally linked neighbouring ecosystems, as well as human responses to climate change. Of all the outcomes from changes in the atmosphere's composition and alterations to land surfaces, relative sea level rise is the greatest threat to mangroves. The adverse effect gets much more magnified if the mangrove flora is freshwater loving in nature like Heritiera fomes, Sonneratia apetala or Nypa fruticans. The rising sea level increases the salinity of the ambient water and soil, which poses a negative impact on the growth and physiological set-up of mangroves. The present paper highlights a case study of adaptation of five different mangrove species to increasing salinity in the tiger dominated Indian Sundarbans of lower Gangetic region. Along with the growth rate of the species in natural conditions, their pigment systems have also been analysed with respect to changing salinity levels. The results of the present study can be extrapolated to predict the effect of climate change induced sea level rise in Indian Sundarbans region on mangrove vegetation. The ecological value of the system in terms of carbon sequestration has also been highlighted since salt marshes, mangroves, and seagrasses store ten times more carbon in their soils per hectare than temperate forests and fifty times more than tropical forests. Some management action plans (like regular dredging of the accumulated silt, interlinking of rivers etc.) have also been discussed to restore the mangrove system from the adverse impact of hypersalinization.

Introduction

Mangroves are the characteristic littoral vegetation of tropical and subtropical sheltered coastlines (FAO, 1994). Being on the land - sea interface, they are always associated with and subjected to saline seawater. However saline environment is not a prerequisite for their development, rather mangroves choose saline condition to avoid the competition with the more vigorous terrestrial plants. Based on the physiological studies, Bowman (1917) and Davis (1940) concluded that mangroves are not salt lovers, rather salt tolerant. Excessive saline conditions retard seed germination, impede growth and development of this unique halophytic vegetation.

Indian Sundarbans, the famous mangrove chunk of the tropics is gradually losing *Heritiera fomes* (locally known as Sundari) from certain pockets owing to increase of salinity in the central sector of the delta complex around the Matla River. Reports of variation of growth in mangroves due to difference in salinity between western and central sectors of Indian Sundarbans are available (Mitra et al., 2004). The effects of salinity on mangroves have been studied in relation to antioxidative enzymes (Takemura et al., 2000; Parida et al., 2004b), leaf structure, rates of transpiration, stomatal conductance and rates of photosynthesis (Santiago et al., 2000; Parida et al., 2004a) and changes in chloroplast structure and function (Parida et al., 2003). Also, the mechanism of acclimation to salt in mangroves was suggested to be linked to the changes in the vacuolar size in B. sexangula (Hotta et al., 2000). However no experimental studies have yet been taken up to critically unfold the reasons behind the reduced growth and biomass of certain mangrove species with the increase of aquatic salinity in the framework of Indian Sundarbans.

In this article, we present the effect of salinity on the photosynthetic pigments (chlorophyll a, chlorophyll b and total chlorophyll) in five common mangrove species of Indian Sundarbans (Sonneratia apetala, Avicennia marina, Avicennia officinalis, Rhizophora mangle and *Heritiera fomes*) through hydroponic culture with an aim to obtain insights into the changes in chlorophyll (the basic raw material for photosynthetic process) with salt acclimation. Such study is important from the point of sea level rise and subsequent saline water intrusion into the islands of Indian Sundarbans as the lower Gangetic delta complex is extremely vulnerable to climate change related effects owing to its location below the mean sea level and experiencing a sea level rise of 3.14 mm/yr. This figure is significantly higher than the global average sea level rise of 2.12 mm/yr and 2.50 mm/yr along the Indian coastline (Lal and Aggarwal, 2000). Another aim of our study is to scan the signal of climate change induced salinity rise in the mangrove community of lower Gangetic delta and evaluate the species-wise adaptive power and growth in high saline environment.

Problem identification

The Indian Sundarbans at the apex of the Bay of Bengal (between $21^0$26/N to $22^0$13/ N latitude and $87^0$56/ to $89^0$09/E longitude) is located on the southern fringe of the state of West Bengal (a maritime state in the northeast coast of India). The region is bordered by Bangladesh in the East, the Hooghly River (a continuation of the Ganga-Bhagirathi River) in the West, Dampier and Hodges line in the North, and the Bay of Bengal in the South. With a considerable degree of marine characteristics in major portion of the ecosystem, the important morphotypes of deltaic

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Sundarbans are beaches, mudflats, coastal dunes, sand flats, estuaries, creeks, inlets and mangrove swamps (Chaudhuri and Choudhury, 1994). Although the region is situated south of the Tropic of Cancer, the temperature is moderate due to its proximity to Bay of Bengal in the south. Average annual maximum temperature is around 35^{0}C. The summer (premonsoon) extends from mid of March to mid June and the winter (postmonsoon) from mid November to February. The monsoon usually sets in around middle of June and lasts up to middle of October. Rough weather with frequent cyclonic depressions is common from mid March to mid September. Average annual rainfall is 1920 mm. Average humidity is about 82% and is more or less uniform throughout the year.

The rivers are the live matrix of lower Gangetic delta, on which the unique spectrum of biodiversity is embedded. In Indian Sundarbans, approximately 2069 sq. km area is occupied by tidal river system or estuaries, which finally end up in the Bay of Bengal. The seven main estuaries, from west to east are highlighted in Table 1 along with their salient features.

TABLE 1
Major tidal rivers in Indian Sundarbans

Estuary	Salient feature
Hooghly	➢ It forms the western border of Indian Sundarbans (represented by R1 in Fig. 1). Department of Marine Science, University of Calcutta, 35 B.C. Road, Kolkata 700 019, West Bengal, India Also attached to TECHNO INDIA UNIVERSITY, KOLKATA, INDIA It is the main river of the lower Gangetic region and is a direct continuation of the Ganga-Bhagirathi River system. ➢ Most of the coastal industries of the maritime state of West Bengal are concentrated along the western bank of this river. This has made difficult to segregate the noise caused by industrialization and exclusively isolate the effect of climate change on water chemistry.
Muriganga	➢ It is a branch of the Hooghly River (represented by R2 in Fig. 1). ➢ It flows along the east of Sagar Island, the largest island in the deltaic complex. ➢ Luxuriant mangrove vegetation is found along the western bank of this river.
Saptamukhi	➢ It has its origin at Sultanpur (R3 in the map). ➢ It is connected with the Muriganga (Bartala) branch of the Hooghly River through Hatania-Duania canal.
Thakuran	➢ It begins near Jayanagar in the South 24 Parganas and has a number of connections with the Saptamukhi (represented by R4 in the map). ➢ It was connected in the earlier times with the Kolkata canal through the Kultali and the Piyali rivers, which exist today in a dying state.
Matla	➢ This river originates at the confluence of Bidyadhari, Khuratya and the Rampur Khal close to the town of Canning in 24 Parganas (South). It is in the central sector of Indian Sundarbans (R5 in Fig. 1). ➢ Matla is connected to Bidya and ultimately flows to the Bay of Bengal in the south. The fresh water connection and discharge to this river has been lost in the recent times due to heavy siltation. ➢ Salinity of the river water is relatively high (in comparison to Hooghly or Muriganga) owing to fresh water cut-off from the upstream region. Such hypersaline situation has adversely affected the growth of few mangrove species like *Heritiera fomes, Nypa fruticans* etc.
Bidyadhari*	➢ This was flourishing branch of the Bhagirathi during the 15th and 16th century, but now serves only as a sewage and excess rainwater outlet from the city of Kolkata. ➢ The river bed is completely silted and presently it is almost in dying condition. Because of such massive siltation, the Matla River has become hypersaline and exclusively tide-fed in nature.
Gosaba	➢ The waters of Matla and Harinbhanga (Raimangal) through a large number of canals form the estuary (represented by R6 in Fig. 1). ➢ The estuary and its numerous creeks flow through the reserve forests.
Harinbhanga	➢ It is the extreme easternmost river in the Indian Sundarbans deltaic complex (R7 in Fig. 1). ➢ The Harinbhanga (also known as Ichamati and Raimangal) forms a natural demarcation between India and Bangladesh.
* Presently a dying estuary and not considered within the seven major estuaries of Indian Sundarbans	

The presence of 34 true mangrove species and some 62 mangrove associate species (Mitra, 2000) in the Indian part of Sundarbans is the mangrove based home ground of Royal Bengal tiger (Panthera tigris tigris). The deltaic complex sustains 102 islands, out of which 48 are inhabited and 54 are uninhabited.

The flow of Ganga - Bhagirathi River system through Hooghly estuary in the western sector of Indian Sundarbans to end up at Bay of Bengal has made the geographical situation totally different from the central and eastern sectors, where five major rivers have lost their root with Ganga – Bhagirathi system (Fig. 1) due to heavy siltation. The water chemistry has changed accordingly. Interestingly the rivers of the central sector (like River Matla) are experiencing the pulse of climate change related sea level rise and subsequent saline water intrusion with greater magnitude due to absence of any freshwater discharge/input into the system. On contrary the rivers and estuarine mouth in the western part (like Hooghly and Muriganga) are experiencing decreased salinity due to freshwater input via Ganga-Bhagirathi River system sourced from the Himalayan Glacier.

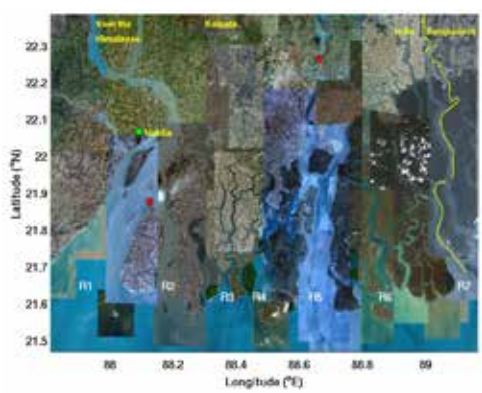

Fig.1. Map of the study region with 2 stations marked in red. The western station is located at 21° 52' 20.78" N, 88° 7' 29.73" E, at the tip of Sagar Island. The seven rivers marked by R1 through R7 from west to east are: Hooghly, Muriganga, Saptamukhi, Thakuran, Matla, Gosaba and Harinbhanga. The discharge system of the two metropolises of Haldia and Kolkata (Calcutta) are connected to the two western rivers, which are also fed by the meltwater from the Himalayas after being regulated through barrages. The central station, at 22° 15' 33.97" N, 88° 39' 34.64" E, is connected to the rivers R4 and R5 which do not have any freshwater input.

The alterations in the salinity profile of oceans, seas, bays and estuaries are an indirect but potentially sensitive indicator for detecting changes in precipitation, evaporation, river run-off, glacier retreat, ice melt and human induced causes (like construction of dams and barrages in the upstream regions). The change in salinity profile is highly region specific, and is a function of geophysical set up of the area that undergoes modifications with time. Therefore short term scale regional based observations do not allow for a reliable estimate of the global average change in salinity in the oceans and adjacent estuaries. The present case study is region specific arising from different geophysical set-up in the framework of mangrove dominated Indian Sundarbans.

We have conducted thirty years (1980 – 2009) of hydrographic observations in the lower Gangetic delta region in northwestern Bay of Bengal and our results clearly indicate that the water temperature in this part of the world oceans has risen at the rate of 0.5°C per decade (Mitra et al., 2009a). This rate is much higher than the globally observed warming rate of 0.06°C per decade [IPCC, 2007], which is expected to increase the salinity of the lower Gangetic system. However contrasting geophysical set-up of the western and central sectors has resulted in the variation of salinity profile. 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. The Farakka barrage discharge contributes substantially to dilute the salinity of the lower Gangetic region, but it is difficult to segregate the noise caused human induced factors (like barrage discharge) at this stage. On the other hand, for the central sector, the increase of aquatic salinity by 6 psu over three decades (~ 2 psu/decade), is much higher than that documented for the average in the Indian Ocean (0.01-0.02 psu/decade) (IPCC, 2007).

These results 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 the impact of climate change could be tested on mangrove vegetation in short-term (over a decade) scale. The presence of rich mangrove vegetation in the deltaic lobe has imparted special significance to the geographical locale for providing the benefit of testing the pulse of climate change induced salinity alteration on the mangrove flora. Like every plant species, the photosynthetic machinery of the mangroves is run by basic raw materials like water, carbon dioxide, solar energy and chlorophyll to yield organic compounds (glucose). However the normal situation may deviate due to intrusion of saline water in the river systems and estuaries connected to oceans and seas. This deviation is highlighted in Fig. 2 in the form of a hypothesis.

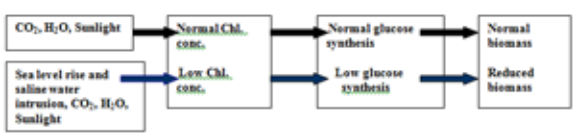

Fig. 2. Flowchart showing the impact of sea level rise on mangrove biomass. Black arrows and scripts represent normal situation; red arrows and scripts are the hypothetical scenario to validate our case study.

On the basis of this hypothesis we attempted to investigate the effect of rising salinity on the chlorophyll level of the mangrove species (in laboratory condition) and confirm our results with the biomass (above ground stem biomass) of the same species in the natural condition during 2012.

Actions taken to evaluate the impacts of climate change

The action in the present programme is entirely technical research oriented and focuses on tracking indicators of salinity change in the biochemical and ecological level of mangroves, studying cause-effect relationship and forecasting impacts on the mangrove biomass (species-wise) through biochemical pathway. The entire experimental network to identify the biological signal of climate change in the mangrove community of lower Gangetic plain may thus be broadly divided into two major phases viz. biochemical and ecological.

Biochemical phase: Hydroponic culture of mangrove seedlings (in laboratory condition)

The chlorophyll pigment converts solar energy into organic nutrients of mangroves with carbon dioxide and water using sunlight as the source of energy. Considering the key role of the pigment a simulation study was conducted to assess the variation of chlorophyll with the increase of salinity that may occur due to climate change induced sea level rise. In this phase seeds of Sonneratia apetala, Avicennia marina, Avicennia officinalis, Rhizophora mangle and *Heritiera fomes* were collected from the intertidal mudflats of deltaic Sundarbans. Seedlings were raised in the laboratory condition by diluting the source water with stored rain water. The source water was collected from the lower stretch of Sundarbans almost near to the Bay of Bengal (salinity = 30 psu). Two month old healthy seedlings were subjected to hydroponic culture in Hoagland's nutrient medium (pH = 5.8–6.0) under photosynthetically active radiation (PAR) of 1220–1236 µmol m^{-2} s^{-1} .The experiments were carried out in the selected species at six different salinities (2 psu, 5 psu, 10 psu, 15 psu, 20 psu and 30 psu respectively) in order to determine the optimum range of salinities in relation to photosynthetic pigments. The cultures were aerated continuously with an air bubbler. The hydroponic cultures were maintained in a culture room under a 14 h photoperiod at PAR of 300 µmol m^{-2} s^{-1}, 26 ± 3^0C and 80% RH. The culture medium was changed every 7 days. Leaves were harvested at 7, 14, 21 and 30 days intervals to measure the pigment concentrations.

Leaves (0.5 g) from the seedlings of each species were homogenized in chilled N, N-dimethylformamide (DMF) in a mortar and pestle in dark condition at 4^0C and the homogenates were centrifuged at 8800×g for 10 min. The supernatants were collected and absorption spectra at 663.8 and 646.8 nm were recorded using Jasco V-530 UV–vis spectrophotometer for estimation of chlorophyll a, chlorophyll b and total chlorophyll following the procedure of Porra et al. (1989).

Ecological phase:

Above ground stem biomass estimation (in natural condition)

Aquatic salinity has profound influence on the growth and biomass of mangrove floral species. The degree of influence is, however, extremely species-specific depending on the mode of salt regulation. We monitored the above ground stem biomass (AGSB) in the same set of species in two stations selected in western and central Indian Sundarbans (marked in red dots in Fig. 1). Ten experimental plots (of dimension 10 m × 10 m) were selected at random in each of these stations. The species-wise AGSB of individual trees was estimated using non-destructive method in which the diameter at the breast height (DBH) was measured with a measuring tape and height with laser beam (BOSCH DLE 70 Professional). Form factor was determined as per the expression outlined by Koul and Panwar (2008) and volume (V) was estimated using the expression ΠR^2HF, where F is the form factor, R is the radius of the tree derived from its DBH and H is the height of the target tree. Specific gravity (G) was estimated taking the stem cores of each species considered in the study, which was further converted into stem biomass (B_S) as per the expression $B_S = GV$.

Results

Biochemical analysis

A very interesting picture was generated after statistical analysis on the inter-relationship between ambient aquatic salinity and chlorophyll concentrations (Chlorophyll a, chlorophyll b and total chlorophyll) of the mangroves. The concentrations of chlorophyll decreased significantly with salinity in Sonneratia apetala, Avicennia marina, Avicennia officinalis and *Heritiera fomes*, but for Rhizophora mangle a reverse situation was observed. This species could tolerate salinity up to 30 psu (in the laboratory condition) and could be maintained for more than 30 days. The chlorophyll level also increased significantly with the increase of salinity which confirms the adaptation of the species at biochemical level to high salinity related to rising sea level (Table 1). The decrease of chlorophyll pigment in rest four species is a clear indication of the failure of photosynthetic machinery in hypersaline situation, which the central Indian Sundarbans is facing due to absence of head-on freshwater discharge to push back the saline water intrusion from the Bay of Bengal.

TABLE 1

Inter-relationships between salinity and chlorophyll in selected mangrove species

Species	Combination	'r' value	'p' value
Sonneratia apetala	Salinity × Chl. a	-0.7986	<0.01
	Salinity × Chl. b	-0.7746	<0.01
	Salinity × Total Chl.	-0.7947	<0.01

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Avicennia marina	Salinity × Chl. a	-0.5416	<0.05
	Salinity × Chl. b	-0.8006	<0.01
	Salinity × Total Chl.	-0.6161	<0.01
Avicennia officinalis	Salinity × Chl. a	-0.6964	<0.01
	Salinity × Chl. b	-0.6742	<0.01
	Salinity × Total Chl.	-0.6976	<0.01
Rhizophora mangle	Salinity × Chl. a	0.6045	<0.01
	Salinity × Chl. b	0.7803	<0.01
	Salinity × Total Chl.	0.6764	<0.01
Heritiera fomes	Salinity × Chl. a	-0.9111	<0.01
	Salinity × Chl. b	-0.9018	<0.01
	Salinity × Total Chl.	-0.9096	<0.01

Ecological analysis

We analysed the stem biomass in natural plantation of the selected species (~ 11 years plantation age) in the western and central Indian Sundarbans during January, 2010 and observed consistency in the data of Rhizophora mangle in both the regions. For Sonneratia apetala, Avicennia marina, Avicennia officinalis and *Heritiera fomes* the difference was significant. The biomass of the species was much lower in the central sector around the Matla River in comparison to those around the River Hooghly receiving fresh water from the Himalayan glacier after being regulated by barrages on the way. It appears from the AGSB data set (Table 2) that salinity has reduced the yield/ha in Sonneratia apetala, Avicennia marina, Avicennia officinalis and Heritiera fomes by 24.10%, 18.03%, 33.94% and 64.45% respectively, but in case of Rhizophora mangle the AGSB has increased by 1.38% confirming the ability of the species to resist the hypersaline environment. The significant decrease of AGSB in central Indian Sundarbans (by 64.45% in comparison to western sector) is a clear indication of the sensitivity of Heritiera fomes to high saline conditions and may face extinction from certain pockets of lower Gangetic plain (particularly in and around the Matla River) if the current trend of salinity rise (~ 2 psu/decade) continues (Mitra et al., 2009a).

TABLE 2

Above ground stem biomass (AGSB) in t/ha of five selected mangrove species in the western and central Indian Sundarbans

Year	Western (t/ha)	Central (t/ha)
Sonneratia apetala	19.79	15.02
Avicennia marina	18.14	14.87
Avicennia officinalis	7.75	5.12
Rhizophora mangle	13.78	13.97
Heritiera fomes	5.71	2.03

The carbon sequestration capacity of mangroves may also shrink in hypersaline condition. The carbon content (in %) analyzed on a LECO® CHN-600 analyzer in the present programme reflects relatively lower carbon in the mangroves of central sector (Table 3) which may be attributed to lower AGSB and relative density of the species.

TABLE 3

Above ground stem carbon stock (in t/ha) of five selected mangrove species in the western and central Indian Sundarbans. The figures in bracket represent the percentage of carbon present

Year	Western (t/ha)	Central (t/ha)
Sonneratia apetala	8.39 (42.4%)	6.17 (41.1%)
Avicennia marina	7.22 (39.8%)	5.84 (39.3%)
Avicennia officinalis	3.37 (43.5%)	2.13 (41.7%)
Rhizophora mangle	6.15 (44.6%)	6.57 (43.9%)
Heritiera fomes	2.35 (41.1%)	0.80 (39.4%)

Mangroves are unique storehouse for carbon. The global storage of carbon in mangrove biomass is estimated to be 4.03 pg, 70% of which occurs in coastal margins from 0^0 to 10^0 latitude (Twilley et al., 1992). The data generated in the present geographical locale show high degree of variation between the two sectors. The carbon sequestered by mangroves in the central sector is not in alignment (in terms of magnitude) to the stored carbon in different categories of mangrove ecosystems of Asia – Pacific region. In a Rhizophora apiculata dominated coral reef mangrove habitat consisting of a 2 m thick mangrove peat layer in Phonpei island in Pacific, the stored carbon was estimated as 130 Kg C m^{-2} (=1300 t C ha^{-1}), and in a estuary type habitat, the value reached about 200 Kg C m^{-2} (Fujimoto et al., 1999). The hypersalinity of the central part of Indian Sundarbans may be considered as one of the important reason for this shortfall that not only causes stunted growth, but poor survival percentage leading to low relative density.

Superimposing the results of biochemical and ecological analyses, it can be stated that if the current trend of salinity rise persists in and around the Matla River then Heritiera fomes will be the foremost mangrove species to face extinction due to adverse impact on chlorophyll pigment. Other species like Sonneratia apetala, Avicennia marina and Avicennia officinalis may also find difficulty at extreme salinity in terms of growth. The most befitting species around the hypersaline tide fed Matla River is Rhizophora mangle.

Conclusions and recommendations

Indian Sundarbans and its adjacent estuaries situated in the lower Gangetic matrix at the apex of Bay of Bengal are one of the less studied regions of the world ocean in context to impact of rising salinity fluctuation on mangrove floral community, although the region sustains the 5th largest mangrove chunk in the world. The present study is extremely important from the point of view of rising salinity in the central sector of Indian Sundarbans over a period of two decades (Mitra et al., 2009a) due to complete obstruction of the freshwater supply of Ganga-Bhagirathi-Hooghly River as a result of heavy siltation since the late 15th century (Chaudhuri and Choudhury, 1994) and rising sea level at the rate of 3.14 mm/yr (Hazra et al., 2002), which is higher than the global average sea level rise of 2.12 mm/yr and 2.50 mm/yr along the Indian coastline (Lal and Aggarwal, 2000). Increased salinity due to lack of freshwater is likely to result in a decrease in mangrove productivity, growth and seedling survival, and may change species composition favoring more salt tolerant species (Ellison 2000, 2004). This may be the future situation in central Indian Sundarbans due to intrusion of saline water from Bay of Bengal.

We conclude that all species except Rhizophora mangle are sensitive to high saline conditions (~30 psu) and may not cope up with predicted scenario of central sector of Indian Sundarbans where the Ganges lost its flow on account of heavy siltation. Amongst all the four species Heritiera fomes seems to be highly fragile and sensitive as the chlorophyll pigment of the species gets significantly affected in high saline condition as revealed from our laboratory experiment and subsequent statistical interpretation (vide Table 1 for statistical significance).

The pigments, being the key machinery in regulating the growth and survival of mangroves require an optimum salinity range between 4 to 15 psu (Downton, 1982; Burchett et al., 1984) for proper functioning. It appears that the growth of the species (preferably Heritiera fomes) would be better if fresh water of the western sector of Indian Sundarbans is channelized to the central sector or the river bed of Bidyadhari is subjected to capital dredging (initially) and periodic dredging (yearly). The processes will not only help to ecorestore the system, but may also help to combat the intrusion of seawater from the southern part due to expansion of Bay of Bengal water on account of warming (Mitra et al., 2009b).

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