Changes in mangrove species assemblages and future prediction of the Bangladesh Sundarbans using Markov Chain model and Cellular Automata

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Environmental impact statement

Mangrove forest is a highly diverse and enriched ecosystem, in terms of floral and faunal biodiversity and ecosystem services. Sundarbans mangrove forest is the largest chunk of mangroves in the world which is changing in the terms of area, density and species composition under the several anthropogenic and environmental threats. It is therefore necessary to study the pattern of changes of mangrove species assemblages taking place in the Sundarbans and to assess its probable future conditions. An attempt has been made to predict the direction of future changes in species zonation of mangroves of Sundarban in Bangladesh , which not only indicates the future mangrove assemblages, but also indicates the implied environmental conditions in this area and probable threats to ecosystem services.

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ARTICLE

Changes in mangrove species assemblages and future prediction of the Bangladesh Sundarbans using Markov Chain model and Cellular Automata

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The composition and assemblage of mangroves in the Bangladesh Sundarbans is changing systematically in response to several environmental factors. In order to understand the impact of the changing environmental conditions on the mangrove forest, species composition maps for the year 1985, 1995 and 2005 were studied. In the present study, 1985 and 1995 species zonation maps were considered as base data and Cellular Automata-Markov chain model was run to predict the species zonation for the year 2005. The model output was validated against the actual data set for 2005 and calibrated. Finally, using the model, mangrove species zonation maps for the year 2025, 2055 and 2105 have been prepared. The model was run with the assumption that the continuation of the current tempo and mode of drivers of environmental factors (temperature, rainfall, salinity change) of the last two decades will remain the similar in the next few decades. Present findings show that the area distribution of the following species assemblages like Goran (*Ceriops*), Sundari (*Heritiera)*, Passur *(Xylocarpus)*, Baen (*Avicennia)* would decrease in descending order, whereas the area distribution of Gewa (*Excoecaria*), Keora (*Sonneratia)* and Kankra (*Bruguiera*) dominated assemblages would increase. The spatial distribution of projected mangrove species assemblages shows that more salt tolerant species will dominate in the future; which may be used as a proxy to predict the increase of salinity and its spatial variation in Sundarbans. Considering the present rate of loss of forest land, 17% of total mangrove cover is predicted to be lost by the year 2105 with significant loss of fresh water loving mangroves and related ecosystem services. This paper describes a unique approach to assess future change in species composition and future forest zonation in mangroves under 'business as usual' scenario of climate change.

Environmental Science: Processes & Impacts

Introduction

Mangroves are very diverse assemblages of woody spermatophytes lying along tropical coastlines in the saline environment under tidal influence.[1] Tomlinson[2] described the term 'mangrove' as an intertidal ecosystem comprising of highly adapted plant groups that live in the coastal environment. The species composition and distribution depends on distance from the sea or estuary bank, duration and frequency of the tidal inundation and soil composition.[3] Mangroves are ecologically highly stable with regard to their persistence and resilience but highly sensitive to the hydrological changes.[4] The mangrove ecosystem is as important ecologically as economically. Mangrove ecosystems are enriched with many organisms having significant ecological and economic values. It supports both the terrestrial and aquatic food chains that support a diverse group of flora and fauna. Mangrove ecosystems act as a natural barrier to protect the shoreline and island areas from various natural hazards (such as tropical cyclones, and tsunamis). Not only do they prevent coastal erosion by breaking the force of the waves, they also maintain the water quality by acting as biological filters, separating sediment and nutrient from polluted coastal water. Mangroves are very significant for maintaining carbon balance in coastal areas and for tourism as ecotourism which may maintain the pristine environment and also serve recreation purpose[3] and contributes to economy of the coastal community. In addition to these services, mangroves economically contribute to the human livelihood by providing a nursery for fisheries, aquaculture, fuel, honey, traditional medicines etc. During recent decades, mangroves have been facing tremendous threats. In the global scenario, it has been found that about 35% of the mangrove forest area has disappeared since 1980. The average rate of mangrove area loss is about 2.1% per year, which reaches a maximum of up to 3.6% in America.[5] In spite of various attempts to protect mangrove resources; they have been facing tremendous anthropogenic pressure due to unwise exploitation for multiple uses like wood, fodder, fuel, charcoal and honey.[6] The Sundarbans mangrove forest is the single largest contiguous area of mangrove forest in the world. It is located in the lower Ganges-Brahmaputra Delta spanning an area of about one million hectors including India and Bangladesh.[7, 8, 9, 10] A majority of this total area lies at present in Bangladesh (60%) and the rest falls in India (40%). The Sundarbans consist of 10,200 km^2 area, of which 5937 km^2 and 4263 km^2 of Reserve forests spread respectively over Bangladesh and India.[11] The Sundarbans are rich in mangrove species diversity.[12,13] The mangrove species distribution pattern can be related to mangrove zonation and its controlling factors.[2, 7,13,14,15] The Sundarbans account for 4.2 per cent of the total land area of Bangladesh and about 40 per cent of the country's forests. The Sundarbans forest is basically a salt-tolerant forest ecosystem, like other coastal mangroves of Southeast Asia, but a relatively sweet water ecosystem also coexists. It is feared that the anticipated sea level rise due to global warming will degrade the forest environment predominantly by increasing salinity and erosion if sedimentation cannot keep pace with sea level rise and hence will destroy major forest resources.[16]

The present study focuses on the changes in mangrove species assemblages in the Bangladesh Sundarbans in the last two decades and how the species composition will change in future under business as usual scenario, i.e. if the trend of recent environmental factors remains unaltered. For a future prediction, a hybrid methodology has been adopted using a statistical model (Markov Chain analysis) for calculating the transition probabilities of the mangrove species assemblages which have been incorporated into a Cellular Automata (CA) nonlinear geospatial model for projecting the future conditions.

Study area

The study area of the Bangladesh Sundarbans Fig. 1 lies between the latitudes 21° 30' N and 22° 30' N and longitudes 89°7' E and 89°55' E. It occupies a total land area of 5773 sq. km, of which 4074 sq. km is mangrove reserve forest and 1699 sq. km is open water bodies. The Bangladesh Sundarbans are bounded by heavily populated agricultural land in the north and east and by the Indian Sundarbans in the west whereas the Bay of Bengal lies to the south.[17]

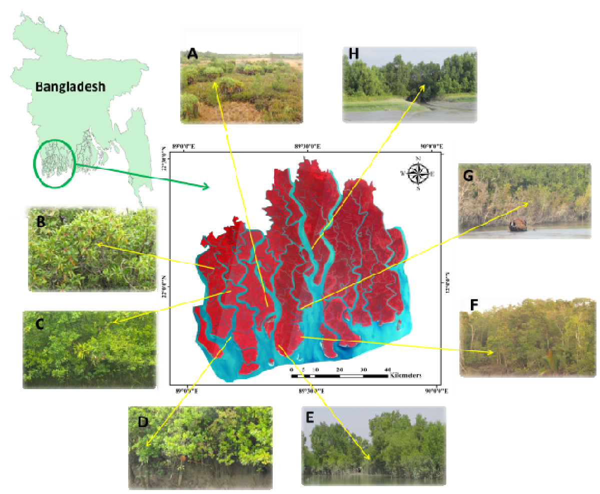

Fig. 1 Study area, Bangladesh Sundarbans [Green flags demarcates spatial location of few dominant species from the field study, A: Grass and Fern with Bare Ground; B: *Bruguiera* (Kankra); C: *Ceriops* (Goran); D: *Xylocarpus* (Passur); E: *Avicennia* (Baen); F: *Excoecaria* (Gewa); G: *Heritiera* (Sundari); H: *Sonneratia* (Keora)]

Methodology

To assess the changes of the species assemblages and make future predictions, the existing mangrove zonation data of 1985, 1995 and 2005 have been used. These data have been prepared by the Bangladesh Forest Department (BFD) and International Union for Conservation of Nature (IUCN) from survey methods in combination with satellite image analysis Fig. 2. The mangrove forest has been classified into 16 classes Table 1.

Table 1 Classes of the Bangladesh Sundarbans Mangrove forest

CLASS		
No	**Common Name**	**Scientific Name**
1	Baen	*Avicennia*
2	Gewa & Gewa Mathal	*Excoecaria*
3	Gewa Goran	*Excoecaria* Dominated and *Ceriops*
4	Gewa Sundri	*Excoecaria* Dominated and *Heritiera*
5	Sundri Passur	*Heritiera* Dominated and *Xylocarpus*
6	Sundri	*Heritiera*
7	Sandbar	Sandbar
8	Sundri Gewa	*Heritiera* Dominated and *Excoecaria*
9	Goran	*Ceriops*
10	Goran Gewa	*Ceriops* Dominated and *Excoecaria*
11	Grass and Bare Ground	Grass and Bare Ground
12	Keora	*Sonneratia*
13	Passur Kankra	*Xylocarpus* Dominated and *Bruguiera*
14	Passur Kankra Baen	*Xylocarpus* Dominated and *Bruguiera* and *Avicennia*
15	Sundri Passur Kankra	*Heritiera* Dominated and *Xylocarpus* and *Bruguiera*
16	Mixed Forest	Mixed (Plantation and Built-ups etc.)

The data have been converted into geospatial format. To predict the future scenario, a hybrid methodology has been adopted assuming that the trend of causative environmental factors will remain the same in the near future. A Markov chain model in combination with Cellular Automata has been used to generate the future scenario of mangrove species zonation in the Bangladesh Sundarbans. Both Cellular Automata and the Markov model have great advantages in the study of land use changes.[18] In this case each of the mangrove species assemblages has been taken as one land use class and the total Sundarbans forest has hence been classified into 16 classes. A Markov-CA model incorporated with GIS data is claimed to be a suitable approach to model the temporal and spatial change of land use[19].

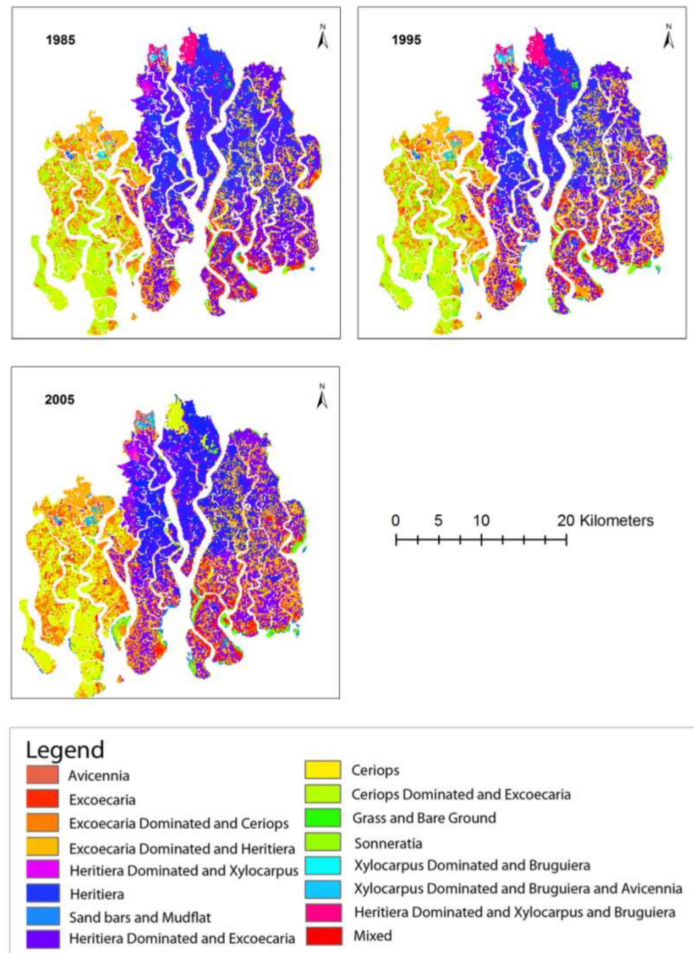

Fig. 2 Map showing Mangrove species assemblages of Bangladesh Sundarbans

In the Markov-CA model, the Markov chain process controls the temporal change among the land use types based on transition matrices,[20] while the CA model controls spatial pattern change through local rules considering neighbourhood configuration and transition potential maps.[21,22,23] GIS can be used to define the initial conditions, to parameterize the Markov-CA model, to calculate transition matrixes, and to determine the neighbourhood rules.[24,25,26] The Markov chain model is based on a stochastic process that describes how likely it is that one state is going to change into another state.[27] In other words, a Markovian process predicts the state of a system at time (t_2) depending upon the state of the system at time (t_1).[28] In fact, the Markov model is not at all influenced by the state of the neighbour cells and is only dependent on the individual cell states at time t_1 and t_2.[29] This process consists of a key-descriptive tool, i.e. the transition probability matrix[30] from which a transition area matrix is obtained for the different mangrove classes. The transition area matrix records the number of pixels that are expected to change from their existing mangrove class to any other mangrove class (or stay the same) over the specified number of time units. The transition probability matrix records the probability that each mangrove class would change to any other mangrove class; while the transition area matrix records the number of pixels that are expected to change from one mangrove class to the other over the specified number of time units.[31] The transition area matrix, obtained from two time periods, was used as the basis for predicting the future mangrove species zonation scenario. In the Markov chain model, a chain represents a stochastic process at time t, X_t, which exclusively depends on the value at time $t-1$, X_{t-1}, and not depending on the previous series of values (i.e. X_{t-2}, X_{t-3}……..X_0), and the transition probability equation may be written as[25].

$$P\{X_t = a_j | X_0 = a_0, X_1 = a_1, ..., X_{t-1} = a_i\} = P\{X_t = a_j | X_{t-1} = a_i\} \quad (1)$$

The $P\{X_t = a_j | X_{t-1} = a_i\}$ is recognized as the one-step transitional probability, which gives the possibility of creating the transition from state a_i to state a_j in one time period. When ℓ steps are necessary to implement this transition, the $P\{X_t = a_j | X_{t-1} = a_i\}$ is then called the ℓ step transition probability, $P_{ij}^{(\ell)}$.

When $P_{ij}^{(\ell)}$ is time independent and is dependent only on the states a_i, a_j and ℓ, then the Markov chain is regarded as homogeneous, i.e.

$$P\{X_t = a_j | X_{t-1} = a_i\} = P_{ij} \quad (2)$$

Where P_{ij} is derived from the observed data, after determination of the number of times the observed data goes from state i to j, n_{ij}, and the number of occurrences of the state a_i, n_i is summed up. Then the equation becomes,

$$P_{ij} = n_{ij} / n_i \quad (3)$$

As the Markov chain proceeds, the probability of remaining in the state j becomes independent of the initial state of the chain after many steps. As this condition is achieved, the chain is believed to have attained a steady state and accordingly P_j, i.e., the limit probability, is applied for the determination of the value of $P_{ij}^{(\ell)}$ according to the equation

$$\lim_n P_{ij}^{(n)} = P_j \quad (4)$$

Where, $P_j = P_i P_{ij}^{(n)}$ j=1, 2,…, m (state); P_i=1; P_j >0

In the case of the transition probability matrix, each of the elements consists of a category with observed and expected number of transitions as per the equation

$$\chi^2 = \sum \frac{(O-E)^2}{E} \quad (5)$$

Here O is the observed number of transitions from one state to another and E is the expected number of transition; in each case, the successive states are independent.

The Markov model alone cannot solve the entire problem, since it does not take into account the spatial distribution within each category, hence it might depict the correct magnitude of change however it cannot give the right direction.[32] In order to incorporate the spatial attribute and hence direction to the modeling, the Cellular Automata (CA) model is implemented.[33] One of the most crucial geospatial elements that principally governs and regulates the variability of the change events is proximity.[27] A cellular automaton (in this case a pixel or a mangrove class) is considered to be an entity that independently varies its state not only based on its pre-existing state but also on the state of its immediate neighbors (i.e. most proximal classes).[34] The overall performance of the system will be decided from the combined actions of all the locally defined transition rules, therefore, the state of the system moves forward in discrete time steps. The CA model can be expressed as follows[35]

S (t, t+1) = f (S (t), N) (6)

Thus the spatial and temporal attributes of the prediction made in this study is achieved by the fusion of the Markov chain model and the CA model. The CA model with powerful spatial computing was used to simulate the spatial variation of the system effectively[36], while the CA–Markov model was used to achieve better simulation for temporal and spatial patterns of land class changes in quantity and space.[37]

Initially, mangrove species zonation prediction was done for the year 2005 based on the 1985 and 1995 data sets and it was validated using the observed data for 2005. Multi-Criteria Evaluation (MCE) was applied on the mangrove classes for better accuracy of the model; finally prediction was done for the years 2025, 2055 and 2105. At first, the preceding state transition rules have been calculated using Markov chain methods. The calculated transition probability matrix so obtained serves as the transformation rules in the CA–Markov model simulations. CA filters are known to produce a clear sense of the space weighting factor, which can be changed according to the current adjacent cellular state. The standard 5 * 5 contiguity filter has been used as the neighbourhood definition in this study, which means that each cellular centre is surrounded by a matrix space which is composed of 5 * 5 cells to impact the cellular changes significantly.

Regarding the limitation of the model, it can be stated that any kind of unprecedented anthropogenic, environmental or climatic changes could not be taken into account in the present model. Sudden hazards like cyclone, tsunami tectonic movement or a forest policy change which might have profound impact also have not been considered in the model.

Result and Discussion

The model shows that the spatial distribution of mangrove species assemblages will change and the total forest cover area will decrease in the future. Using the data of 1985 and 1995 the model has been run to produce predicted data for 2005, which has been validated with the actual data set for 2005. The confidence level of the validation result was 92%. Then the multi-criteria evaluation (MCE) table was formulated to reduce this error level, especially for the

Planted Mangroves and Built-up areas which have been given the name ‘Mixed class’, assuming that these will not change. Change will only occur in natural processes and to the natural vegetation. The model was run using the assumption that the continuation of the current trend of causative environmental factors of the last two decades will remain the similar in the next few decades. The mangrove species assemblages prediction has been done for the years 2025, 2055 and 2105 (Fig. 3).

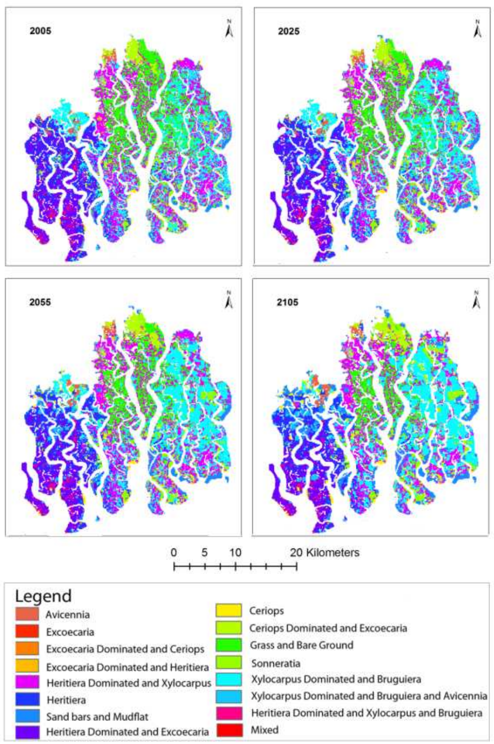

Fig. 3 Projected Mangrove species assemblages of Bangladesh Sundarbans of the year 2005, 2025, 2055 and 2105

From the results, it was observed that the areal distribution of the following mangrove species dominated assemblages: Goran (*Ceriops*), Sundari (*Heritiera)*, Passur*(Xylocarpus)* and Baen (*Avicennia)* would decrease in descending order; whereas the areal distribution of Gewa- (*Excoecaria*), Keora- (*Sonneratia)* and Kankra- (*Bruguiera*) dominated assemblages would increase in the forest. Some assemblages like Sundari-, Keora- and Baen-dominated areas showed almost identical distributions for the considered period of study (Fig. 4)**.** Considering the present rate, only 17% of total mangrove cover has been predicted to be lost by the year 2105.

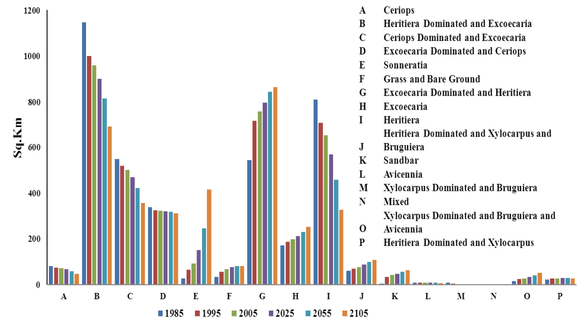

Fig. 4 Changes in Mangrove species assemblages

Another important finding comes out regarding the future spatial distribution of mangrove species according to the salinity dependence. Mangrove species distribution pattern can be related to mangrove zonation and its controlling factors.[2,7,13,14,15] In order to establish this relationship, identification of mangrove zonation and its controlling factor estimation are necessary in the Sundarbans. Many scientists have considered salinity as a major controlling factor of the mangrove vegetation pattern.[15,38,39,40,41,42] Species distribution based on salinity has already been established by different workers.[40,41,43,44,45] The western side of the Sundarbans mainly has the higher salinity regime[46] and the eastern side of the Sundarbans (extreme east of the Bangladesh Sundarbans) has a lower salinity regime[47] whereas, the middle part of Sundarban which is present in both India and Bangladesh, is polyhaline in nature.[48]

Karim[48] and Hoque*et al.*[17] differentiated these salinity zones as oligohaline, mesohaline and polyhaline region for the Sundarbans mangrove forest. Using that concept, study locations are categorized into three zones in the present study: ‘Low Salinity Zone’ (Oligohaline), Medium Salinity Zone’ (Mesohaline) and ‘High Salinity Zones’ (Oligohaline) (Fig. 5).

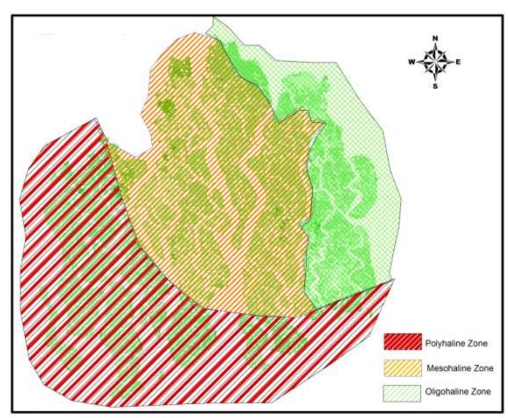

Fig. 5 Map showing different salinity zones of Bangladesh Sundarbans (After Hoque*et al.*, 2006)

Past scientific studies found *Heritiera* (Sundari), as a species of the ‘Low Salinity Zone’. *Ceriops* (Goran), *Sonneratia* (Keora) , *Xylocarpus* (Kankra) can be found in the mid-saline zone with varying abundance and *Avicennia*(Baen) and *Exoecaria* (Gewa) grow in the high saline zones.[13, 14, 38, 49, 50] According to these studies, the mangrove species assemblages of the present-day (2005) and the future (2105) have been classified according to the salinity tolerance Table 2.

Table 2 Mangrove assemblages according to the salinity preferences

Salinity	Mangroves Species assemblages	
Low Saline	Sundari	*Heritiera*
Low Saline	Sundari Gewa	*Heritiera* Dominated and *Excoecaria*
Mid Saline	Goran	*Ceriops*
Mid Saline	Keora	*Sonneratia*
Mid Saline	Gewa Sundari	*Excoecaria* Dominated and *Heritiera*
Mid Saline	Sundari Passur Kankra	*Heritiera* Dominated and *Xylocarpus* and *Bruguiera*
Mid Saline	Sundari Passur	*Heritiera* Dominated and *Xylocarpus*
High Saline	Baen	*Avicennia*
High Saline	Gewa & Gewa Mathal	*Excoecaria*
High Saline	Passur Kankra	*Xylocarpus* Dominated and *Bruguiera*
High Saline	Passur Kankra Baen	*Xylocarpus* Dominated and *Bruguiera* and *Avicennia*

The spatial distribution of the mangrove species after classifying them according to the salinity dependency Fig. 6 shows that freshwater-dependent mangrove species will decrease from 43% to 29% and the high saline-dependent species will remain more or less the same whereas the mid-saline-dependent species will increase from 26% to 41% from the year 2005 to 2105.

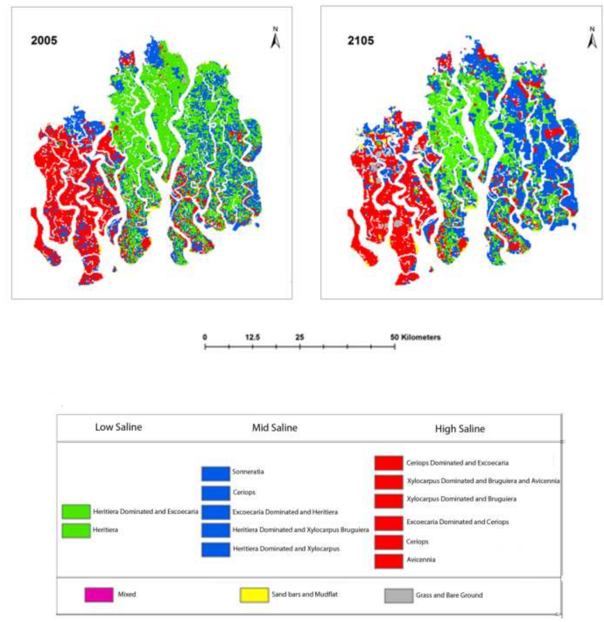

Fig. 6 Predicted Changes in spatial distribution of Mangrove species assemblages according to salinity.

Conclusion

From the present study it may be concluded that the total coverage of mangrove forest of Bangladesh Sundarbans will decline by 17% in the year 2105, which will be a great loss of biodiversity and ecosystem services. Also the dominance of more salt tolerant species has been projected in the future which indicates a more saline environment for which the ecosystem as well as the economy of the local inhabitants will be under threat. For example the essential services of *Nypa fruticans* or *Golpata* which commonly thrive in freshwater *Sundari* dominated zone and are widely used by the local community will reduce further. This work is mainly based on a projection of the present tendency and inept to consider new threats due to the acceleration of SLR or drastic changes in the fresh water supply.

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Notes & Reference

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