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Assessment of suitable habitat of mangrove species for prioritizing restoration in coastal ecosystem of Sundarban Biosphere Reserve, India

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Mangrove forests being the abode of diverse fauna and flora are vital for healthy coastal ecosystems. These forests act as a carbon sequester and protection shield against floods, storms, and cyclones. The mangroves of the Sundarban Biosphere Reserve (SBR), being one of the most dynamic and productive ecosystems in the world are in constant degradation. Hence, habitat suitability assessment of mangrove species is of paramount significance for its restoration and ecological benefits. The study aims to assess and prioritize restoration targets for 18 true mangrove species using 10 machine-learning algorithm-based habitat suitability models in the SBR. We identified the degraded mangrove areas between 1975 and 2020 by using Landsat images and field verification. The reserve was divided into 5609 grids using 1 km grid size for understanding the nature of mangrove degradation and collection of species occurrence data. A total of 36 parameters covering physical, environmental, soil, water, bio-climatic and disturbance aspects were chosen for habitat suitability assessment. Niche overlay function and grid-based habitat suitability classes were used to identify the species-based restoration prioritize grids. Habitat suitability analysis revealed that nearly half of the grids are highly suitable for mangrove habitat in the Reserve. Restoration within highly suitable mangrove grids could be achieved in the areas covered with less than 75 percent mangroves and lesser anthropogenic disturbance. The study calls for devising effective management strategies for monitoring and conserving the degraded mangrove cover. Monitoring and effective management strategies can help in maintaining and conserving the degraded mangrove cover. The model proves to be useful for assessing site suitability for restoring mangroves. The other geographical regions interested in assessing habitat suitability and prioritizing the restoration of mangroves may find the methodology adopted in this study effective.

Mangrove forests play a significant role in maintaining the health of the coastal ecosystems globally and support life for birds, flora, and fauna^{1–4}. Healthy mangrove forests protect the coastal ecosystem against natural hazards and are a great source of carbon sequestration than any other type of forest^{5,6}. The mangrove forests provide significant ecological, social, and economic services to the coastal communities^{7,8}. Mangrove forests are one of the most productive ecosystems in the world, being the abode of diverse fauna and flora^{9–11}. In spite of providing immense benefits, these ecosystems are under constant degradation due to anthropogenic disturbance and climate change^{12,13}. Nearly half of the mangrove biomes have been despaired since 1950 due to huge habitat alteration and inadequate protection¹⁴. It is anticipated that if this rate of loss is continued then the mangrove biome will be vanished from the earth by the next 100 years². A recent study by Polidoro et al.¹⁵ on mangrove species over the world reported that more than 16% of species are in the state of becoming extinct and another 10% are under threat of degradation. The mangroves experience higher losses than the average losses of the tropical and sub-tropical^{12,16}.

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India has a total area of 4975 km² under mangroves which constitutes 0.14% of the country's total geographical area¹⁷. The Sundarbans has the largest halophytic mangrove forest in the world and spread over Ganga- Brahmaputra and Meghna delta. The Indian Sundarban Biosphere Reserve (SBR) is a significant ecological region due to its luxuriant mangrove forest and high biodiversity¹⁸. However, the area under mangrove forests has sharply decreased during the last few decades¹⁹. Sea level rise, sudden disaster events, over-harvesting, aquaculture expansion, shrimp and salt farming, regular oil spills, and lack of sustainable adaptive strategies may be attributed to the decline of forests^{20–22}. Nearly 76% area under *Heritiera fomes* species has declined during 1959–2005^{23,24}. The other dominant mangrove species in Sundarbans namely *Ceriops decandra*, *Excoecaria agallocha* and *Xylocarpus mekongensis* also reported having a higher rate of decline^{25,26}.

Limited information on the habitat distribution of mangrove species has restricted successful mangrove conservation^{27–29}. Advancements in geospatial technology have helped in providing spatial, comprehensive, reliable, and up-to-date information on forest dynamics for effective management^{30–32}. Species distribution models (SDM) supported by geoinformatics and machine learning-based spatial analysis have been widely used for mapping, conserving, and management of endangered, threatened, and vulnerable species^{33–35}. SDM is a very powerful tool for identifying suitable habitats for the present scenarios and future predictions creating a relation between the known occurrence data and environmental and climatic variables^{36–38}.

Different mangrove restoration programmes were promulgated over the last 50 years³⁹. During 1980, silviculture and reforestation were programmes for the mangrove restoration⁴⁰. Later, ecological mangrove restoration (EMR) and community-based restoration approaches were introduced in 2000⁴¹. Presently, ecological engineering and ecosystem design are one of the most popular mangrove restoration approaches⁴². Romañach et al.⁴³ recommended that integrated community-based balances conservation goals are very necessary for conservation and restoration of the mangrove. Sulochanan et al.⁴⁴ used water and sediment quality parameters based pragmatic approach to restore the mangrove ecosystems in Dakshina Kannada district of India. Lovelock et al.⁴⁵ identified technical issues and over ambitiousness as the major failure of mangrove restoration programmes. They emphasized on the need of identification of suitable land and species for mangrove restoration. Lovelock and Brown⁴⁶ proposed land tenure consideration as one of the important factors for mangrove restoration. Su et al.⁴⁷ conducted a meta-analysis of the outcome of the mangrove restoration from 167 peer-reviewed articles and they stressed on ecological analysis for mangrove restoration. Lee et al.⁴⁸ focused on the evidence-based restoration policies for both short term and long-term restoration programmes.

Many scholars have utilized SDMs for mapping suitable habitats of mangroves species^{1,4,24,49–53}. Sarker et al.²⁴ prepared spatial density maps of prominent mangrove species and analyzed habitat suitability in Bangladesh Sundarban using generalized additive models (GAMs). Hu et al.^{4,51} used the maximum entropy (MaxEnt) model for assessing the habitat suitability of mangrove forests in China. Rodríguez-Medina et al.⁵² also used MaxEnt model for determining suitable habitat distribution mangroves in Mexico. Wang et al.⁵³ used this method for assessing habitat suitability in Guangdong Province of coastal China. Chakraborty et al.⁴⁹ used Analytic Hierarchy Process (AHP) for assessing potential mangrove suitability in the Andaman Islands of the Indian Ocean. All these mangrove habitat suitability studies used 'a single model fits all' approach. Such an approach may not always provide a complete picture of the habitat distribution due to physiographic differences, species-specific responses to the climate and environmental conditions. To overcome this problem, Banerjee et al.¹ assessed mangrove habitat suitability for seven true mangroves species over the Indo-West Pacific region using an ensemble of eight different machine learning models. However, the wide resolution being 2.5 arc minutes resolution was the major limitation of this study. Such a resolution cannot provide accurate information on species distribution. Multi-modeling habitat suitability assessment based on fine resolution using species occurrence data can help in protecting the threatened ecosystems. Thus, this is an urgent need to apply the species occurrence and environmental data to setup a finer resolution multi-modelling habitat suitability assessment at regional scale for protecting threatened ecosystems. Furthermore, linking the species distribution models with nature-based restoration of mangrove species is an important research gap. Thus, we have applied the multi-modeling species distribution approach in Indian Sundarban- the largest single block of mangrove species. Our study aims to achieve two specific objectives. Firstly, assessment of multi-modeling habitat suitability for 18 true mangrove species at a finer spatial scale, and secondly, prioritization of species-specific ecological restoration using a grid-based approach.

Study area

Sundarban Biosphere Reserve (SBR) extends between 21° 31' N and 22° 30' N latitudes and 88° 10' E and 89° 51' E longitudes (Fig. 1). Of the total geographical area (9630 km²), 4266 km² area is under mangrove forest. Of the total islands in the SBR (102), 48 islands are uninhabited and covered by mangrove forests. Most of the Reserve consists of low-lying alluvial mudflats, tidal creeks, and multiple river channels. Sundarban has great mangrove diversity because of its highest number of mangrove plant species and the densest and tallest mangrove forest in the world⁵⁴. It provides the best example of a low-energy wave coast, where mangroves grow luxuriantly along the seashore⁵⁵. Mangrove forests can best be flourished in the estuarine regions where a large amount of freshwater is discharged for a longer duration of time in a year. The richness of the Sundarban mangrove forest depends on the freshwater flow from the River Ganges and the Brahmaputra and its tributaries/distributaries throughout the year. The Sundarban mangrove support sustaining the habitat of the Royal Bengal tiger (*Panthera tigris*) and Ganges river dolphin (*Platanista gangetica*). Recently Indian Sundarban has been declared a Ramsar site under the Ramsar Convention in 2020 because of its ecosystem's services, biological diversity, and universal value^{18,55,56}. The total area of Sundarban Biosphere Reserve is divided into the core zone (national park), buffer zone (reserve forest and bird sanctuary and the transition zone (human habitation).

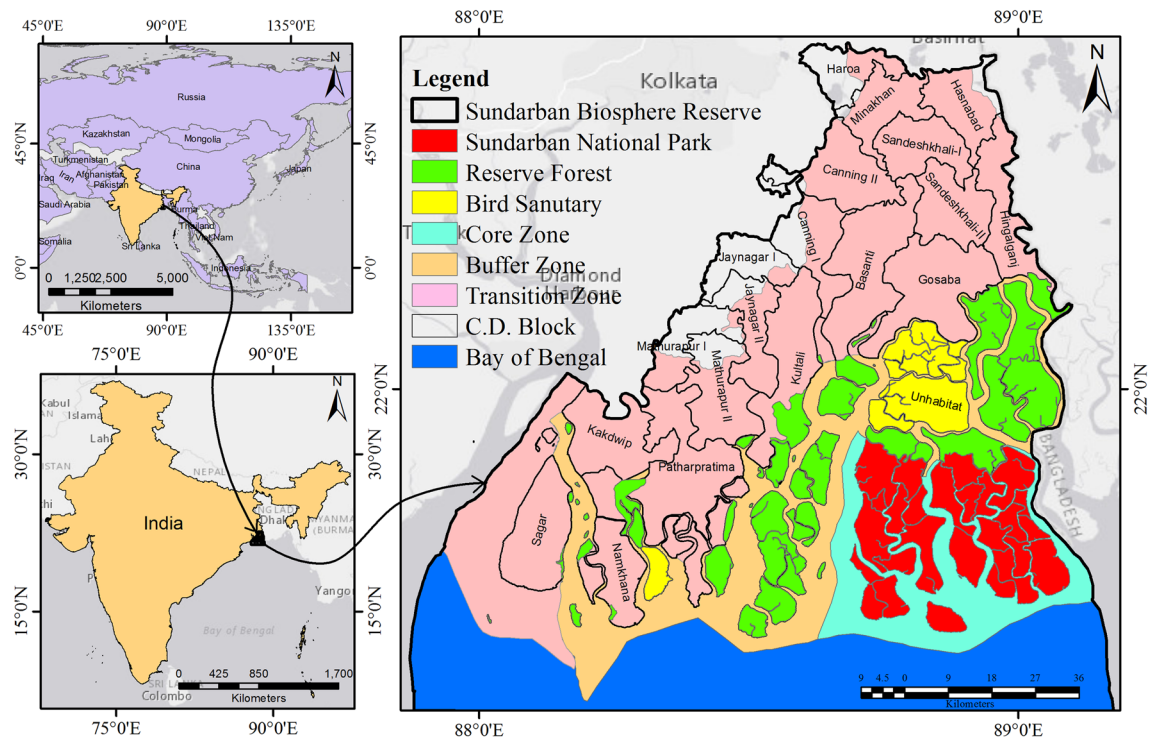


Figure 1. Location of Sundarban Biosphere Reserve in India (The map was prepared using ArcGIS 10.8.2 software [<https://desktop.arcgis.com>].)

Methodology

The present study makes an attempt to prioritize restoration target areas by using mangrove habitat suitability models, niche overlay function, and mangrove degradation rate using a grid-based approach over the Sundarban Biosphere Reserve. Degraded mangrove areas between 1975 and 2020 were identified using Landsat images and field verification of the specific sites. The SBR was divided into 5609 grids using a 1 km grid to understand the nature of mangrove degradation and modeling purpose (Fig. 3). Landsat MSS (1975) and Landsat 8 OLI (2020) satellite data were utilized for preparing a land use/landcover map of the SBR using a supervised classification technique. The classification accuracy was assessed through the confusion matrix and kappa coefficient. Overall accuracy was found 87.62% for 1975 and 94.9% for 2020 and the kappa coefficient values was 0.89 for 1975 and 0.96 for 2020. Post classification change matrix technique was used to prepare land use/land cover change map during 1975 and 2020. The area under vegetation cover and mangrove was extracted from the land use land cover map. NDVI maps during different seasons were utilized to improve the accuracy of the vegetation cover map of the SBR. Ten influencing drivers were selected for analyzing the habitat suitability of mangrove forests (Table 1). The details of the methodological framework are presented in Fig. 2.

Occurrence data. We selected 18 dominant mangrove species in Indian Sundarban for preparing a habitat suitability model (Table 2). The occurrence data of the selected mangrove species have been collected from Global Biodiversity Information Facility (GBIF) and the existing published literature^{68,69}. The occurrence data were collected from the published sources^{70–74} and field survey using a grid-based stratified random sampling approach during 2018–2019. We received help from the local fisherman, crab and honey collector to identify mangrove species and collected samples from the core forest areas. The total grids were divided into 19 strata as per the administrative blocks for an easy process and 50 samples were selected from each stratum. In this way, a total of 950 occurrence locations were selected from the field survey (Fig. 3). The secondary occurrence data was verified through google earth images to avoid duplication. Further, the occurrence data was run through a statistical assessment using spatially rarefied in ArcGIS SDM toolbox by selecting a single point grid cell for individual species (1 km grid). Finally, we selected a total of 1560 occurrence data (707 from the archive sources and 853 from the field survey (Table 2) to develop species distribution models.

Data preparation and variable selection. After a detailed literature review and field knowledge, we considered 36 variables from 6 different parameters for the present study. The data source, data structure, spatial resolution, and references of the data have been provided in Appendix 1. All the raster variables were re-sampled into 1 km resolution using resample tool in ArcGIS to match the original resolution of WorldClim data and the 1 km sampling grid⁷⁶. All 30-m raster images were reclassified into 1 km grid cell and the average number of pixels over 5609 grids in Sundarban were determined to be 33,334. From the topographical parameters, we selected six important variables (Appendix 2A) namely, elevation, slope, curvature, geomorphology, topographic wetness index (TWI), and stream power index (SPI) (Appendix 1). All the selected topographical

No	Factors	Major drivers	References
1	Deforestation and habitat fragmentation	Nearly 341 sq. km area under mangrove forest has decreased during 1975–2018 due to natural hazards and anthropogenic factors	57
2	Natural hazards and extreme weather	The SBR has registered a 26% increase in tropical cyclones in last 120 years. Natural hazards and extreme weather events are the main factors of mangrove degradation	22
3	Salinity intrusion	Increase in soil salinity is one of the important problems for mangrove degradation in Sundarban. Intrusion of saline water from Bay of Bengal is the reason for increased of salinity in the SBR. Increase in salinity in the Reserve is due to intrusion of saline water	58
4	Sea level rise	The rate of sea level change is higher than global average	59
5	Coastal erosion and losses of islands	Southern part of the Reserve is active delta. So, erosion and accretion are important factors for mangrove loss and gain. The average rate of erosion in SBR was found to be 5.98 m ² /year	60,18
6	Construction of earthen embankments	Construction of earthen embank is an important problem for mangrove degradation. The length of the embankments in Sundarbans alone is 3638 km which altered the tidal inundation, sediment accretion and geomorphic character of the deltaic inlets	61
7	Aqua-culture/ shrimp farming	In last few decades many agricultural land, mangrove patches and fallow areas has been converted to shrimp farming. These types of conversion have huge impact on small mangrove patches within the upper part of the Reserve	62,63
8	Population growth and built-up expansion	Many studies indicate that tremendous increase in built-up area, concrete road, brick kilns has impacted on decrease in forest areas. The Sundarban has 4.37 million population with 975 persons/sq. km population density which is a huge pressure on forest ecosystems	64,59
9	Pollutions and industrial waste	A large volume of sewage from the city of Kolkata is drained into East Kolkata Wetland. Industrial pollution from river Hooghly and arsenic pollution have become serious threat to the mangrove ecosystems and habitat	65
10	Poverty and backwardness and lack of awareness	Inadequacy of resources, poverty and remoteness are big challenges for the Sundarban community. Nearly 43.5% population lives below poverty line. So due to large scale poverty, local communities very much depend on the forest products. Most of the islands of the SBR have low health and education facilities and inadequate amenities	66,67

Table 1. Major drivers of mangrove degradation in Sundarban Biosphere Reserve.

variables were intricately linked with the tidal inundation and temperature, which can directly influence the distribution of mangrove species⁷⁷. From environmental parameters, 6 variables (Appendix 2B) were selected namely normalized difference vegetation index (NDVI), level of flood inundation, mean tidal range, storm surge height, normalized difference moisture index (NDMI), and rate of erosion/accretion (Appendix 1). Mangroves are known as salt-tolerant higher groups of coastal plants⁷⁸ which are mainly flourish in the backwater, estuaries, creeks, and lagoons. These flowering plants are inundated and exposed two times a day during high tide and low tide with coastal marine water and grow up by the mixture of the freshwater flow from upstream. Thus, water is a very important parameter for assessing mangrove habitat suitability. Six variables were selected as underwater parameters namely water surface temperature, water salinity, PH value, distance from water, drainage density, and modified normalized difference water index (Appendix 2C). All these variables are directly associated with the growth and distribution of mangrove species in Sundarban (Appendix 1). Soil is considered an influencing parameter along with climate for the distribution of flora at spatial scales^{1,79}. However, few studies have considered soil variables in modeling mangrove distribution⁵². Six important variables namely soil texture, soil salinity index, soil fertility index, sediment yield factor (Ton), electronic conductivity (EC), and vegetation soil salinity index (VSSI) were selected to examine the influence of soil (Appendix 2D).

Bioclimatic layers are one of the popular variables widely used by various scholars in order to build species distribution and ecological niche modeling⁸⁰. Many researchers have also used the bioclimatic variables for mangrove habitat suitability models because of their association with climate-related phenomena, especially temperature and precipitation⁸¹. Principle component analysis (PCA) was performed to remove the data redundancy and avoid the random error and uncertainty of the model (Appendix 3). Of the 19 variables only the most suitable 6 bioclimatic variable layers were used for this study: BIO1, Annual Mean Temperature; BIO2, Mean Diurnal Range; BIO3, Isothermality; BIO4, Temperature Seasonality, BIO12 = Annual Precipitation and BIO15 = Precipitation Seasonality (Appendix 2E) Anthropogenic activities are the main factors for the decrease in areas under mangroves globally⁸², Sundarban is no exception to this encroachment. Six disturbance variables namely distance from the road, road density, distance from Settlement, population density, distance from agriculture field, and embankment density were selected for habitat suitability analysis based on local knowledge (Appendix 2F).

Variable performance for habitat suitability model. Model collinearity among the variables was checked to avoid the negative influence of variables on the performance of the model. The predictive ability of all individual variables was tested before performing the suitability model⁸³. The linear support vector machine (LSVM) model was utilized for assessing the prediction capacity of variables. LSVM can be expressed as:

$$g(x) = \text{Sgn}(w^T a + b)$$

where, w^T is the weight matrix of the habitat suitability variables, $a = (a_1, a_2, \dots, a_{14})$ vector inputs of the variables, b is the offset from the origin of the hyper-plane. The variables i th with the weight w_i close to 0 has a smaller effect on the prediction than the one with larger values of w_i . The average merit (AM) for each variable and its ability for prediction ranged between 1 and 10 (Table 3). The values > 5 represent the potential influencing variables for habitat suitability model.

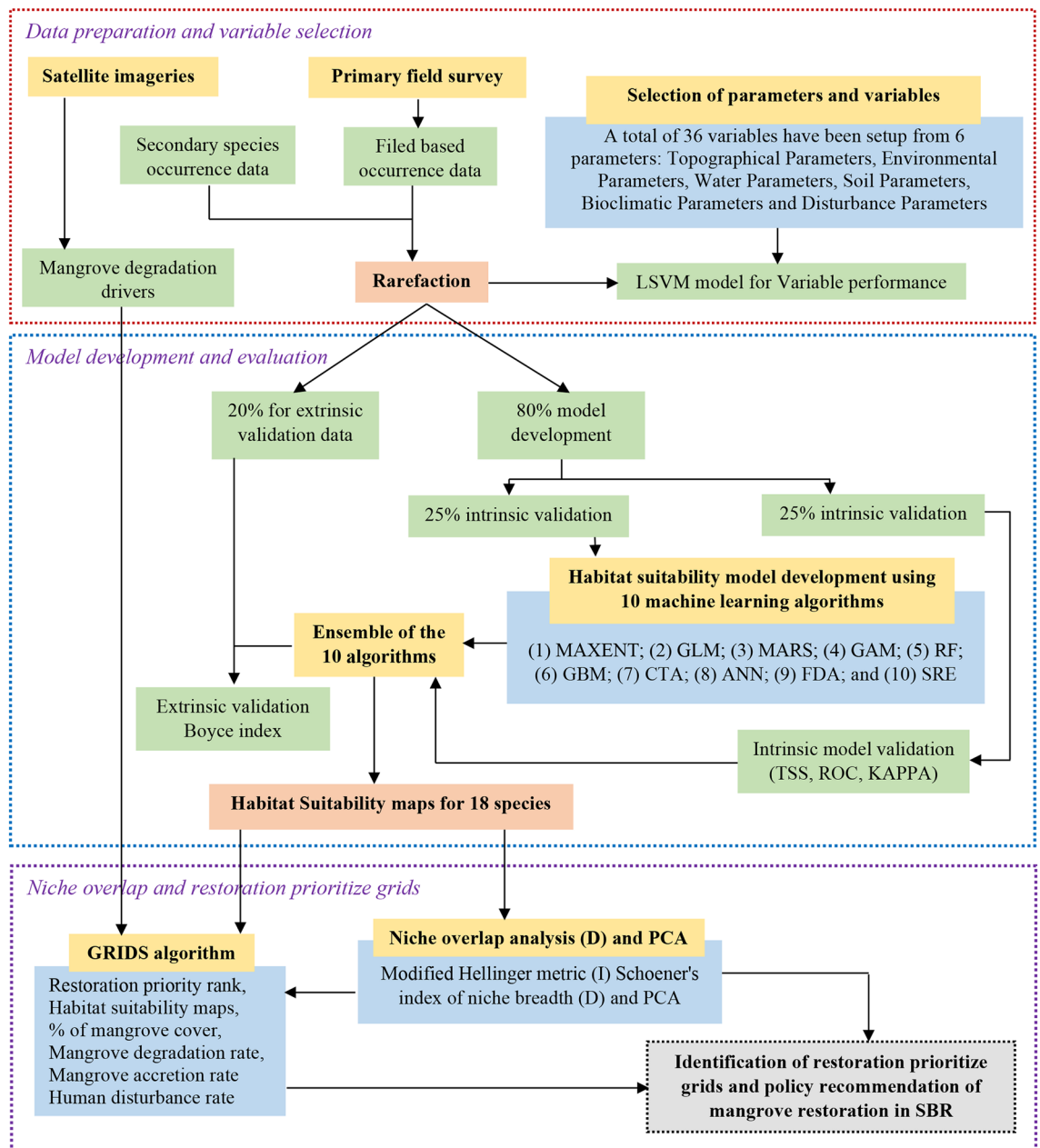


Figure 2. Methodological framework of the study.

Model development and validation. The habitat suitability models for 18 selected mangrove species were constructed using ten algorithms through the biomod2 package in R studio. Machine learning algorithms and statistical models can be set up in the R studio package for getting different complex conditions and properties which can give a possible higher accuracy on the species distribution model⁸⁴. For the present study, we performed 10-machine learning algorithms: (1) MAXENT: Maximum Entropy; (2) GLM: Generalized Linear Model; (3) MARS: Multiple Adaptive Regression Splines; (4) GAM: Generalized Additive Model; (5) RF: Random Forest; (6) GBM: Boosted Regression Trees model; (7) CTA: Classification Tree Analysis, (8) ANN: Artificial Neural Network; (9) FDA: Flexible Discriminant Analysis and (10) SRE: Surface Range Envelop model. The performance of all ten models has been assessed through the intrinsic model building process and extrinsic validation methods. For this, we have split the occurrence data into 80% for training and 20% for testing the model. For creating the intrinsic model, we randomly used 75% of the occurrence data for training the model and the remaining 25% for testing each individual model. The modeling process was run for 18 different species using 10 machine learning algorithms. In this way, 180 models were run. Cohen's Kappa (KAPPA), true skill statistic (TSS), and the receiver operating characteristics (ROC) models were used for validated all the individual models.

Finally, for the extrinsic evaluation, the algorithms which have >0.75 predicting performance for all the validation models (KAPPA, TSS, and ROC) were used to build the final ensemble model (Appendix 4). We have

Sl no	Local name	Code	Scientific name	Family	IUCN status	Occurrence data	GPS verified points	Inter tidal position
1	Tora	AR	<i>Aegialitis rotundifolia</i>	Plumbaginaceae	Near threatened	35	60	Low
2	Khalsi	AC	<i>Aegiceras corniculatum</i>	Myrsinaceae	Least concern	34	55	Middle
3	Kalo Baine	AA	<i>Avicennia alba</i>	Acanthaceae	Least concern	45	60	Low
4	Peara Baine	AM	<i>Avicennia marina</i>	Acanthaceae	Least concern	56	60	Middle
5	Jat Baine	AO	<i>Avicennia officinalis</i>	Acanthaceae	Least concern	65	40	Middle
6	Bakul Kankra/Champa	BG	<i>Bruguiera gymnorrhiza</i>	Rhizophoraceae	Least concern	64	80	Low
7	Jhanti Garan/Jele Garan	CD	<i>Ceriops decandra</i>	Rhizophoraceae	Near threatened	50	30	Low
8	Jat Garan	CT	<i>Ceriops tagal</i>	Rhizophoraceae	Least concern	38	65	Low
9	Genwa	EA	<i>Excoecaria agallocha</i>	Euphorbiaceae	Least concern	25	25	Middle, high
10	Sundari	HF	<i>Heritiera fomes</i>	Malvaceae	Endangered	10	15	Middle, high
11	Goria	KC	<i>Kandelia candel</i>	Rhizophoraceae	Least concern	23	35	Middle, high
12	Kripa/ Kripal	LR	<i>Lumnitzera racemosa</i>	Combretaceae	Least concern	40	45	Middle
13	Gol Pata	NF	<i>Nypa fruticans</i>	Arecaceae	Least concern	25	25	High
14	Hental	PP	<i>Phoenix paludosa</i>	Arecaceae	Near threatened	36	60	Middle, High
15	Garjan/ Bhara	RM	<i>Rhizophora mucronate</i>	Rhizophoraceae	Least concern	45	47	Middle
16	Tak Keora	SA	<i>Sonneratia apetala</i>	Lythraceae	Least concern	60	66	Middle
17	Dhundul	XG	<i>Xylocarpus granatum</i>	Meliaceae	Least concern	36	55	Middle, high
18	Pashur	XM	<i>Xylocarpus mekongensis</i>	Meliaceae	Near threatened	20	30	Middle, high

Table 2. Details of the selected mangrove species and the occurrence data. The species code has been prepared using the first letter of the species, hereafter this species code has been used throughout the manuscript. The species name and family name has been standardized through IUCN species list and the World Flora Online⁷⁵. The species occurrence point data has been collected from different sources like the Global Biodiversity Information Facility (GBIF) database and literature. The GPS survey was carried out to collect the maximum possible occurrence data from the field. The information about the common local habitat of the selected species was confirmed through the local people and the literature.

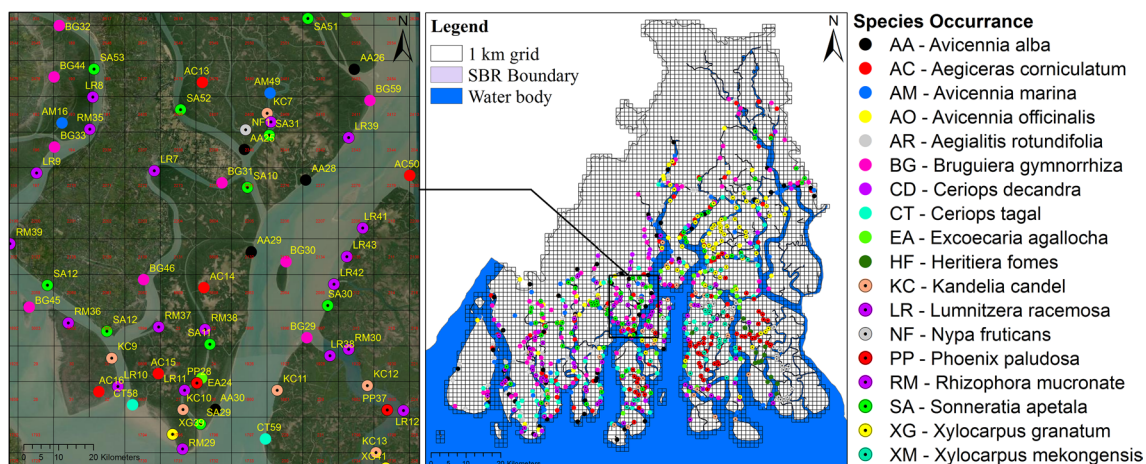


Figure 3. A grid-based field survey (2018–2019) has been conducted to collect the species occurrence data of 18 mangrove species. (The satellite images are obtained from the ArcGIS google earth base map. The species occurrence locations were collected through Garmin eTrex 32 × Outdoor Handheld GPS and the maps were prepared using ArcGIS 10.8.2 software [<https://desktop.arcgis.com>].)

No	Species	Intrinsic			Extrinsic
		ROC	TSS	KAPPA	Boyce Index
1	<i>Aegialitis rotundifolia</i>	0.923	0.914	0.936	0.874
2	<i>Aegiceras corniculatum</i>	0.895	0.901	0.914	0.841
3	<i>Avicennia alba</i>	0.856	0.914	0.987	0.879
4	<i>Avicennia marina</i>	0.954	0.939	0.964	0.903
5	<i>Avicennia officinalis</i>	0.865	0.996	0.967	0.988
6	<i>Bruguiera gymnorrhiza</i>	0.821	0.761	0.988	0.859
7	<i>Ceriops decandra</i>	0.854	0.981	0.787	0.852
8	<i>Ceriops tagal</i>	0.882	0.978	0.932	0.847
9	<i>Excoecaria agallocha</i>	0.987	0.987	0.852	0.895
10	<i>Heritiera fomes</i>	0.862	0.869	0.847	0.866
11	<i>Kandelia candel</i>	0.889	0.941	0.873	0.888
12	<i>Lumnitzera racemosa</i>	0.841	0.789	0.896	0.989
13	<i>Nypa fruticans</i>	0.832	0.919	0.853	0.788
14	<i>Phoenix paludosa</i>	0.943	0.928	0.908	0.987
15	<i>Rhizophora mucronate</i>	0.938	0.976	0.909	0.967
16	<i>Sonneratia apetala</i>	0.994	0.806	0.994	0.969
17	<i>Xylocarpus granatum</i>	0.955	0.821	0.828	0.998
18	<i>Xylocarpus mekongensis</i>	0.951	0.842	0.847	0.906
Average (\pm SE)		0.902 (0.018)	0.904 (0.017)	0.905 (0.013)	0.905 (0.011)

Table 3. Intrinsic and extrinsic model evaluation scores for each species.

used the ensemble forecast method using a weighted mean approach in biomod2 packages within R studio for producing the final habitat suitability models for all the selected species. The final habitat suitability models for all 18 species were again validated through the Boyce index (BI) using the 20% data which were kept aside for validation⁸⁵ (Table 3). The output habitat suitability raster index from the ensemble models for all species was then categorized into four classes namely highly suitable, moderately suitable, slightly suitable, and not suitable.

Niche overlap analysis and setting restoration prioritization. Modified Hellinger metric (I) and Schoener's index of niche breadth (D) were used to estimate the niche overlap among 18 species. The spatial similarity and dissimilarity of niche area for the selected species has been calculate using the raster calculator spatial overlay function in ArcGIS.

We have applied a principal component analysis (PCA) to prepare a restoration priority rank for all 18 species based on their niche characteristics, estimated potential distribution, local knowledge, and degradation status.

Identification of restoration prioritize grids. Percentage of niche overlap data, restoration priority rank for all species, habitat suitability maps for all individual species, percentage of mangrove cover, mangrove degradation rate, mangrove accretion rate, and human disturbance rate were used as input functions for identifying the restoration prioritized grids over 5609 grids in Sundarban. Grid-wise total mangrove area for the present scenario was calculated from the land use/land cover map for 2020. A grid-wise mangrove degradation rate and mangrove accretion rate have been calculated using the land use land cover change between 1975 and 2020. The human disturbance rate was calculated using the following equation:

$$\text{HDR} = \frac{(\text{BR} + \text{NP} + \text{RD} + \text{AR})}{1\text{km}} * 100$$

where HDR is the human disturbance rate, BR is the percentage of built-up area in each grid, NP is the number of populations in each grid, RD = road density in each grid and AR is the percentage of agricultural area in each grid.

For the preparation of final restoration prioritize grids we developed a species-wise grid-based algorithm using the FactomineR package in R studio. The final output of the species level restoration prioritize grids were assessed by using negative and positive indicators function. The negative indicators included: (1) > 80% present mangrove cover grid in 2020, (2) HDR value more than > 75%, (3) not suitable and slightly suitable grids, (4) natural accretion rate as > 75%. The positive indicators for this algorithm involved: (1) restoration priority rank for each individual species, (2) niche overlap grid for each individual species ($P < 0.05$), (3) highly and moderately suitability grids for each individual species, (4) degradation date > 75%.

Results

Mangrove degradation in SBR. The land use land cover change analysis revealed that the Sundarban mangrove forest has decreased by nearly 341 sq. km from 1975 to 2020 mainly due to anthropogenic encroachments, geomorphic processes, and climate change-induced hazards. The area under mangrove has transformed into swamps (176 km²) followed by water bodies (121 km²), settlements 8.6 km²), wetlands (6.5 km²), and sand

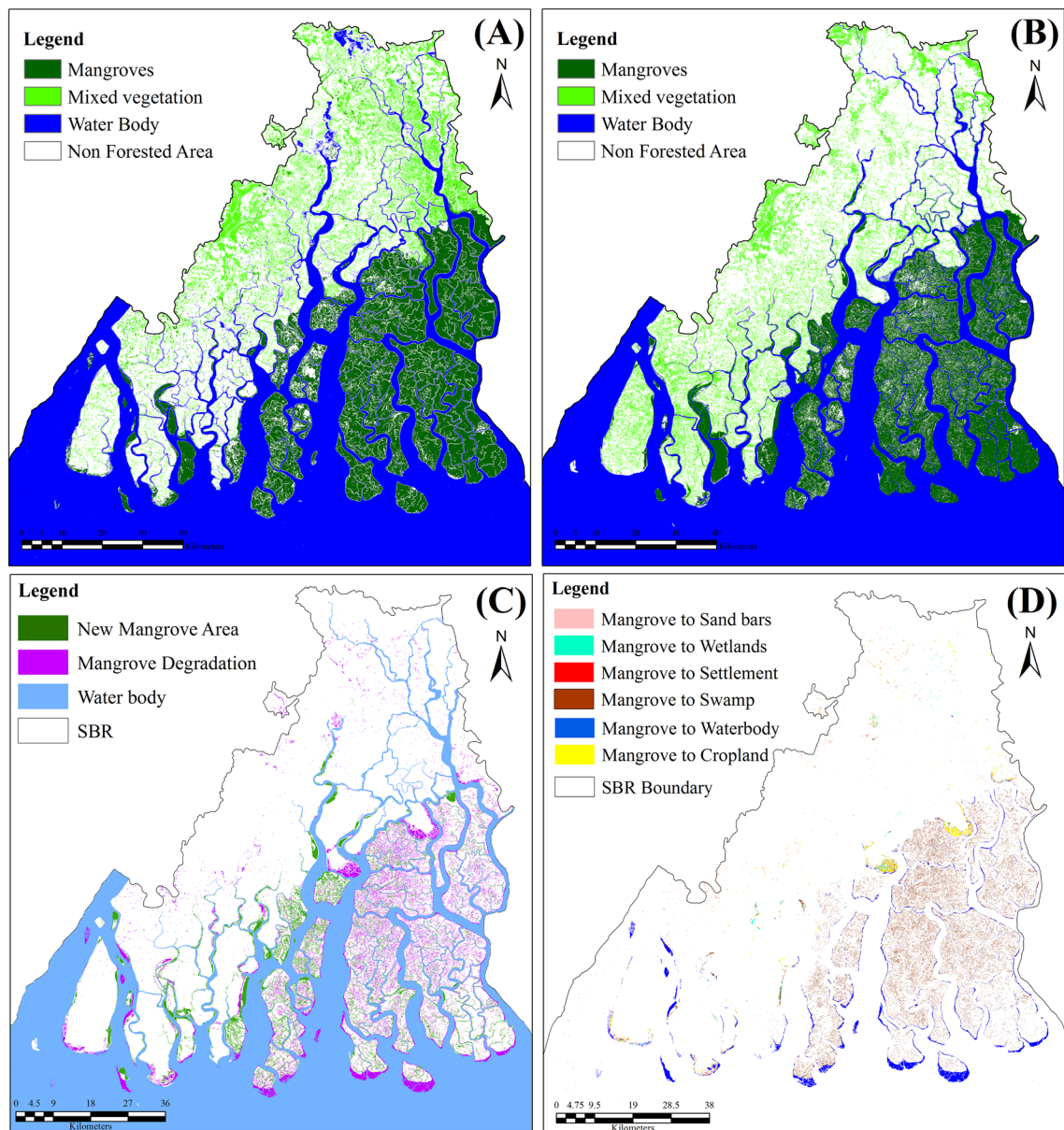


Figure 4. Mangrove cover map of Sundarban Biosphere Reserve during 1975 (A) and 2020 (B), Mangrove accretion and mangrove degradation over 1975–2020 (C) and Nature of mangrove degradation in Sundarban Biosphere Reserve (D). (The Landsat satellite images are obtained from the EarthExplorer [<https://earthexplorer.usgs.gov/>]. The maps were prepared using ERDAS IMAGINE 2014 [<https://hexagon.com/products/erdas-imagine>] and ArcGIS 10.8.2 software [<https://desktop.arcgis.com/>].)

bars (1.7 km²). The main causes of the degradation included sea-level rise, sudden disaster events, over-exploitation, and lack of sustainable adaptive strategies. The area under mangroves in the Reserve has decreased from 22.9% in 1975 to 19.8% in 2020 (Fig. 4, Appendix 5). As Sundarbans is a dynamic active delta, thus natural regeneration of new mangrove and mangrove degradation occurred together but the rate of mangrove degradation is much higher than the natural regeneration. The regeneration of new mangroves was mostly observed in the new char islands due to the depositional process (Fig. 5). The regeneration of the new mangrove rate has been increased after 1990 due to the new land reformation and conservation laws implemented by the government.

The analysis here shows that the degradation of mangroves occurring in the SBR is due to both anthropogenic and natural factors. It has been observed that about 85% area under mangroves has been converted to sand bars, wetlands, swamps, settlements, cropland, and water body. It signifies that major mangrove degradation in the SBR is due to geomorphological, hydrological, and climatic factors. However, the analysis shows that the remnant 15% area under mangroves is under degradation due to anthropogenic activities. This percentage is likely to increase more in the future with the continuous rise in the population and increasing pressure on the already existing land resources (Fig. 6). Thus, anthropogenic activities need to be checked for better management of mangroves in the region.

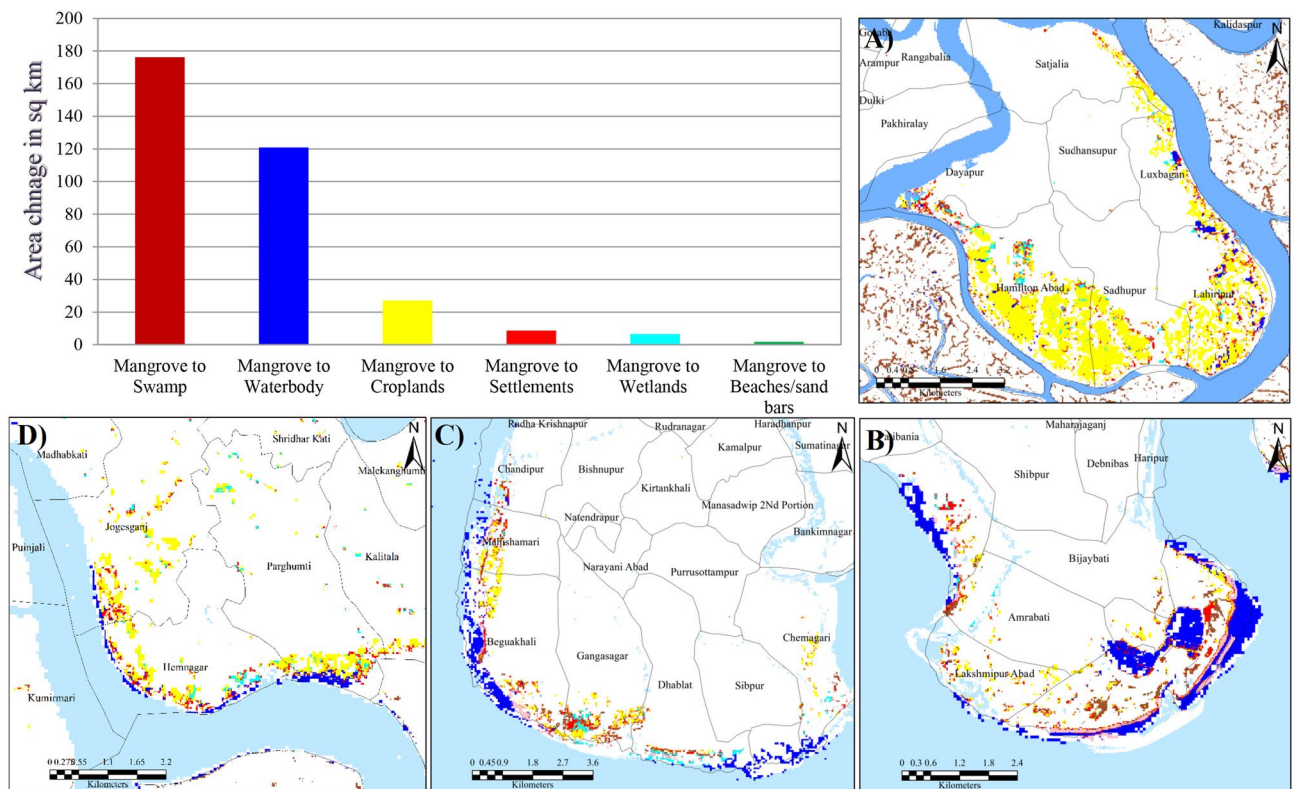


Figure 5. Change of mangrove cover under different land use/land cover classes Four important degraded mangrove hotspots in SBR; (A) Dayapur and Annpur village of Gosaba block mainly due the agricultural encroachment, (B) major built-up expansion Bakkhali area due the tourism development and coastal erosion at, (C) beaches and sand bar expansion at southern part of Sagar Island, (D) waterlogging wetlands and agricultural encroachment at Southern part of Hingalganj.). (The Landsat satellite images are obtained from the EarthExplorer [<https://earthexplorer.usgs.gov/>]. The maps were prepared using ERDAS IMAGINE 2014 [<https://hexagon.com/products/erdas-imagine>] and ArcGIS 10.8.2 software [<https://desktop.arcgis.com/>].)

Mitigation with respect to climatic factors responsible for degradation requires a significant long-term approach. However, when we consider mitigating the anthropogenic factors, it is still very much under control. A slight modification in our approach can lead to utilizing these resources to manage and conserve the rich mangrove ecosystem in this region. Most of the area under mangrove forest in the SBR is facing the threat of degradation either from natural factors or from human encroachment⁸⁶. Certain pockets in the SBR have become the hotspots of mangrove degradation.

Contribution of variables for habitat suitability models. Linear support vector machine (LSVM) model-based variable performance analysis revealed that the variables with >5.0 average have the maximum influence on mangrove habitat suitability models in the SBR (Table 4). Six bioclimatic variables have a high contribution to the habitat suitability for most of the species. Four variables from disturbance indicators have a higher contribution to the habitat suitability models namely distance from Settlement, population density, distance from crop field, and embankment density. The only slope has performed well from the topographical variables. NDVI, mean tidal range and rate of erosion/accretion among the environmental parameters were found influencing variables for habitat suitability. Distance from water and drainage density among water parameters and only soil salinity index variable from soil parameter were found good performance variables. However, the contribution of these variables varied among species.

Potential distribution of mangrove species. The final ensemble models-based habitat suitability maps for all species were categorized into four suitability classes namely highly suitable, moderately suitable, slightly suitable, and not suitable girds. The habitat suitability models revealed that the largest area of the SBR was found under highly suitable habitats (36.6%) followed by slightly suitable (32%), not suitable (16.5%), and moderately suitable (13%) (Fig. 7). The spatial distribution of the habitat suitability analysis revealed that northern and north-western parts of the Reserve were found under the not suitable category for most of the species due to human disturbance and their location away from the actual coast (Fig. 8). The individual species-level analysis also revealed that highly suitable habitats for rare and endangered species like *Heritiera fomes*, *Phoenix paludosa*, *Nypa fruticans* and *Xylocarpus mekongensis* were found in the core and buffer zone of the Sundarban which are situated within the uninhabited islands. Highly suitable habitats for the species like *Bruguiera gymnorhiza*,

Legend

- Mangrove to Beaches/sand bars
- Mangrove to Wetlands
- Mangrove to Settlement
- Mangrove to Swamp
- Mangrove to Waterbody
- Mangrove to Cropland
- Village Boundary

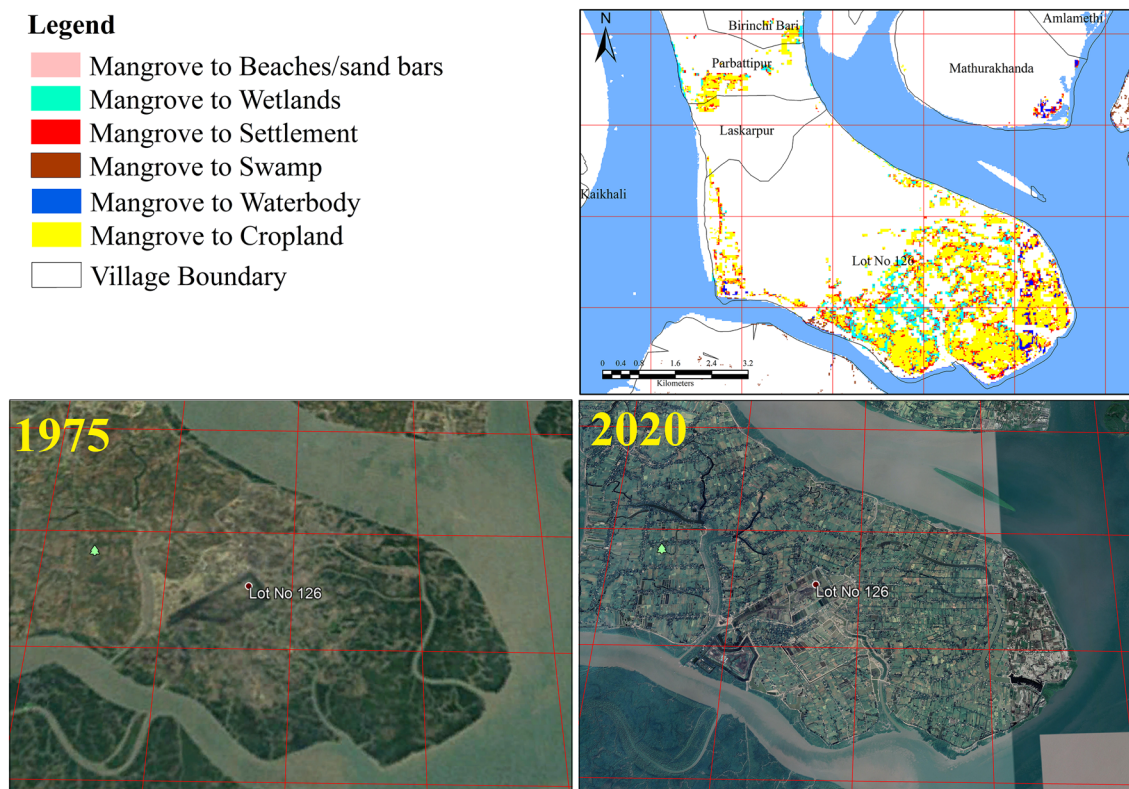


Figure 6. Deforested mangrove areas due to resettlement of partition refugees and recently tourism development (google earth images and LULC change map 1975–2020). (The satellite images are obtained from the google earth pro software [https://www.google.com/intl/en_uk/earth/about/versions/]; version 7.3 and EarthExplorer [<https://earthexplorer.usgs.gov/>]. The maps were prepared using ERDAS IMAGINE 2014 [<https://hexagon.com/products/erdas-imagine>] and ArcGIS 10.8.2 software [<https://desktop.arcgis.com/>].)

Avicennia alba, *Aegialitis rotundifolia*, *Sonneratia apetala*, *Aegiceras corniculatum*, *Rhizophora mucronate* were also found far away from the actual coast. These species were distributed in human habitats. Further, low intertidal position species like *Bruguiera gymnorrhiza*, *Ceriops decandra*, *Ceriops tagal*, *Avicennia alba* and *Aegialitis rotundifolia* were commonly found in the buffer and transitional zones of the Reserve (Fig. 7, Appendix 6).

Niche overlap and validation of models. The principal component analysis revealed that all the selected species have a specific niche area within the Reserve. Very high niche overlap was identified mostly for the same family species and sometimes for the different family species also. The grid-based spatial similarity and dissimilarity analysis revealed that the highest species level niche overlap has been found within the uninhabited areas where the species varieties are maximum within the grids. Low niche overlap among all species was found in the areas located away from the coast. The areas located near the river bank were also found to have high to moderate level spatially niche overlap (Table 5).

Restoration prioritization. The grid-based restoration prioritization analysis revealed that out of 5609 grids, 1203 grids were found restoration prioritized grids. Further, restoration prioritized grids were categorized into 8 specific prioritization categories. In the first category, two species namely *Aegialitis rotundifolia* and *Aegiceras corniculatum* from *Plumbaginaceae* and *Myrsinaceae* found highly suitable species for restoration prioritization covering an area of over 38 km² in the SBR (Fig. 9). The spatial distribution of these restoration prioritized areas showed that nearly 13% area was found under the uninhabited islands and over 87% area was found under the human habitat islands. In the second category, *Avicennia alba*, *Avicennia marina* and *Avicennia officinalis* from *Acanthaceae* family were found highly suitable species and covered an area of 74 km² in the SBR. In the third category, four species from *Rhizophoraceae* family namely *Bruguiera gymnorrhiza*, *Ceriops decandra*, *Ceriops tagal*, and *Rhizophora mucronate* were found highly suitable species and covered a 127 km² area. Again, for this category, 85% of restoration prioritized areas were found under the habitat islands. In the fourth category, the restoration prioritized areas included the endangered mangrove species in Sundarban namely *Heritiera fomes*, *Kandelia candel* and *Excoecaria agallocha* covering 35 km² areas in the core forest. The fifth category of the restoration prioritized areas included *Nypa fruticans* and *Phoenix paludosa* species that come under *Arecaceae* family which are also rare and mostly found in the core forest areas. This category covered 77 km² restoration possible areas within the uninhabited islands and most of these areas are located on the edge of the islands as these species are high intertidal species. Three important species namely *Sonneratia apetala*, *Xylocarpus granatum* and *Xylocarpus mekongensis* (Near Threatened) within *Lythraceae* and *Meliaceae* family were included in the

Sl	Parameters	Variables / Species	Species																		
			<i>Aegialitis rotundifolia</i>	<i>Aegiceras corniculatum</i>	<i>Avicennia alba</i>	<i>Avicennia marina</i>	<i>Avicennia officinalis</i>	<i>Bruguiera gymnorhiza</i>	<i>Ceriops decandra</i>	<i>Ceriops tagal</i>	<i>Excocarpus acuminatus</i>	<i>Heritiera fomes</i>	<i>Kandelia candel</i>	<i>Rhizophora mucronata</i>	<i>Nypa fruticans</i>	<i>Phoenix paludosa</i>	<i>Sonneratia apetala</i>	<i>Xylocarpus mekongensis</i>			
1	Topographical Parameters	Elevation	3.4	2.6	3.5	3.6	3.2	3.4	3.6	3.9	2.4	2.3	3.6	3.6	3.6	3.3	3.2	3.5	3.6	3.3	
2		Slope	5.4	5.1	4.2	5.5	4.6	5.2	4.7	6.2	6.2	4.5	5.8	4.7	5.4	4.3	4.6	5.9	5.1	5.1	
3		Curvature	3.1	3.8	3.5	3.9	3.5	3.5	3.9	4.2	4.0	3.7	3.9	3.9	3.9	3.6	3.5	3.8	3.9	3.6	
4		Geomorphology	4.2	4.3	4.4	4.5	4.3	4.3	4.6	4.9	4.7	4.5	4.6	4.6	4.7	4.3	4.2	5.4	4.6	4.3	
5		TWI	3.9	4.1	4.0	4.1	4.0	4.0	4.3	4.6	4.4	4.1	4.3	4.3	4.3	4.0	3.9	4.2	4.3	4.0	
6	Environmental Parameters	SPI	2.9	2.8	3.7	4.5	3.1	3.5	3.7	4.0	2.3	2.4	3.7	3.7	3.8	3.4	3.3	3.6	3.8	3.5	
7		NDVI	5.6	5.4	5.7	5.8	5.6	5.7	5.9	6.2	4.8	4.9	5.9	5.9	5.9	5.6	5.4	5.8	5.9	5.6	
8		Level of flood inundation	4.6	4.7	4.6	4.6	4.6	4.6	4.6	4.9	5.2	5.0	4.7	5.4	4.9	4.9	4.6	4.5	4.8	4.9	4.6
9		Mean tidal range	5.1	5.9	5.5	5.8	5.5	5.7	7.6	6.1	6.9	5.4	5.8	5.8	5.9	5.5	5.3	5.7	5.8	5.5	
10		Storm surge height	4.5	4.2	4.7	4.8	4.5	4.6	4.9	5.2	5.0	4.7	5.7	4.9	4.9	4.6	4.4	5.4	4.9	4.6	
11	Water Parameters	NDMI	2.3	2.9	2.6	2.9	2.4	2.6	3.0	3.3	1.6	1.5	3.0	3.0	2.5	2.7	2.9	3.0	2.7		
12		Rate of Erosion/accretion	5.6	3.4	5.6	5.7	5.4	4.6	5.6	5.7	5.4	4.6	5.4	5.4	5.4	5.1	4.9	5.4	5.5	5.2	
13		Water surface temperature	2.8	3.1	4.4	5.9	3.4	4.0	4.2	4.5	4.3	4.1	4.2	4.2	4.3	3.9	3.8	4.1	4.3	4.0	
14		Water salinity	3.5	3.0	3.6	3.7	3.4	3.5	3.8	4.1	3.9	2.5	3.8	3.8	3.8	3.5	3.4	3.7	3.8	3.5	
15		PH value	3.4	3.4	3.6	3.8	3.5	3.6	3.8	4.1	3.9	2.5	3.8	3.8	3.9	3.5	3.5	3.7	3.9	3.6	
16	Soil Parameters	Distance from water	5.6	5.1	5.8	5.9	5.5	5.7	5.9	6.2	6.0	5.0	5.9	5.9	5.9	5.6	5.4	5.8	5.9	5.6	
17		Drainage density	6.5	6.2	6.7	6.8	6.5	6.6	6.9	7.2	7.0	6.7	6.9	7.6	6.9	7.6	6.3	6.8	7.6	6.6	
18		NDWI	4.3	5.4	4.6	5.1	5.5	4.5	4.8	5.1	4.9	4.6	5.4	4.8	6.1	4.5	5.5	4.7	5.7	4.5	
19		Soil texture	3.6	3.9	3.8	3.9	3.8	3.8	4.1	4.4	4.2	3.9	4.1	4.1	4.1	3.8	3.7	4.0	4.1	3.8	
20		Soil salinity Index	5.2	5.4	5.8	5.3	5.5	5.7	5.6	6.2	6.0	5.0	5.9	5.1	5.2	5.7	5.4	5.6	5.5	5.7	
21	Bioclimatic Parameters	Soil fertility index	3.4	4.5	3.6	3.7	3.8	3.6	4.1	4.4	4.2	3.9	4.1	4.1	4.1	3.8	3.7	3.9	4.1	3.8	
22		Sediment yield factor	2.8	3.6	3.2	3.5	2.4	3.2	3.5	3.8	1.7	2.0	3.5	3.5	3.6	2.5	3.2	3.4	3.5	3.2	
23		Electronic conductivity	3.4	3.8	3.5	3.6	3.6	3.5	3.9	4.2	4.0	3.7	3.9	3.9	3.9	3.6	3.5	3.8	3.9	3.6	
24		VSSI	4.7	3.4	4.8	4.9	4.3	4.6	4.8	5.1	4.9	4.6	4.8	4.8	4.5	4.3	4.7	4.8	4.5		
25		Annual Mean Temperature (BIO1)	9.6	9.8	9.6	9.5	9.7	9.6	9.9	9.9	9.7	9.7	9.7	9.7	9.6	9.7	9.4	9.0	9.6	9.8	9.5
26	Mean Diurnal Range (BIO2)	9.1	9.5	9.3	9.4	9.3	9.3	9.6	9.9	9.7	9.4	9.6	9.6	9.6	9.3	8.8	9.5	9.6	9.3		
27	Isothermality (BIO3)	8.2	9.2	8.7	9.2	8.7	8.7	9.1	9.4	9.2	8.9	9.1	9.1	9.1	8.8	8.4	9.0	9.1	8.8		
28	Temperature Seasonality (BIO4)	7.9	8.6	8.4	8.9	8.3	8.4	8.7	9.0	8.8	7.5	8.7	8.7	8.8	8.4	8.0	8.6	8.7	8.4		
29	Annual Precipitation (BIO12)	6.5	6.7	6.9	7.2	6.7	6.8	7.1	7.4	7.2	6.9	7.1	7.6	7.1	7.6	6.5	7.0	7.6	6.8		
30	Precipitation Seasonality (BIO15)	8.2	8.1	8.4	8.5	8.2	8.3	8.6	8.9	8.7	7.4	8.6	8.6	8.6	8.3	7.9	8.5	8.6	8.3		
31	Disturbance Parameters	Distance from road	1.2	2.1	2.4	3.5	1.9	2.2	2.5	2.8	1.5	1.3	2.5	2.5	2.6	2.2	2.4	2.5	2.2		
32		Road density	0.9	1.5	1.4	1.9	1.3	1.4	1.7	2.0	1.8	1.1	1.7	1.7	1.7	1.4	1.5	1.6	1.7	1.4	
33		Distance from Settlement	7.6	8.4	7.2	6.8	7.7	7.4	7.8	8.1	7.5	7.2	7.8	7.8	7.8	7.6	7.2	7.7	7.8	7.5	
34		Population density	6.9	7.5	6.9	6.9	7.1	7.0	7.3	7.6	7.4	7.2	7.3	7.6	7.4	7.6	6.7	7.2	7.6	7.0	
35		Distance from crop field	6.4	6.4	6.6	6.7	6.5	6.5	6.8	7.1	6.9	5.0	6.8	6.8	6.8	7.6	6.2	6.7	6.8	6.5	
36	Embankment density	8.1	7.4	8.1	8.0	7.9	8.0	8.2	8.5	7.4	7.3	8.2	8.2	8.2	7.9	7.5	8.1	8.2	7.9		

Scale	Level of performance
> 7.5	Very good performance
5.0 - 7.5	Good performance
2.5 - 5.0	Average performance
< 2.5	Poor performance

Table 4. Contribution of the individual layers to the habitat suitability models (average merit (0–10), > 5.0 is good performance).

sixth category of prioritization. These species were found within the core dense forest areas and covered 107 km² restoration possible area within the core forest and edge areas of the uninhabited islands (Fig. 9).

Mixed species were put under the seventh category of restoration prioritized areas. Under this category, *Avicennia alba*, *Avicennia marina*, *Avicennia officinalis*, *Bruguiera gymnorhiza*, *Ceriops decandra*, *Ceriops tagal* and *Rhizophora mucronata* were prioritized for restoration. This category covered the highest number of possible restoration areas over 431 km² area. Most of these areas are located on inhabited islands. These restoration prioritized areas are highly associated with the recent mangrove degradation due to anthropogenic and natural causes. The eight categories of restoration prioritized areas were mainly based on the most common species found in the SBR (*Aegialitis rotundifolia*, *Aegiceras corniculatum*, *Avicennia alba*, *Avicennia marina* and *Avicennia officinalis*) and covered an area of 314 km² within the Inhabited islands. The selected species for this category are commonly used by the local people for their basic needs. This kind of restoration can be helpful for the development and regeneration of community forests which can help to reduce pressure on the core and dense forest areas (Appendix 7).

Discussion

Mangroves are threatened ecosystems globally due to their coastal location and extensive resources utilized by humans for their needs. The Sundarban mangrove is the largest single block of mangrove in the world and is highly threatened and drastically reducing at an alarming rate due to the overexploitation of resources, land transformation for aquaculture practice, increase in paddy cultivation, infrastructure development, and human settlements.

Climate change-induced coastal hazards and sea-level rise are acting as a significant challenge for mangrove species inhabited in the coastal ecosystems. Such ecosystems are facing habitat degradation due to unprecedented changes in annual mean temperature and precipitation cycle. Thus, habitat suitability modeling can effectively be utilized for conservation planning⁸⁷. However, a lack of understanding of the mangrove distribution and non-availability of occurrence data is an important challenge^{88,89} for habitat suitability modeling. To overcome this problem and to achieve maximum acceptable habitat modeling the present study developed comprehensive field-based occurrence data for 18 mangrove species for conservation and management of mangrove ecosystems

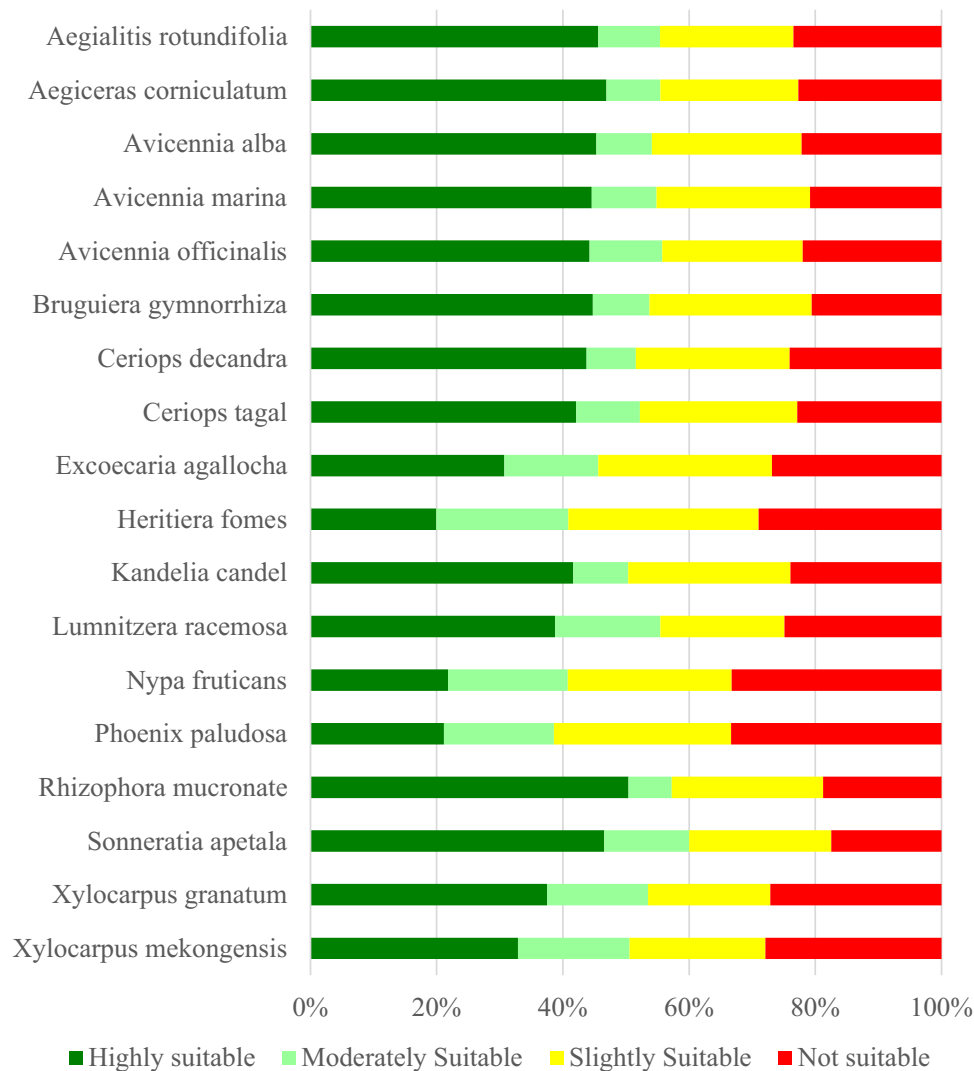


Figure 7. Species-wise percentage of area under different habitat suitability classes.

in Indian Sundarbans. The present study has adopted a 1 km GRID approach to maintaining consistency in the modeling for each stage to prepare the restoration prioritized grids for individual species. Selection of the habitat suitability variables is an important and crucial task for the construction of the species distribution models³⁶. Our result revealed that bioclimatic parameters and disturbance parameters proved to be influencing parameters for analyzing habitat suitability in the SBR. Precipitation was found more influencing variable than temperature. The finding is in line with the observation made by a few scholars on a global scale^{1,90} and few are at regional scale^{91,92}. The slope was found the most important variable among the environmental parameter for mangrove habitat suitability. Hu et al.^{4,51} and Banerjee et al.¹ found elevation an important variable. The human disturbance was also found influencing variables for mangrove habitat suitability assessment. The finding is in tune with Banerjee et al.¹, Hu et al.^{4,51} and Srivastava et al.⁹³.

The soil salinity has been significantly negatively correlated with the dominant species habitat such as *Avicennia alba*, *Avicennia marina* and *Avicennia officinalis*. Spatio-temporal variation of the salinity adversely affected the mangrove species distribution and composition. Extreme salt stress and high-level salinity affected the growth and structural development of mangrove species in Sundarban^{94,95}. A decrease in area under *Heritiera fomes* (endangered) habitat is attributed to increased salinity in the upper part of the Reserve⁹⁶. Intertidal distribution and spatial location of the Sundarban mangrove is also important for species conservation and restoration strategies such as *Heritiera fomes* and *Phoenix paludosa* in the interior part of the delta, *Excoecaria agallocha* along the riverbank while *Nypa fruticans*, *Bruguiera gymnorhiza*, *Ceriops tagal* in the moderate location of delta and *Xylocarpus* varieties and *Aegiceras corniculatum* in the more interior parts⁹⁷. The buffer zone of the Sundarban has experienced a high level of deforestation, high level of coastal erosion, high human disturbance, and niche mismatch among the mangrove species. Shortage of freshwater in follow from the upstream, changes in temperature and precipitation pattern caused the habitat shifting and niche mismatching between same family species in the Sundarban. Therefore, the areas that are highly suitable but do not currently have extensive mangrove forests may be locations where mangroves had been previously deforested. These areas could be potential habitats for

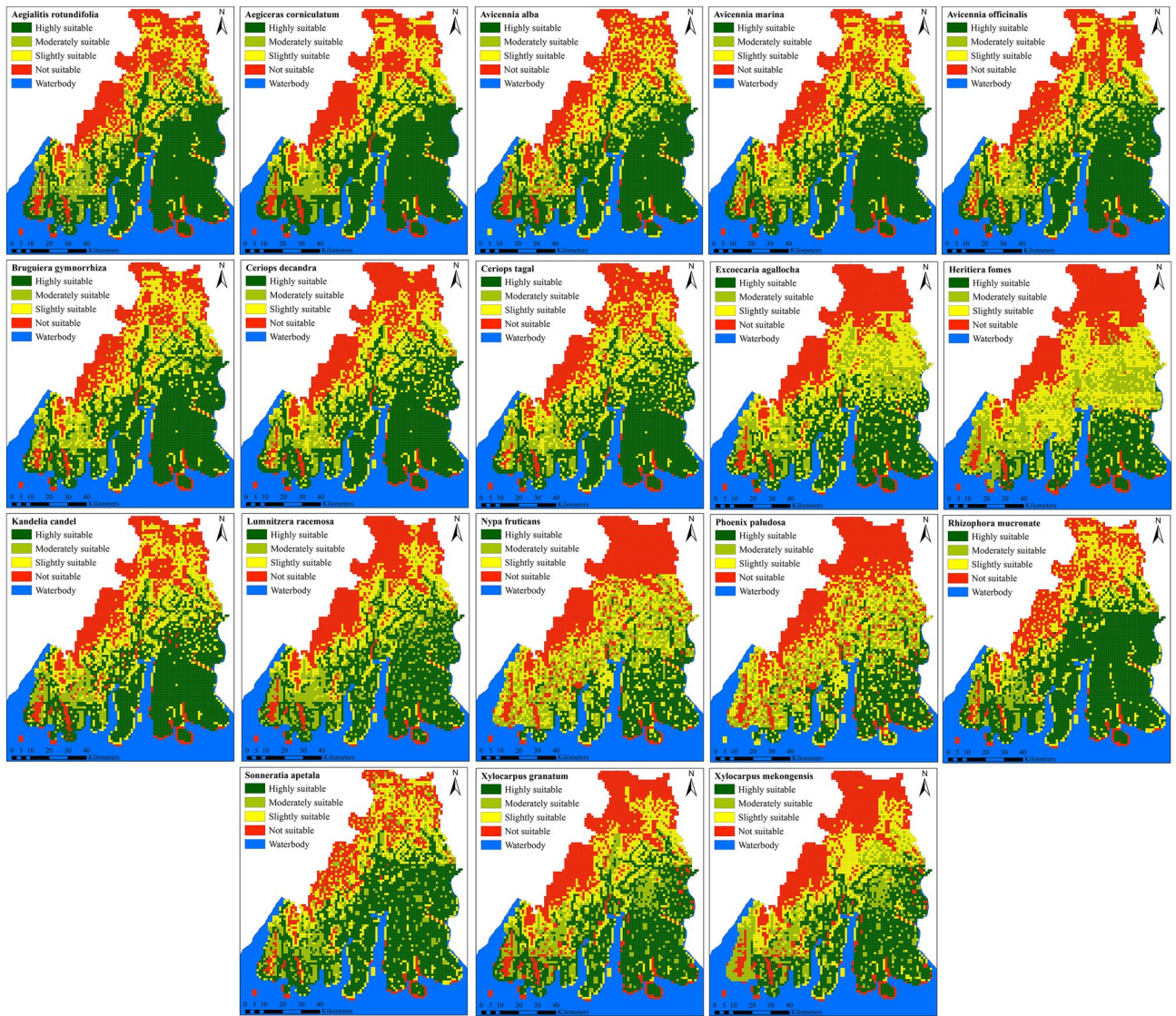


Figure 8. Habitat suitability maps for the selected 18 true mangrove species in the Sundarban Biosphere Reserve. The maps were prepared using ArcGIS 10.8.2 software (<https://desktop.arcgis.com/>.)

Species	AR	AC	AA	AM	AO	BG	CD	CT	EA	HF	KC	LR	NF	PP	RM	SA	XG	XM	Avg.D
AR		0.859	0.825	0.795	0.841	0.901	0.802	0.679	0.551	0.652	0.696	0.785	0.789	0.854	0.902	0.725	0.805	0.702	0.774
AC	0.885		0.812	0.797	0.963	0.852	0.935	0.671	0.788	0.741	0.665	0.741	0.731	0.574	0.752	0.654	0.955	0.744	0.773
AA	0.841	0.752		0.741	0.941	0.963	0.924	0.817	0.685	0.699	0.864	0.862	0.652	0.658	0.712	0.852	0.871	0.801	0.800
AM	0.905	0.732	0.698		0.966	0.771	0.845	0.765	0.427	0.552	0.767	0.801	0.761	0.765	0.702	0.811	0.844	0.802	0.751
AO	0.979	0.715	0.758	0.795		0.852	0.863	0.838	0.577	0.852	0.561	0.831	0.705	0.419	0.698	0.806	0.944	0.935	0.759
BG	0.935	0.905	0.738	0.702	0.852		0.935	0.753	0.638	0.741	0.714	0.582	0.831	0.821	0.689	0.685	0.925	0.885	0.775
CD	0.756	0.852	0.889	0.735	0.635	0.741		0.852	0.532	0.685	0.739	0.874	0.823	0.561	0.762	0.712	0.759	0.735	0.743
CT	0.889	0.964	0.797	0.541	0.953	0.639	0.847		0.684	0.756	0.859	0.652	0.746	0.829	0.712	0.765	0.888	0.712	0.772
EA	0.621	0.663	0.902	0.905	0.625	0.654	0.724	0.665		0.784	0.727	0.864	0.761	0.896	0.862	0.763	0.895	0.652	0.771
HF	0.625	0.523	0.552	0.621	0.652	0.698	0.711	0.741	0.914		0.896	0.685	0.558	0.788	0.812	0.714	0.652	0.762	0.705
KC	0.741	0.702	0.854	0.836	0.825	0.774	0.699	0.698	0.934	0.915		0.687	0.685	0.707	0.752	0.665	0.732	0.902	0.773
LR	0.752	0.756	0.762	0.769	0.858	0.789	0.741	0.954	0.842	0.841	0.785		0.841	0.728	0.789	0.712	0.814	0.852	0.802
NF	0.687	0.714	0.881	0.778	0.911	0.915	0.789	0.915	0.741	0.874	0.698	0.746		0.681	0.832	0.822	0.725	0.832	0.803
PP	0.741	0.752	0.952	0.854	0.673	0.836	0.885	0.874	0.895	0.716	0.741	0.791	0.695		0.563	0.652	0.698	0.654	0.764
RM	0.789	0.955	0.962	0.803	0.875	0.854	0.896	0.789	0.874	0.851	0.852	0.703	0.941	0.968		0.621	0.785	0.917	0.853
SA	0.852	0.889	0.841	0.801	0.828	0.826	0.827	0.902	0.821	0.615	0.698	0.763	0.852	0.685	0.725		0.755	0.795	0.789
XG	0.741	0.784	0.967	0.896	0.845	0.815	0.841	0.809	0.841	0.741	0.799	0.786	0.874	0.745	0.765	0.712		0.711	0.808
XM	0.753	0.896	0.951	0.839	0.908	0.741	0.955	0.801	0.789	0.841	0.810	0.784	0.721	0.904	0.815	0.712	0.795		0.829
Avg.I	0.794	0.785	0.832	0.776	0.832	0.795	0.839	0.803	0.749	0.763	0.761	0.76	0.761	0.733	0.746	0.729	0.815	0.793	

Table 5. Estimates of niche overlap between selected species: upper diagonals: Schoener's index of niche breadth (D); lower diagonals: modified Hellinger metric (I). The green colour indicate significance at $p < 0.05$ level.

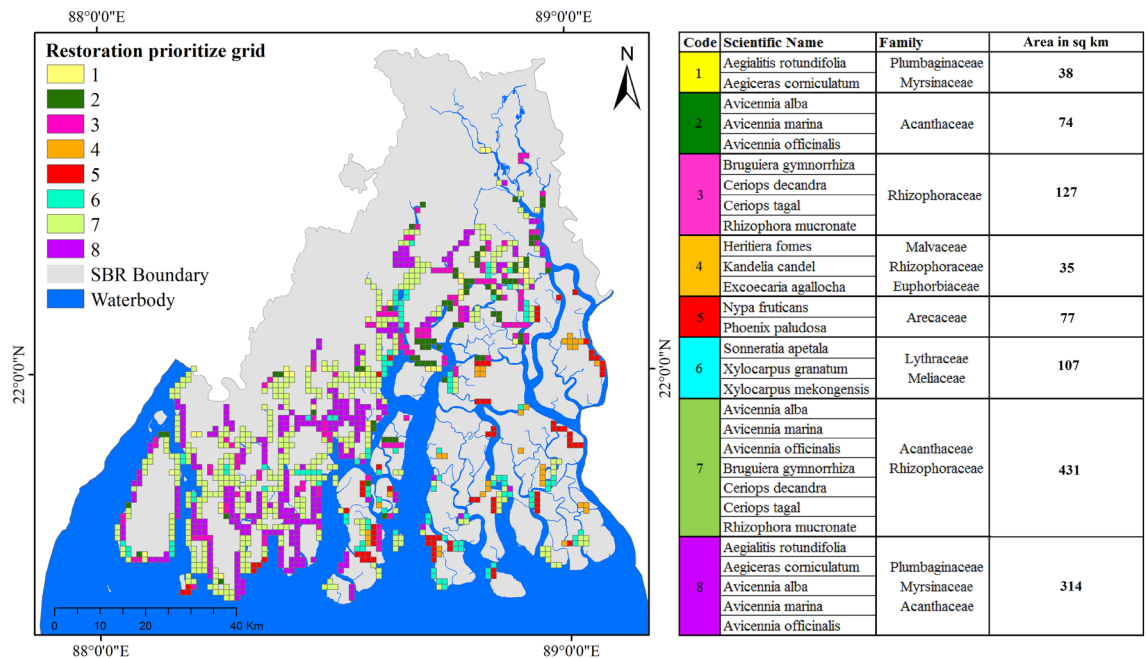


Figure 9. Species wise restoration prioritize grids for 18 selected mangrove species (The map were prepared using ArcGIS 10.8.2 software [<https://desktop.arcgis.com>].)

mangroves. Further, low niche overlap and moderate suitability of maximum species in the eastern part of the Reserve indicated low freshwater supply in the eastern tributaries and streams due to the construction of Farakka Barrage in Murshidabad and thus caused heavy siltation within the creeks and internal channels⁹⁸. Thus, a decrease in freshwater supply could lead to an increase in salinity and push the endangered and threatened species over the edge of abrogation. The increased rate of tropical cyclones during the last few decades has hugely impacted the mangrove density and created a canopy gap in the core forest areas⁹⁹.

Sundarban is one of the most densely populated deltas in the world. A high population has created a huge threat to the species. More than 85% of people in this biosphere region are directly or indirectly dependent on the mangrove ecosystem⁵⁵. The species like *Avicennia alba*, *Avicennia marina*, *Avicennia officinalis* and *Rhizophora mucronate* are being threatened due to overexploitation¹⁰⁰. Thus, the forest dependency of the local people needs to be decreased. Introduction of mangrove social forestry, stakeholder commitment, ecosystems-based community development is required for sustainable mangrove management^{101,102}. Further, urban expansion is divested threat to the mangrove ecosystem globally. In Brazil, more than 30% area under mangroves has been destroyed due to urbanization¹⁰³. In Honduras, 9.1% area under mangroves has been destroyed¹⁰⁴. Urban expansion has greatly impacted the mangrove trees in Mumbai city¹⁰⁵. Expansion of Kolkata metropolitan areas towards the southwards and many new megaprojects like Joka urban development, a new airport in Bhanga, the rapid growth of Baruipur and Canning are alarming threats to the Sundarban mangrove ecosystem^{106,107}. In spite of various laws promulgated by the government for restricting the encroachment of mangrove habitats, this is still being made in the buffer and core forest areas. So, identified restoration prioritized areas can help in the sustainable management and restoration of mangroves in Indian Sundarban.

Our species distribution models and the restoration prioritized locations are based on the 1 km grids-based model output which may not be effective for the real-world implication of restoration programme for few cases. For example, 100% area under all the recommended grids may not be restored due to the real-world shape and other limitations. In our species distribution models, bioclimatic and the environmental factors have played an important role habitat suitability analysis, thus, major uncertainties can be distinguished for the raster binary data of other parameters. Though, biases and uncertainties for the SDM outputs can vary with species and different models used in this study may further improve different grain size output of SDM models. The northern part of the Biosphere Reserve has very sparse mangrove patches mixed with other forest areas and this may affect the result of the habitat distribution models. Due to the restriction in the core forest area under the Sundarban national park, we have collected species samples only in the edge of the delta and this may be a limitation for SDM models for few species. Our ecological niche overlay analysis is based on the habitat suitability models and we did not carry out further field verification for validating the niche overlay assessment.

Policy recommendations for conservation and restoration

Sundarban is a heterogeneous region and several physical and anthropogenic causes are held responsible for mangrove degradation. However, since the last few decades, afforestation and plantation activities have been carried out in various degraded patches involving multiple stakeholders. The study has suggested 10 tier policy measures for the successful restoration of mangroves in the SBR:

1. The first steps of a restoration programme should be directed toward the identification of the environmental stressors and potential threats to restoration sites^{27,108,109}. In Sundarban many past replantation programmes have failed due to a lack of proper knowledge, research communication, and documentation on mangrove ecology^{110–112}. Thus, the present study recommended a holistic mangrove restoration plan by bridging ecology, society, and economics. So, setting appropriate restoration goals and creating separate standard operating procedures are essential for the restoration of different nature of degraded mangrove areas.
2. Nature-Based Solutions (NbS)¹¹³ for mangrove regeneration and regional seas programmes (RSP) should be indicated for innovation on mangrove regeneration^{114–116}. Mangrove conservation and regeneration can be one of the best opportunities to improve the blue carbon stock which can be restored by the investment of resources for both training and building of technical and institutional capacity. NbS is a very smarter and cheap solution for restoration and conservation programmes¹¹⁷. Thus, NbS can be recommended for the Sundarban mangrove restoration programme and this can help to control stormwater intrusion and control the soil salinity in the region, which can help to improve the regeneration of mangrove species occurrence in the degraded areas.
3. Mangrove ecological integrity, community awareness, sustainable harvesting, community participation, stakeholder integration, and investment from the corporate sectors are the most important areas for the promotion of mangrove restoration and conservation^{118,119}. Further, this can help to contribute to the sustainable development goals (SDGs) including inclusive and fair quality education towards mangrove restoration¹²⁰, responsibility to make and use of mangrove resources, conservation and sustainable use of the coastal resources, protecting, restoring, and promoting sustainable ecosystems and sustainable management of forest, implementing international mangrove regeneration programme and introducing the local and global partnership to protect and restore the mangrove ecosystems.
4. The surrounding of aquaculture ponds, wetlands, and swamp areas can be considered the most useful areas for mangrove restoration. This kind of mangrove restoration approach is a great success in the coastal areas of China¹²¹. Some experts also advised that the restoration of coastal wetlands mangrove adopted aquaculture ponds can be helpful for future mangrove restoration^{122,123}. Recently Indian Sundarbans has been declared as a Ramsar site, so restoration of coastal wetlands could be a cost-effective approach for both mangrove and wetland restoration.
5. Effective disaster and socioeconomic management schemes and strategies, and proper monitoring of mangroves can be helpful in maintaining the mangrove cover and conserving large tracts¹²⁴. Identifying appropriate restoration techniques will be incisive for the rejuvenation of mangroves in already degraded areas. Fishbone techniques in high tidal areas and Parallel restoration techniques in low and middle tidal areas may help in restoring mangroves within the restoration prioritized areas in the Reserve¹²⁵.
6. The habitat of *Xylocarpus mekongensis* and *Xylocarpus granatum* is restricted to a few patches within the core forest areas as these species have been targeted for illegal felling by the wood due to high price in the market¹²⁶. Furthermost of this species has been infected by heart root disease¹²⁷. Thus, restoration is recommended for this species within the core forest canopy gap areas.
7. Tourist willingness to pay for restoration (WTP) is an adaptive and useful approach for sustainable ecosystem restoration in Sundarbans which can help revenue generation, community engagement, livelihood options, wellbeing, and decent tourist activity for coastal ecosystems^{128,129}.
8. Participatory Rural Appraisal (PRA) and Joint Forest Management (JFM) can be adopted along with the community-based mangrove reforestation (CBMR) programme and NGO initiated plantation and management within buffer and transition zones of the reserve^{130–133}. Thus, the present study proposed to adopt CBMR approach along with JFM and PRA methods within the restoration prioritized areas located in the transitional zone and *Aegialitis rotundifolia*, *Aegiceras corniculatum*, *Avicennia alba*, *Avicennia marina* species can be adopted for this types of the restoration programme.
9. Few experimental studies have established that native grasses offered osmotic protection from tidal surges and create a favorable environment for the root establishment of mangrove species^{134,135,136}. Thus, halotolerant grasses along with the mangrove species within the high eroded land areas and mudflat areas should be planted for successful restoration. The southern islands of the Sundarban are under serious threat due to storm surges, high tide, high wave height, erosion, and frequent cyclone. Thus, native grasses plantations can be very effective for these islands. These have been paid very less attention to mangrove regeneration compared to the northern part of the SBR.
10. Finally, the adoption of the multidisciplinary approach involving state governments, universities, research institutions, NGOs, and local organizations may provide the adaptive pathways to successful mangrove restoration in the SBR.

Conclusion

Identification, mapping, and evaluation of the suitable habitat for mangrove species and finding restoration prioritized areas may prove an important scientific framework for sustainable mangrove conservation and protection. Our study has prepared extensive field-based species occurrence data and used 36 variables from six different parameters to develop higher accuracy habitat suitability maps for 18 true mangrove species in the Sundarbans Biosphere Reserve. We constructed ensemble models using 10 machine learning algorithms our finding identified restoration prioritized areas in the Sundarban. The findings revealed that slope and temperature have greatly influenced the mangrove habitat of the selected species. Further, human disturbance variables have also influenced the species distribution and niche lap for the Sundarban mangrove. A total of 1203 km² restoration prioritize areas have been identified and prepared a species-based strategy for future restoration in the

Sundarban. Strong technical and species-based knowledge is important for successful mangrove restoration^{45,137}. Thus, the findings of our study will help restoration organizations in selecting species and suitable locations for the successful restoration programme. The national, state and local government authorities of India have launched different programmes for the Sundarban Biosphere Reserve for protecting, restoring and managing of the mangrove ecosystem. The Ministry of Environment, Forests and climate change of India has established a National Mangrove Committee in 1979 to protect and restore the mangrove ecosystems in India and established a large number of mangrove restoration program but most of the programme are unable to achieve their target. Thus, the present study can be helpful for understanding the nature of species distribution and a systematic way for the selection of species within the restoration prioritized areas. The findings of the present study are also in line with the ecosystem design approaches¹³⁸, land suitability approaches⁴⁶, and evidence-based restoration policies⁴⁸ for scientific mangrove restoration programmes. We argue that the findings of this study can be useful for preparing a decision-making plan to prioritize conservation and mangrove restoration targets in Sundarban. The methodology adopted in this study can be applied in other geographical regions for conservation, restoration, and sustainable management of the mangrove ecosystem.

Data availability

All datafile produced by this study will be published in the University of Manchester official website datafile portal after publication of the main manuscript: [https://www.research.manchester.ac.uk/portal/en/researchers/mehebeb-sahana\(e6116fb8-31a7-4c83-a3ab-fbbfea3f36bb\)/datasets.html](https://www.research.manchester.ac.uk/portal/en/researchers/mehebeb-sahana(e6116fb8-31a7-4c83-a3ab-fbbfea3f36bb)/datasets.html). The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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References

- Banerjee, A. K. *et al.* Setting the priorities straight—Species distribution models assist to prioritize conservation targets for the mangroves. *Sci. Total Environ.* **806**, 150937 (2022).
- Duke, N. C. *et al.* A world without mangroves?. *Science* **317**(5834), 41–42 (2007).
- Friess, D. A. Ecosystem services and disservices of mangrove forests: Insights from historical colonial observations. *Forests* **7**(9), 183 (2016).
- Hu, W. *et al.* Mapping the potential of mangrove forest restoration based on species distribution models: A case study in China. *Sci. Total Environ.* **748**, 142321 (2020).
- Blankespoor, B., Dasgupta, S. & Lange, G. M. Mangroves as a protection from storm surges in a changing climate. *Ambio* **46**(4), 478–491 (2017).
- FAO. *The World's Mangroves 1980–2005. Food and Agriculture Organization of the United Nations, Rome.* <http://www.fao.org/3/a1427e/a1427e00.htm>. (2007).
- Abd-El Monsef, H., Hassan, M. A. & Shata, S. Using spatial data analysis for delineating existing mangroves stands and siting suitable locations for mangroves plantation. *Comput. Electron. Agric.* **141**, 310–326 (2017).
- Donato, D. C. *et al.* Mangroves among the most carbon-rich forests in the tropics. *Nat. Geosci.* **4**, 293–297. <https://doi.org/10.1038/ngeo1123> (2011).
- Aheto, D. W. *et al.* Community-based mangrove forest management: Implications for local livelihoods and coastal resource conservation along the Volta estuary catchment area of Ghana. *Ocean Coast. Manag.* **127**, 43–54 (2016).
- Costanza, R. *et al.* Changes in the global value of ecosystem services. *Glob. Environ. Chang.* **26**, 152–158. <https://doi.org/10.1016/j.gloenvcha.2014.04.002> (2014).
- Stephanie, S. R. *et al.* Conservation and restoration of mangroves: Global status, perspectives, and prognosis. *Ocean Coast. Manag.* **154**, 72–82. <https://doi.org/10.1016/j.ocecoaman.2018.01.009> (2018).
- Friess, D. A. *et al.* Mangroves give cause for conservation optimism, for now. *Curr. Biol.* **30**, R153–R154 (2020).
- Valiela, I., Bowen, J. L. & York, J. K. Mangrove forests: One of the world's threatened major tropical environments: At least 35% of the area of mangrove forests has been lost in the past two decades, losses that exceed those for tropical rain forests and coral reefs, two other well-known threatened environments. *Bioscience* **51**, 807–815. [https://doi.org/10.1641/0006-3568\(2001\)051\[0807:MFOOTW\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2001)051[0807:MFOOTW]2.0.CO;2) (2001).
- Feller, I. C. *et al.* Biocomplexity in mangrove ecosystems. *Ann. Rev. Mar. Sci.* **2**, 395–417 (2010).
- Polidoro, B. A. *et al.* The loss of species: Mangrove extinction risk and geographic areas of global concern. *PLoS ONE* **5**, e10095 (2010).
- IUCN. *Global Assessments of Mangrove Losses and Degradation*, 2016; https://www.iucn.org/sites/dev/files/content/documents/mangroveloss-brief-4pp-19.10.low_.pdf.
- Sreelekshmi, S., Nandan, S. B., Kaimal, S. V., Radhakrishnan, C. K. & Suresh, V. R. Mangrove species diversity, stand structure and zonation pattern in relation to environmental factors—a case study at Sundarban delta, east coast of India. *Reg. Stud. Mar. Sci.* **35**, 101111 (2020).
- Sahana, M. *et al.* Assessing coastal island vulnerability in the Sundarban Biosphere Reserve, India, using geospatial technology. *Environ. Earth Sci.* **78**(10), 1–22 (2019).
- FSI. *India State of Forest Report. Forest Survey of India, Dehradun* (2017).
- Ellison, A. M., Mukherjee, B. B. & Karim, A. Testing patterns of zonation in mangroves: Scale dependence and environmental correlates in the Sundarbans of Bangladesh. *J. Ecol.* **88**(5), 813–824 (2000).
- Sahana, M., Rehman, S., Sajjad, H. & Hong, H. Exploring effectiveness of frequency ratio and support vector machine models in storm surge flood susceptibility assessment: A study of Sundarban Biosphere Reserve, India. *CATENA* **189**, 104450 (2020).
- Sahana, M. & Sajjad, H. Vulnerability to storm surge flood using remote sensing and GIS techniques: A study on Sundarban Biosphere Reserve, India. *Rem. Sens. Appl. Soc. Env.* **13**, 106–120 (2019).
- Chowdhury, M. Q. *et al.* Nature and periodicity of growth rings in two Bangladeshi mangrove species. *IAWA J.* **29**(3), 265–276 (2008).
- Sarker, S. K., Reeve, R., Thompson, J., Paul, N. K. & Matthiopoulos, J. Are we failing to protect threatened mangroves in the Sundarbans world heritage ecosystem?. *Sci. Rep.* **6**(1), 1–12 (2016).
- Iftikhar, M. S. & Saenger, P. Vegetation dynamics in the Bangladesh Sundarbans mangroves: A review of forest inventories. *Wetlands Ecol. Manag.* **16**(4), 291–312 (2008).
- Siddiqi, N. A. In *Mangrove forestry in Bangladesh, Institute of Forestry and Environmental Sciences. University of Chittagong, Chittagong, Bangladesh* 201 (2001).

27. Lewis, R. R. III. Ecological engineering for successful management and restoration of mangrove forests. *Ecol. Eng.* **24**(4), 403–418 (2005).
28. Peterson, T. A., Papeş, M. & Eaton, M. Transferability and model evaluation in ecological niche modeling: A comparison of GARP and Maxent. *Ecography* **30**, 550–560. <https://doi.org/10.1111/j.0906-7590.2007.05102.x> (2007).
29. Stockwell, D. & Peters, D. The GARP modelling system: problems and solutions to automated spatial prediction. *Int. J. Geogr. Inf. Sci.* **13**, 143–158. <https://doi.org/10.1080/136588199241391> (1999).
30. Guisan, A. & Thuiller, W. Predicting species distribution: Offering more than simple habitat models. *Ecol. Lett.* **8**, 993–1009. <https://doi.org/10.1111/j.1461-0248.2005.00792.x> (2005).
31. Phillips, S. J., Anderson, R. P. & Schapire, R. E. Maximum entropy modeling of species geographic distributions. *Ecol. Model.* **190**, 231–259. <https://doi.org/10.1016/j.ecolmodel.2005.03.026> (2006).
32. Feng, Z. *et al.* Dynamics of mangrove forests in Shenzhen Bay in response to natural and anthropogenic factors from 1988 to 2017. *J. Hydrol.* **591**, 125271. <https://doi.org/10.1016/j.jhydrol.2020.125271> (2020).
33. Kaky, E. & Gilbert, F. Using species distribution models to assess the importance of Egypt's protected areas for the conservation of medicinal plants. *J. Arid Environ.* **135**, 140–146. <https://doi.org/10.1016/j.jaridenv.2016.09.001> (2016).
34. Pecchi, M. *et al.* Species distribution modelling to support forest management A literature review. *Ecol. Model.* **411**, 108817 (2019).
35. Spiers, J. A., Oatham, M. P., Rostant, L. V. & Farrell, A. D. Applying species distribution modelling to improving conservation-based decisions: A gap analysis of Trinidad and Tobago's endemic vascular plants. *Biodivers. Conserv.* **27**, 2931–2949 (2018).
36. Elith, J. & Leathwick, J. R. Species distribution models: Ecological explanation and prediction across space and time. *Annu. Rev. Ecol. Evol. Syst.* **40**, 677–697. <https://doi.org/10.1146/annurev.ecolsys.110308.120159> (2009).
37. Fois, M., Cuenca-Lombrana, A., Fenu, G. & Bacchetta, G. Using species distribution models at local scale to guide the search of poorly known species: Review, methodological issues and future directions. *Ecol. Model.* **385**, 124–132 (2018).
38. Gilani, H., Goheer, M. A., Ahmad, H. & Hussain, K. Under predicted climate change: Distribution and ecological niche modeling of six native tree species in Gilgit-Baltistan, Pakistan. *Ecol. Indic.* **111**, 106049 (2020).
39. Ellison, A. M., Felson, A. J. & Friess, D. A. Mangrove rehabilitation and restoration as experimental adaptive management. *Front. Mar. Sci.* **7**, 327. <https://doi.org/10.3389/fmars.2020.00327> (2020).
40. Ellison, A. M. Mangrove restoration: Do we know enough?. *Restor. Ecol.* **8**(3), 219–229 (2000).
41. Brown, B., Fadillah, R., Nurdin, Y., Soulsby, I., & Ahmad, R. CASE STUDY: Community Based Ecological Mangrove Rehabilitation (CBEMR) in Indonesia. In *From small (12–33 ha) to medium scales (400 ha) with pathways for adoption at larger scales (> 5000 ha)*. SAPI EN. S. *Surveys and Perspectives Integrating Environment and Society* 7.2 (2014).
42. Rodríguez-Rodríguez, J. A., Mancera-Pineda, J. E. & Tavera, H. Mangrove restoration in Colombia: Trends and lessons learned. *For. Ecol. Manage.* **496**, 119414 (2021).
43. Romañach, S. S. *et al.* Conservation and restoration of mangroves: Global status, perspectives, and prognosis. *Ocean Coast Manag.* **154**, 72–82. <https://doi.org/10.1016/j.ocecoaman.2018.01.009> (2018).
44. Sulochanan, B. *et al.* Water and sediment quality parameters of the restored mangrove ecosystem of Gurupura River and natural mangrove ecosystem of Shambhavi River in Dakshina Kannada, India. *Marine Pollution Bulletin* **176**, 113450. <https://doi.org/10.1016/j.marpolbul.2022.113450> (2022).
45. Lovelock, C. E., Barbier, E. & Duarte, C. M. Tackling the mangrove restoration challenge. *PLoS Biol.* **20**(10), e3001836 (2022).
46. Lovelock, C. E. & Brown, B. M. Land tenure considerations are key to successful mangrove restoration. *Nature Ecol. Evol.* **3**(8), 1135–1135 (2019).
47. Su, J., Friess, D. A. & Gasparatos, A. A meta-analysis of the ecological and economic outcomes of mangrove restoration. *Nat. Commun.* **12**(1), 1–13 (2021).
48. Lee, S. Y., Hamilton, S., Barbier, E. B., Primavera, J. & Lewis, R. R. Better restoration policies are needed to conserve mangrove ecosystems. *Nature Ecol. Evol.* **3**(6), 870–872 (2019).
49. Chakraborty, S., Sahoo, S., Majumdar, D., Saha, S. & Roy, S. Future Mangrove suitability assessment of Andaman to strengthen sustainable development. *J. Clean. Prod.* **234**, 597–614 (2019).
50. Charrua, A. B., Bandeira, S. O., Catarino, S., Cabral, P. & Romeiras, M. M. Assessment of the vulnerability of coastal mangrove ecosystems in Mozambique. *Ocean Coast. Manag.* **189**, 105145 (2020).
51. Hu, W. *et al.* Predicting potential mangrove distributions at the global northern distribution margin using an ecological niche model: Determining conservation and reforestation involvement. *For. Ecol. Manage.* **478**, 118517 (2020).
52. Rodríguez-Medina, K., Yañez-Arenas, C., Peterson, A. T., Euán Ávila, J. & Herrera-Silveira, J. Evaluating the capacity of species distribution modeling to predict the geographic distribution of the mangrove community in Mexico. *PLoS ONE* **15**(8), e0237701 (2020).
53. Wang, Y. *et al.* Simulating spatial change of mangrove habitat under the impact of coastal land use: Coupling MaxEnt and Dyna-CLUE models. *Sci. Total Environ.* **788**, 147914 (2021).
54. Gopal, B. & Chauhan, M. Biodiversity and its conservation in the Sundarban mangrove ecosystem. *Aquat. Sci.* **68**(3), 338–354 (2006).
55. Sahana, M., Rehman, S., Paul, A. K. & Sajjad, H. Assessing socio-economic vulnerability to climate change-induced disasters: Evidence from Sundarban Biosphere Reserve, India. *Geol. Ecol. Landsc.* **5**(1), 40–52 (2021).
56. Giri, C. *et al.* Mangrove forest distributions and dynamics (1975–2005) of the tsunami-affected region of Asia. *J. Biogeogr.* **35**(3), 519–528 (2008).
57. Giri, C., Pengra, B., Zhu, Z., Singh, A. & Tieszen, L. L. Monitoring mangrove forest dynamics of the Sundarbans in Bangladesh and India using multi-temporal satellite data from 1973 to 2000. *Estuar. Coast. Shelf Sci.* **73**(1–2), 91–100 (2007).
58. Islam, S. N. & Gnauck, A. Effects of salinity intrusion in mangrove wetlands ecosystems in the Sundarbans: An alternative approach for sustainable management. *Wetlands Monitor. Modell. Manag.* **2007**, 315 (2007).
59. Hazra, S., Ghosh, T., DasGupta, R. & Sen, G. Sea level and associated changes in the Sundarbans. *Sci. Cult.* **68**(9/12), 309–321 (2002).
60. Purkait, B. Coastal erosion in response to wave dynamics operative in Sagar Island, Sundarban delta, India. *Front. Earth Sci. China* **3**(1), 21–33 (2009).
61. World Bank (2014). Building resilience for sustainable development of the Sundarbans: Strategy report (No. 20116; World Bank Other Operational Studies). The World Bank Group. <https://ideas.repec.org/p/wbk/wboper/20116.html>.
62. Das, M. A. H. U. A. Impact of commercial coastal fishing on the environment of Sundarbans for sustainable development. *Asian Fish. Sci.* **22**(1), 157–167 (2009).
63. Hoq, M. E. An analysis of fisheries exploitation and management practices in Sundarbans mangrove ecosystem, Bangladesh. *Ocean Coast. Manag.* **50**(5–6), 411–427 (2007).
64. Census of India (2011). Primary census abstract, census of India. The government of India, Registrar General and Census Commissioner of India, Ministry of Home Affairs, New Delhi, India. <https://censusindia.gov.in/nada/index.php/catalog/41021>
65. Chowdhury, A. & Maiti, S. K. Assessing the ecological health risk in a conserved mangrove ecosystem due to heavy metal pollution: A case study from Sundarbans Biosphere Reserve, India. *Hum. Ecol. Risk Assess. Int. J.* **22**(7), 1519–1541 (2016).
66. Hajra, R. *et al.* Unravelling the association between the impact of natural hazards and household poverty: Evidence from the Indian Sundarban delta. *Sustain. Sci.* **12**(3), 453–464 (2017).

67. Sahana, M. & Sajjad, H. Assessing Influence of Erosion and Accretion on Landscape Diversity in Sundarban Biosphere Reserve, Lower Ganga Basin: A Geospatial Approach. In *Quaternary Geomorphology in India*, (eds Das, B. *et al.*) (Springer, Cham, 2019). https://doi.org/10.1007/978-3-319-90427-6_10 (2018).
68. Chaudhuri, A. B., Choudhury, A., Hussain, Z., & Acharya, G. *Mangroves of the Sundarbans. Vol. I. India, The IUCN Wetlands Programme 247* (IUCN, 1994).
69. GBIF.org. GBIF Occurrence Download, 2018. <https://www.gbif.org/>. *Avicennia marina*: <https://doi.org/10.15468/dl.vml00q> and *R. mucronata*: <https://doi.org/10.15468/dl.ewnqnm> (accessed March 2019).
70. Mandal, R. N. & Naskar, K. R. Diversity and classification of Indian mangroves: A review. *Trop. Ecol.* **49**(2), 131–146 (2008).
71. Mandal, A. K., & Nandi, N. C. *Fauna of Sundarban mangrove ecosystem, west Bengal, India, Vol. 3* (Zoological Survey of India, 1989).
72. Mitra, A. & Pal, S. *The Oscillating Mangrove Ecosystem and the Indian Sundarbans* (WWF-India-WBSO, 2002).
73. Naskar, K., & Guha Bakshi, D. N. *Mangrove Swamps of the Sundarbans* (Naya Prokash, 1987).
74. Barik, J. & Chowdhury, S. True mangrove species of Sundarbans delta, West Bengal, eastern India. *Check list* **10**(2), 329–334. <https://doi.org/10.15560/10.2.329> (2014).
75. IUCN 2018. *The IUCN Red List of Threatened Species. Version 2018. 2018*. Electronic database accessible, accessed 15 Nov 2018; <http://www.iucnredlist.org>.
76. Guyon, I. & Elisseeff, A. An introduction to variable and feature selection. *J. Mach. Learn. Res.* **3**, 1157–1182 (2003).
77. Cavanaugh, K. C. *et al.* Climate-driven regime shifts in a mangrove–salt marsh ecotone over the past 250 years. *Proc. Natl. Acad. Sci.* **116**(43), 21602–21608 (2019).
78. Naskar, K. & Mandal, R. *Ecology and Biodiversity of Indian Mangroves, Vol. 1* (Daya Books, 1999).
79. Figueiredo, F. O. *et al.* Beyond climate control on species range: The importance of soil data to predict distribution of Amazonian plant species. *J. Biogeogr.* **45**(1), 190–200 (2018).
80. Booth, T. H., Nix, H. A., Busby, J. R. & Hutchinson, M. F. BIOCLIM: The first species distribution modelling package, its early applications and relevance to most current MAXENT studies. *Divers. Distrib.* **20**(1), 1–9 (2014).
81. Asbridge, E., Lucas, R., Ticehurst, C. & Bunting, P. Mangrove response to environmental change in Australia's Gulf of Carpentaria. *Ecol. Evol.* **6**(11), 3523–3539 (2016).
82. He, Q. & Silliman, B. R. Climate change, human impacts, and coastal ecosystems in the Anthropocene. *Curr. Biol.* **29**(19), R1021–R1035. <https://doi.org/10.1016/j.cub.2019.08.042> (2019).
83. Beaumont, L. J., Hughes, L. & Poulsen, M. Predicting species distributions: Use of climatic parameters in BIOCLIM and its impact on predictions of species' current and future distributions. *Ecol. Model.* **186**(2), 251–270 (2005).
84. Guisan, A., Thuiller, W. & Zimmermann, N. E. *Habitat Suitability and Distribution Models: With Applications in R* (Cambridge University Press, 2017).
85. Boyce, M. S., Vernier, P. R., Nielsen, S. E. & Schmiegelow, F. K. A. Evaluating resource selection functions. *Ecol. Model.* **157**, 281–300 (2002).
86. STR Annual Report. In *Conservator of Forest & Field Director, Sundarban Tiger Reserve. Canning, West Bengal, India: Directorate of Forests, Government of West Bengal* (2013–2014).
87. Segurado, P. & Araujo, M. B. An evaluation of methods for modelling species distributions. *J. biogeogr.* **31**(10), 1555–1568. <https://doi.org/10.1111/j.1365-2699.2004.01076.x> (2004).
88. Kadmon, R., Farber, O. & Danin, A. A systematic analysis of factors affecting the performance of climatic envelope models. *Ecol. Appl.* **13**(3), 853–867. [https://doi.org/10.1890/1051-0761\(2003\)013\[0853:ASAOFA\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2003)013[0853:ASAOFA]2.0.CO;2) (2003).
89. Wisz, M. S. *et al.* Effects of sample size on the performance of species distribution models. *Divers. Distrib.* **14**(5), 763–773. <https://doi.org/10.1111/j.1472-4642.2008.00482.x> (2008).
90. Simard, M. *et al.* Mangrove canopy height globally related to precipitation, temperature and cyclone frequency. *Nat. Geosci.* **12**(1), 40–45 (2019).
91. Hogue, A. M., Hill, A. E., Simpson, J. H. & Bowers, D. G. Diurnal and tidal variation of temperature and salinity in the Ponta Rasa mangrove swamp, Mozambique. *Estuar. Coast. Shelf S.* **49**(2), 251–264. <https://doi.org/10.1006/ecss.1999.0499> (1999).
92. Sanders, C. J. *et al.* Are global mangrove carbon stocks driven by rainfall? *J. Geophys. Res. Biogeosci.* **121**(10), 2600–2609. <https://doi.org/10.1002/2016JG003510> (2016).
93. Srivastava, J., Farooqui, A. & Seth, P. Pollen-vegetation relationship in surface sediments, Coringa mangrove ecosystem, India: palaeoecological applications. *Palynology* **43**(3), 451–466. <https://doi.org/10.1080/01916122.2018.1458755> (2019).
94. Nandy, P., Das, S., Ghose, M. & Spooner-Hart, R. Effects of salinity on photosynthesis, leaf anatomy, ion accumulation and photosynthetic nitrogen use efficiency in five Indian mangroves. *Wetlands Ecol. Manage.* **15**(4), 347–357 (2007).
95. Washington, W., Kathiresan, K. & Bingham, B. L. Biology of mangroves and mangrove ecosystems. *Adv. Mar. Biol.* **2001**, 40 (2001).
96. Blasco, F., Aizpuru, M. & Gers, C. Depletion of the mangroves of Continental Asia. *Wetlands Ecol. Manage.* **9**(3), 255–266 (2001).
97. Datta, D. & Deb, S. Forest structure and soil properties of mangrove ecosystems under management scenarios: Experiences from the intensely humanized landscape of Indian Sunderbans. *Ocean Coast. Manage.* **140**, 22–33 (2017).
98. Wahid, S. M., Babel, M. S. & Bhuiyan, A. R. Hydrologic monitoring and analysis in the Sundarbans mangrove ecosystem, Bangladesh. *J. Hydrol.* **332**(3–4), 381–395 (2007).
99. Iftikhar, M. S. & Islam, M. R. Degeneration of Bangladesh's Sundarbans mangroves: A management issue. *Int. For. Rev.* **6**(2), 123–135 (2004).
100. Saenger, P. *Mangrove Ecology, Silviculture, and Conservation* (Kluwer Academic Publishers, 2002).
101. Feka, Z. N. Sustainable management of mangrove forests in West Africa: A new policy perspective?. *Ocean Coast. Manage.* **116**, 341–352. <https://doi.org/10.1016/j.ocecoaman.2015.08.006> (2015).
102. Giri, S. *et al.* A study on abundance and distribution of mangrove species in Indian Sundarban using remote sensing technique. *J. Coast Conserv.* **18**, 359–367. <https://doi.org/10.1007/s11852-014-0322-3> (2014).
103. Moschetto, F. A., Ribeiro, R. B. & De Freitas, D. M. Urban expansion, regeneration and socioenvironmental vulnerability in a mangrove ecosystem at the southeast coastal of São Paulo, Brazil. *Ocean Coast. Manage.* **24**, 105418. <https://doi.org/10.1016/j.ocecoaman.2020.105418> (2020).
104. Tuholska, C., Tane, Z., López-Carra, D., Roberts, D. & Cassels, S. Thirty years of land use/cover change in the Caribbean: Assessing the relationship between urbanization and mangrove loss in Roatán, Honduras. *Appl. Geogr.* **88**, 84–93. <https://doi.org/10.1016/j.apgeog.2017.08.018> (2017).
105. Kantharajan, G. *et al.* Vegetative structure and species composition of mangroves along the Mumbai coast, Maharashtra, India. *Reg. Stud. Mar. Sci.* **19**, 1–8 (2018).
106. Marcinko, C. L. *et al.* The development of a framework for the integrated assessment of SDG trade-offs in the Sundarban Biosphere Reserve. *Water* **13**(4), 528 (2021).
107. Sahana, M. *et al.* Assessing Wetland ecosystem health in Sundarban Biosphere Reserve using pressure-state-response model and geospatial techniques. *Remot. Sens. Appl. Soc. Environ.* **26**, 100754. <https://doi.org/10.1016/j.rsase.2022.100754> (2022).
108. Saha, S., & Choudhury, A. Vegetation Analysis of Restored And Natural Mangrove Forest In Sagar Island, Sundarbans, East Coast of India. *Indian J. Mar. Sci.* **24**, 133–136. <http://nopr.niscpr.res.in/bitstream/123456789/37297/1/IJMS%2024%283%29%20133-136.pdf> (1995).

109. Balke, T. & Friess, D. A. Geomorphic knowledge for mangrove restoration: A pantropical categorization. *Earth Surf. Process. Landf.* **41**, 231–239. <https://doi.org/10.1002/esp.3841> (2016).
110. Alongi, D. M. Mangrove forests of timor-leste: Ecology, degradation and vulnerability to climate change. In *Mangrove ecosystems of Asia* 199–212 (Springer, 2014).
111. Biswas, S. R., Mallik, A. U., Choudhury, J. K. & Nishat, A. A unified framework for the restoration of Southeast Asian mangroves—bridging ecology, society and economics. *Wetlands Ecol. Manage.* **17**(4), 365–383 (2009).
112. Dubey, S. K., Censkowsky, U., Roy, M., Chand, B. K., & Dey, A. Framework for rapid evaluation of a mangrove restoration site: A case study from Indian Sundarban. In *Sabkha Ecosystems* 363–378 (Springer, 2019).
113. Islam, M. M. & Shamsuddoha, M. Coastal and marine conservation strategy for Bangladesh in the context of achieving blue growth and sustainable development goals (SDGs). *Environ. Sci. Pol.* **87**, 45–54. <https://doi.org/10.1016/j.envsci.2018.05.014> (2018).
114. Bosire, J., Celliers, L., Groeneveld, J., Paula, J. & Schleyer, M.H. *Regional State of the Coast Report-Western Indian Ocean. UNEP-Nairobi Convention and WIOMSA* 546 (2015).
115. Owuor, M. A., Mulwa, R., Otieno, R., Icely, J. & Newton, A. Valuing mangrove biodiversity and ecosystem services: A deliberative choice experiment in Mida Creek, Kenya. *Ecosyst. Serv.* **40**, 101040. <https://doi.org/10.1016/j.ecoser.2019.101040> (2019).
116. Barwell, L. *et al.* (2018). Regional State of the Coast Report Western Indian Ocean. The United Nations Environment Programme/Nairobi Convention Secretariat. <https://wedocs.unep.org/handle/20.500.11822/9700?show=full>
117. de Jesús Arce-Mojica, T., Nehren, U., Sudmeier-Rieux, K., Miranda, P. J. & Anhuf, D. Nature-based solutions (NbS) for reducing the risk of shallow landslides: where do we stand? *Int. J. disaster risk reduct.* **41**, 101293. <https://doi.org/10.1016/j.ijdr.2019.101293> (2019).
118. Bardhan, M. An empirical study on mangrove restoration in Indian Sundarbans—a community-based environmental approach. In *Modern Cartography Series, vol. 10* 387–405 (Academic Press, 2021).
119. Kumar, M. C., Bholanath, M. & Debashis, S. Study on utility and revival through community approach in sundarbans mangrove. *Int. J. Soc. Sci.* <https://doi.org/10.5958/2321-5771.2014.00101.X> (2014).
120. Chakraborty, S. K., Giri, S., Chakravarty, G. & Bhattacharya, N. Impact of eco-restoration on the biodiversity of Sundarbans Mangrove Ecosystem, India. *Water Air Soil Pollut. Focus* **9**(3), 303–320 (2009).
121. Paulson Institute. *Research report on mangrove protection and restoration strategy in China*, 2020; <https://paulsoninstitute.org/wpcontent/uploads/2020/06/%E4%B8%AD%E5%9B%BD%E7%BA%A2%E6%A0%91%E6%9E%97%E4%BF%9D%E6%8A%A4%E4%B8%8E%E6%81%A2%E5%A4%8D%E6%88%98%E7%95%A5%E7%A0%94%E7%A9%B6%E6%8A%A5%E5%91%8A%E2%80%94%E6%91%98%E8%A6%81%E7%89%88.pdf>.
122. Fan, H. Q. & Wang, W. Q. Some thematic issues for mangrove conservation in China. *J. Xiamen Univ. Nat. Sci* **56**, 323–330. <https://doi.org/10.6043/j.issn.0438-0479.201612003> (2017).
123. Wang, W., Fu, H., Lee, S. Y., Fan, H. & Wang, M. Can strict protection stop the decline of mangrove ecosystems in China? From rapid destruction to rampant degradation. *Forests* **11**, 55. <https://doi.org/10.3390/f11010055> (2020).
124. Roy, A. K. D. & Alam, K. Participatory forest management for the sustainable management of the sundarbans mangrove forest. *Am. J. Env. Sci.* **8**(5), 549–555. <https://doi.org/10.3844/ajessp.2012.549.555> (2012).
125. Selvam, V. *et al.* In *Toolkit for establishing coastal bioshield. M. S. Swaminathan Research Foundation, Centre for Research on Sustainable Agriculture and Rural Development* (2005).
126. Raju, J. S. N. *Xylocarpus* (Meliaceae): A less-known mangrove taxon of the Godavari estuary, India. *Curr. Sci.* **84**(7), 879–881. <https://www.currentscience.ac.in/Volumes/84/07/0879.pdf> (2003).
127. Siddiqui, A. H. & Khair, A. Infestation status of heart rot disease of pasur (*Xylocarpus mekongensis*), tree in the sundarbans. *Indian For.* **138**(2), 165–168 (2012).
128. Iqbal, M. & Hossain, M. Tourists' willingness to pay for restoration of Sundarbans Mangrove forest ecosystems: A contingent valuation modeling study. *Env. Dev. Sustain.* **2022**, 1–22 (2022).
129. Ekka, A. & Pandit, A. Willingness to pay for restoration of natural ecosystem: A study of Sundarban mangroves by contingent valuation approach. *Indian J. Agric. Econ.* **67**, 902 (2012).
130. Datta, D., Chattopadhyay, R. N. & Guha, P. Community based mangrove management: A review on status and sustainability. *J. Env. Manag.* **107**, 84–95. <https://doi.org/10.1016/j.jenvman.2012.04.013> (2012).
131. Ghosh, A., Schmidt, S., Fickert, T. & Nusser, M. The Indian Sundarban mangrove forests: History, utilization, conservation strategies and local perception. *Diversity* **7**(2), 149–169. <https://doi.org/10.3390/d7020149> (2015).
132. Ranjan, R. Optimal mangrove restoration through community engagement on coastal lands facing climatic risks: The case of Sundarbans region in India. *Land Use Policy* **81**, 736–749 (2019).
133. Dutta, M., Roy, S. & Nibirh, S. Joint forest management and forest protection committees: Negotiation systems and the design of incentives—a case study of West Bengal. *Electron. J.* <https://doi.org/10.2139/ssrn.2245965> (2001).
134. McKee, K. L., Rooth, J. E. & Feller, I. C. Mangrove recruitment after forest disturbance is facilitated by herbaceous species in the Caribbean. *Ecol. Appl.* **17**(6), 1678–1693 (2007).
135. Begam, M. *et al.* Native salt-tolerant grass species for habitat restoration, their acclimation and contribution to improving edaphic conditions: A study from a degraded mangrove in the Indian Sundarbans. *Hydrobiologia* **803**(1), 373–387 (2017).
136. Donnelly, M. & Walters, L. Trapping of Rhizophora mangle propagules by coexisting early successional species. *Estuaries Coasts* **37**, 1562–1571 (2014).
137. Ren, H. *et al.* *Sonneratia apetala* Buch. Ham in the mangrove ecosystems of China: An invasive species or restoration species?. *Ecol. Eng.* **35**(8), 1243–1248 (2009).
138. Cheong, S.-M. *et al.* Coastal adaptation with ecological engineering. *Nature Clim. Change* **3**, 787–791. <https://doi.org/10.1038/nclimate1854> (2013).

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Competing interests

The authors declare no competing interests.

Additional information

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