WPS8532

Policy Research Working Paper 8532

Aquatic Salinization and Mangrove Species in a Changing Climate

Impact in the Indian Sundarbans

Anirban Mukhopadhyay
David Wheeler
Susmita Dasgupta
Ajanta Dey
Istiak Sobhan

WORLD BANK GROUP
Development Economics
Development Research Group
July 2018

Policy Research Working Paper 8532

Abstract

This paper contributes to understanding the physical and economic effects of salinity diffusion and planning for appropriate adaptation for managing the Sundarbans in a changing climate, with a focus on the West Bengal portion of the tidal-wetland forest delta. A five-step analysis, using high-resolution spatial assessments, was conducted to get a broader picture of the migration of mangrove species with progressive aquatic salinization in a changing climate. A current (2015) basemap, with overlays of salinity tolerance for various mangrove species, and projected location-specific aquatic salinity for 2050 were used to predict the impacts of salinization on mangrove species by 2050. The results indicate patterns of gains and losses, with dominance of salt-tolerant species at the expense of freshwater species. Overall, the impact of salinity-induced mangrove migration will have an adverse effect on the flow of ecosystem services, ultimately impacting the livelihood options of poor households. Resources should be directed to developing alternative livelihoods for mangrove-dependent households. In addition, efforts are needed to develop sustainable policies that incorporate rising salinity, changes in mangrove dynamics, and the welfare impacts on poor communities.

This paper is a product of the Development Research Group, Development Economics. It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are also posted on the Web at http://www.worldbank.org/research. The authors may be contacted at sdasgupta@worldbank.org.

Aquatic Salinization and Mangrove Species in a Changing Climate: Impact in the Indian Sundarbans

Anirban Mukhopadhyay
Senior Researcher, School of Oceanographic Studies, Jadavpur University

David Wheeler
Senior Fellow, World Resources Institute

Susmita Dasgupta*
Lead Environmental Economist, Development Research Group, World Bank

Ajanta Dey
Joint Secretary, Nature Environment & Wildlife Society

Istiak Sobhan
Environment Specialist, World Bank

JEL Classification: Q23; Q54; Q57

Keywords: Mangrove, climate change, aquatic salinization, mangrove-dependent livelihood, Sundarbans

This research was conducted under the South Asia Water Initiative - Sundarbans Landscape.

*Corresponding Author: Susmita Dasgupta. Email: sdasgupta@worldbank.org;
Telephone: 1-202-473-2679; Fax: 1-202-522-2714

We would like to extend our special thanks to Dr. Kakoli Sengupta for her help with the data. Our sincere thanks go to Dr. Anamitra Anurag Danda and Dr. Sunando Bandyopadhyay for their expert opinion. We are thankful to Norma Adams for her help with the editing and Polly Means for her help with the graphics.

1. Introduction

Climate change poses several threats to the Sundarbans—the world's largest remaining contiguous mangrove forest and one of its richest ecosystems.[1] These threats include rise in sea level, rise in air and water temperature, and change in the frequency and intensity of precipitation and storms, among others (Alongi 2008). Worldwide, globally important mangrove ecosystems are at increasing risk from inundation, salinization, and other potential impacts of climate-driven sea-level rise.[2] Rise in sea level may even threaten the survival of mangroves if their landward migration is obstructed by a lack of adequate and suitable space for expansion and the rate of sea-level rise is greater than that at which mangroves can migrate (Ellison and Stoddart 1991; Semeniuk 1994; UNEP 1994; McLeod and Salm 2006; Lange et al. 2010). Historically, mangroves have shown considerable resilience to fluctuations in sea level (Alongi 2002; Gilman et al. 2006; Erwin 2009); however, their future adaptation may not keep pace.

The extent of permanent inundation of the Sundarbans from climate-driven sea-level rise is uncertain as the region is located in the active Ganges-Brahmaputra Delta, where sedimentation is still occurring. For the Sundarbans, increased saltwater intrusion from sea-level rise and shortage of nutrients from freshwater flows are the greatest challenges in a changing climate (Dasgupta et al. 2015a, b; IWM 2003; Peterson and Shireen 2001; SRDI 2000, 2010; UK DEFR 2007). Healthy mangroves require daily fluxes from both ocean and freshwater sources. The Sundarbans is already facing a serious freshwater shortage during the dry season (October–May) because some major distributaries of the Ganges that feed the region are currently moribund. Anticipated alteration of riverine flows from the Himalayas and an increase in sea level will intensify salinity intrusion as climate change continues (Dasgupta et al. 2015a, b; Dasgupta et al. 2014). The associated increase in aquatic salinization will inevitably change the hydrological regime of the Sundarbans and alter its forest ecology (Barik et al. 2018; Dasgupta, Sobhan, and Wheeler 2017).

These changes have significant implications for the present and future management of the Sundarbans, as well as the forest-based livelihoods of tens of thousands of poor inhabitants. Therefore, understanding the physical and economic effects of salinity diffusion and planning for appropriate adaptation will be critical for management of the Sundarbans, as well as for long-term development and poverty alleviation in adjacent areas. This paper attempts to contribute to this understanding by assessing the impact of aquatic salinization on the spatial distribution of mangrove species. The main focus of this analysis is on the Sundarbans in India, which accounts for 40 percent (about 4,200 km^2) of the 10,200 km^2 mangrove wetlands.

---

[1] The Sundarbans is a tidal-wetland forest delta along the Bay of Bengal, spanning coastal segments of Bangladesh and India.

[2] Recent research suggests that sea level may rise by 1 m or more in the 21st century, which would increase the vulnerable population to about 1 billion by 2050 (Hansen et al. 2011; Vermeer and Rahmstorf 2009; Pfeffer, Harper, and O'Neel 2008; Rahmstorf 2007; Dasgupta et al. 2009; Brecht et al. 2012).

2. Data

The Indian Sundarbans Biosphere Reserve comprises a 9,630 km^2 area, with a core zone of 1,700 km^2. The remainder is subdivided into development (5,300 km^2), managed (2,400 km^2), and restoration (230 km^2) zones (Nandy and Kuswaha 2011). Its international border with Bangladesh is demarcated by the Harinbhanga River (known as the Raymangal, Kalindi, and Ichhamati in its north). Blasco, Saenger, and Janodet (1996) reported that the Indian mangroves consist of 58 species; Rao (1986) reported 60 species, while Naskar (1988) reported 35 true mangroves, mentioning that the Indian mangroves are richer than any other tropical mangrove formations in the world. Although ecologically resilient, the mangrove species of the Indian Sundarbans are highly sensitive to hydrological changes (Blasco, Saenger, and Janodet 1996), particularly to the salinity profile of the adjacent water column or soils. Climate- and/or subsidence-driven, sea-level rise is perhaps the single most important factor that threatens the health of the mangroves (McLeod and Salm 2006). Currently, the Indian Sundarbans is already facing a serious freshwater scarcity since most of the rivers in the region have lost connection with their parent river (i.e., glacier-melt perennial sources of freshwater) because of siltation at off-take and have turned into tidal-fed rivers. Their estuarine character is now maintained by the monsoonal runoff alone (Bhadra et al. 2017; Cole and Vaidyaraman 1966; Gopal and Chauhan 2006). Freshwater flow in the region has also been affected by human-induced hydrologic alterations in the upper reaches of the Bhagirathi Hooghly River and the Ganges-Brahmaputra-Meghna system.[3] The region is likely to experience further changes in its salinity profile due to saltwater intrusion from sea-level rise in the future.[4]

Spatial Distribution of Mangrove Species

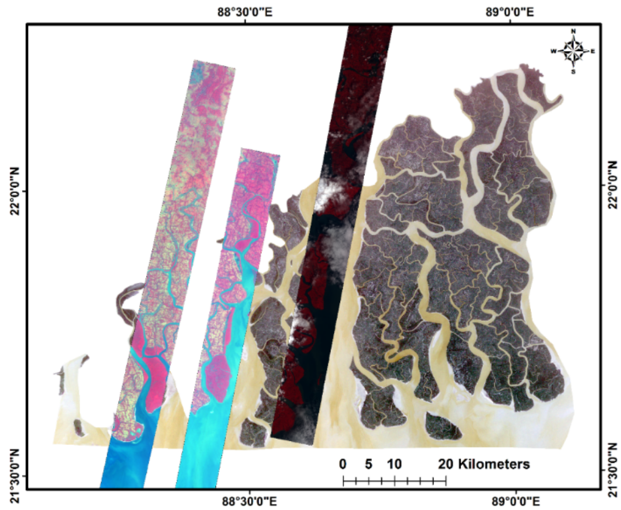
To understand the current spatial distribution of mangrove species in the Indian Sundarbans, Landsat 8 Operational Land Imager (OLI), sentinel, and hyperspectral data from Hyperion were used as the baseline data for this analysis. The acquisition date of the Landsat 8 OLI data is March 18, 2015 and the path/row is 138/45. Landsat 8 (OLI) has 9 spectral channels, ranging from visible to shortwave infrared bands. The spatial resolution is comparable to the ETM+. Temporal resolution of Landsat 8 is 16 days. Hyperspectral data from Hyperion were processed and used for the spectral signature generation of various mangrove species. The acquisition dates of the Hyperion data used are September 10, 2011, November 23, 2014, and November 13, 2016, respectively, and the path/row is 138/45. Hyperion images have 242 bands that include both the Visible and Near Infrared (VNIR) and Shortwave Infrared (SWIR), having a spectral range of 357 to 2,576 nm with a spectral interval of 10 nm (Figure 1).

---

[3] Freshwater flow has become increasingly restricted since the 1975 construction of the Farakka Barrage Township; between 1962 and 2006, water discharge of the Ganges was reduced from 3,700 m^3 per second to 364 m^3 per second, strangling an already parched ecosystem and thus making the distributary networks more dependent on tidal flow bringing in sea water from the Bay of Bengal (Islam and Gnauck 2008).

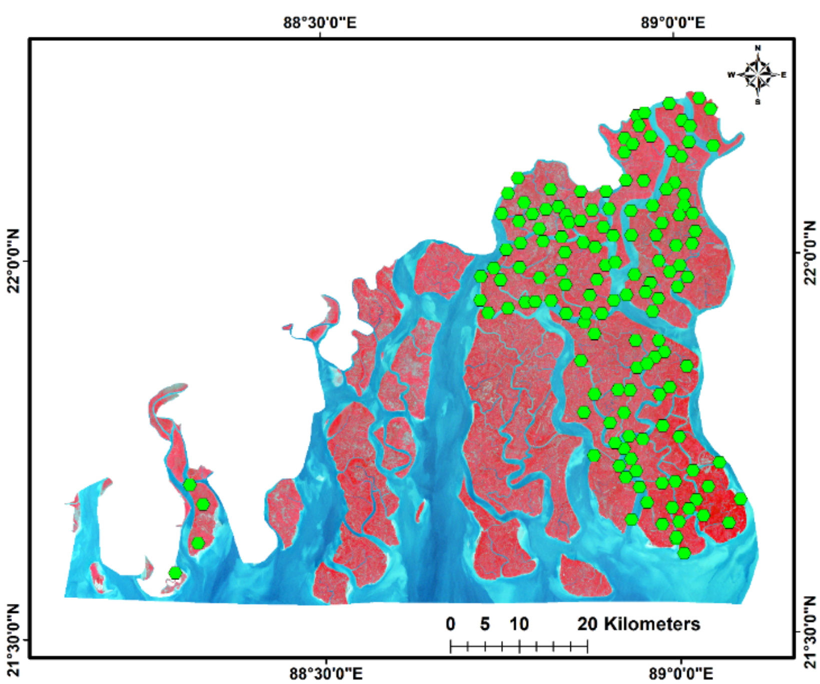
[4] The groundwater is also saline, except for a few meter-thick, confined aquifers.

Figure1: Map showing hyperspectral scenes coverage over mangrove forested areas of the Sundarbans



Finally, field data were used to ground-truth the images. Field data on mangrove species and assemblages for 141 GPS locations were collected for spectral signature generation of mangroves and validation of interpretation of satellite images (Figure 2).

Figure 2: Map showing sampling points for mangrove species identification in the Sundarbans



Salinity Estimates

To generate a baseline profile of aquatic salinity for the Indian Sundarbans,[5] a high-resolution, spatial point file covering four years (2012–15) was created, based on data compiled from field measurements taken by the Nature Environment & Wildlife Society (NEWS) and World Wildlife Fund-India (WWF-India). Given the limited amount of salinity information available for the Indian Sundarbans, this analysis also drew from the most comprehensive study to date on salinity impacts for the Bangladesh Sundarbans—which accounts for 60 percent (about 6,000 km^2) of the wetland forest—in order to arrive at a broader picture of the Sundarbans' current and future salinity (Dasgupta, Sobhan, and Wheeler 2018).[6]

3. Methods

To get a broader picture of the migration of mangrove species with progressive aquatic salinization in a changing climate, a five-step analysis was conducted. In step 1, Landsat 8 (OLI), sentinel, and hyperspectral data from Hyperion were used to generate a basemap (2015) to understand the current spatial distribution of mangrove species. In step 2, a high-resolution spatial point file of aquatic salinity covering four years (2012–15) was created from the best available, location-specific monitored salinity data to understand the baseline aquatic salinity profile of the area. In step 3, salinity tolerance ranges for the mangrove species were computed, combining the baseline mangrove distributions and the baseline, high-resolution aquatic salinity profile. In step 4, projections of location-specific aquatic salinity were made for 2050. Finally, in step 5, the impacts of progressive aquatic salinization on mangrove species by 2050 were projected.

Step 1. Generate a Basemap (2015) of Mangroves in the Indian Sundarbans from Satellite Data

A high-resolution map of mangroves was prepared from hyperspectral data from Hyperion, Landsat 8 Operations Images (OLI), and field survey data using a multi-step procedure.

First, a field survey was conducted at 141 GPS locations to collect geographic location information on five dominant genera of Indian Sundarban mangroves—*Avicennia sp*., *Ceriops sp*., *Excoecaria sp*., *Heritiera sp*. and *Sonneratia sp*.—and their assemblages. This information was later used to generate a spectral signature of mangroves and validate the interpretation of satellite images.

Second, spectral profiles for the various mangrove species were generated from hyperspectral imagery from Hyperion. To start, 67 of 242 bands of Hyperion images were

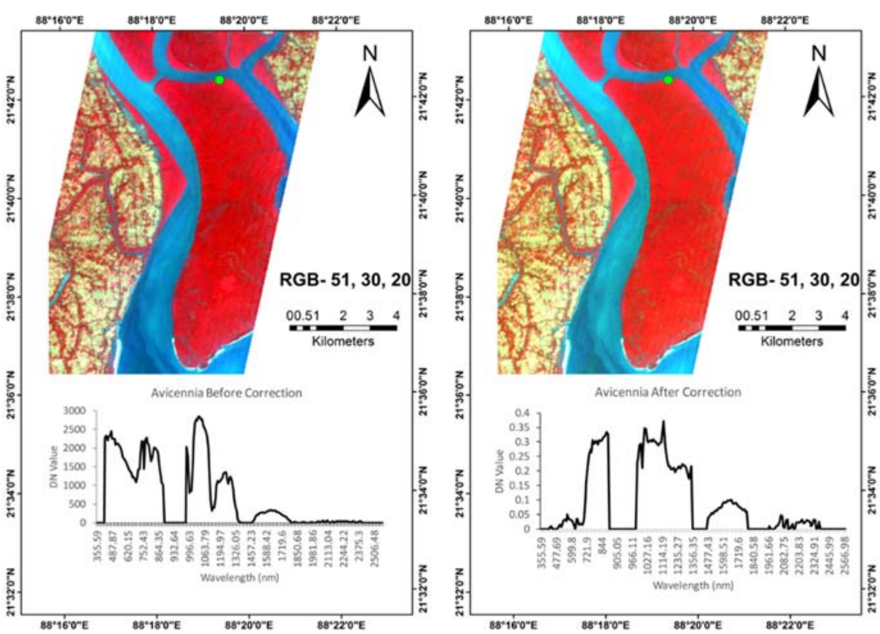
[5] At present, there is no geo-coded database on aquatic or soil salinity for the Indian Sundarbans.

[6] This paper draws extensively on spatial data from the Aquatic Salinity Information System (RSIS) for southwest coastal Bangladesh, including the Sundarbans. The RSIS provides location-specific salinity estimates for December 2011, January–June 2012, December 2049, and January–June 2050 under 27 climate-change scenarios (http://sdwebx.worldbank.org/climateportal/index.cfm?page=websalinity_dynamics&ThisRegion=Asia&ThisCcode=BGD).

eliminated as those bands were water-vapor absorption bands/for overlapping regions/had no information (Barry 2001; Datt et al. 2003). Bad bands were removed while converting Digital Number (DN) value to radiance using the radiometric calibration tool. The output was converted to band-interleaved-by line (BIL) radiance image with floating point values as Fast Line-of-sight Atmospheric Analysis of Spectral Hypercube (FLAASH) correction module use BIL format. After removal of 67 bad bands, a total of 175 calibrated bands were obtained and used for further processing.

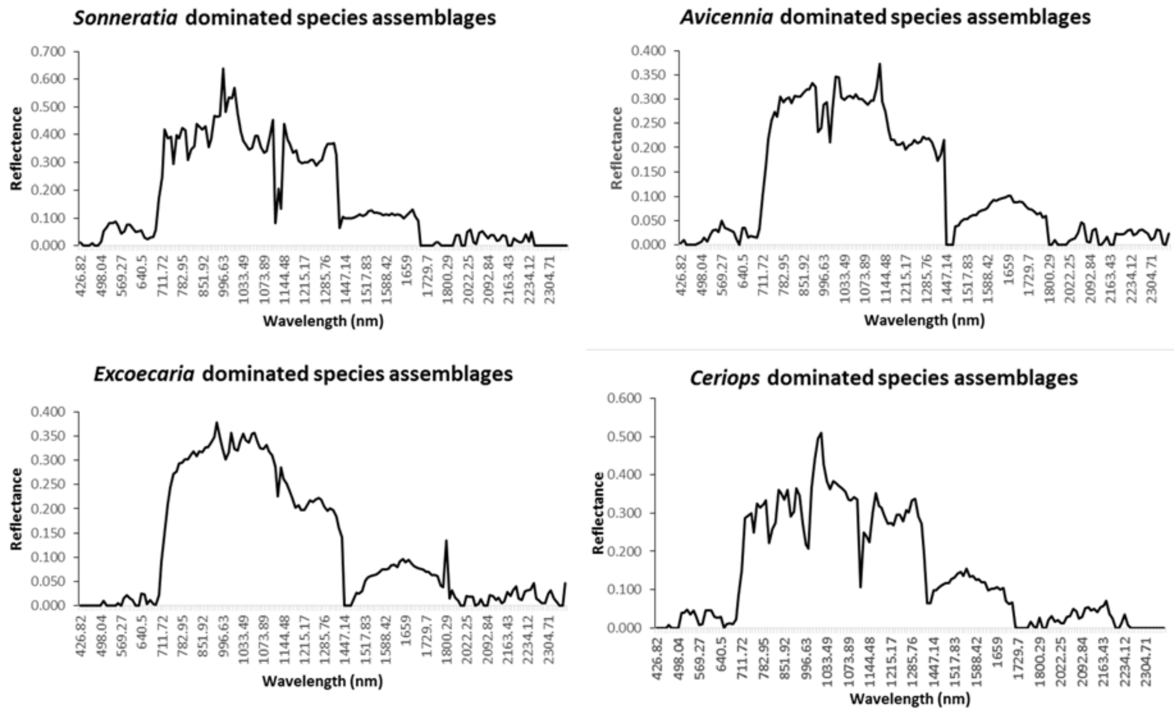
These 175 calibrated bands then underwent visual and statistical examination; and signal-to-noise ratios were determined for all bands. At this stage, several other corrections were made, including de-striping and atmospheric corrections. During the acquisition of Hyperion data, vertical striping occurs at times due to poor calibration of push broom sensors. For this analysis, de-striping was performed by filling up the DN value of the gap line with an average DN value from the previous and the next column (Farooq and Govil 2014). Atmospheric correction was performed using the FLAASH package available in ENVI™. These corrections provided calibrated image spectra of mangrove species (Figure 3).

Figure 3: Comparison of pre- and post-correction images



Mangrove species-specific image spectra were then generated from corrected Hyperion imagery for a subset of GPS locations where field information on existing mangroves was collected (Figure 4). Absorption and peak reflectance detected from the spectral profile indicated the characteristics of each species. All remaining Hyperion images were then classified with those detected spectral signatures using the Spectral Angle Mapper (SAM) in ENVI™.

Figure 4: Spectra generated using the hyperspectral imagery and field survey samples



Third, Landsat 8 OLI images were rescaled to Top of Atmosphere (TOA) radiance and to TOA spectral reflectance, using the rescaling coefficient factor provided in the metadata (Annex).[7] Corrected Landsat OLI images were then classified using unsupervised classification with 200 classes. This process was immediately followed by a knowledge-based classification, whereby the knowledge engine built was based on the correlation between (i) the classified Hyperion images, (ii) the corrected OLI images, and (iii) the field information collected from 100 (of 141) ground-control points. Information from the remaining 41 ground-control points was later used for finalization of the knowledge engine and accuracy assessment of the classified mangrove maps.

Lastly, the classified images were shared with Sundarbans mangrove experts and then revised, taking into account their field experience. The accuracy of the mangrove species map was re-tested and the level of accuracy increased to 70 percent after the revision.

Step 2. Generate a Baseline Aquatic Salinity Profile of the Indian Sundarbans

A high-resolution spatial point file for aquatic salinity covering four years (2012–15) was created from data on aquatic salinity received from various sources, using a seven-step process.

[7] Gain and bias corrections of satellite data through radiometric calibration are prerequisites for the classification and detection of change from the multi-temporal images (Duggin and Robinove 1990).

First, all spreadsheet monitoring information was converted into a spatial panel database. This was an unbalanced panel, with many time-series observations for some monitoring locations and very sparse observations for others.

The second step was to estimate a fixed-effects regression, expressed as follows:

$$\ln S_{it} = \beta_0 + \sum_{j=1}^{N} \beta_j DS_j + \sum_{k=2}^{12} \gamma_k DM_k + \delta y + \varepsilon_{it} ,$$

where *S* equals salinity (ppt) at monitoring location *i* for period t, *DS* is the monitor dummy variable (1 for monitoring location *j* and 0 otherwise), *DM* equals the month dummy variable, and *y* is the year (2012, 2013, 2014, and 2015). The testing of various yearly trends in nine spatial clusters of monitors found no significant differences from the overall trend.

The third step was to generate a projection database for the four years (2012–15) with full dummy variables for monitoring locations and months. Fourth, the projection database was used to predict salinity for all monitoring stations in all months and years. Fifth, predicted salinity was extracted for all monitoring stations in the month of highest salinity (i.e., May 2015). Sixth, the observations were mapped in ArcGIS. Finally, a high-resolution point file was created via spatial interpolation among the observations.

Step 3. Estimate Salinity Tolerance of Various Mangrove Species

Salinity tolerances of various relevant mangrove types (species and mixed species) were computed using geographic overlays of base mangrove distributions derived in Step 1 and the high-resolution spatial aquatic salinity profile developed in Step 2.

Step 4. Estimate Future (2050) Aquatic Salinity for the Indian Sundarbans

To estimate future aquatic salinity for the Indian Sundarbans, a projection model using high-resolution point data was first developed for the Bangladesh Sundarbans. First, the *SP* ratio (salinity in 2012 divided by salinity in 2050) was computed for each point. Next, the *SM* ratio (salinity in 2012 divided by the maximum salinity in 2012 for all points) was computed for each point. The *SP* is distributed (0, 1). Finally, fractional logit was used to estimate $SP = \beta_0 + \beta_1 SM$ for all points. This functional form preserves the (0, 1) bound, while specifying the growth rate of salinity from 2012 to 2050 at a point as a function of the gap between its current salinity and the maximum salinity in the point set (i.e., effectively ocean salinity). The function fits the data extremely well.

To estimate salinity in 2050 for the Indian Sundarbans, the *SM* ratio (salinity in 2012 divided by the maximum salinity in 2012 for all points) was computed for each point. Next, the regression coefficients from the Bangladesh computation above were used to estimate the *SP* ratio (salinity in 2012 divided by salinity in 2050). Finally, *SP* was used to compute salinity in 2050 and salinity in 2012 for each point.

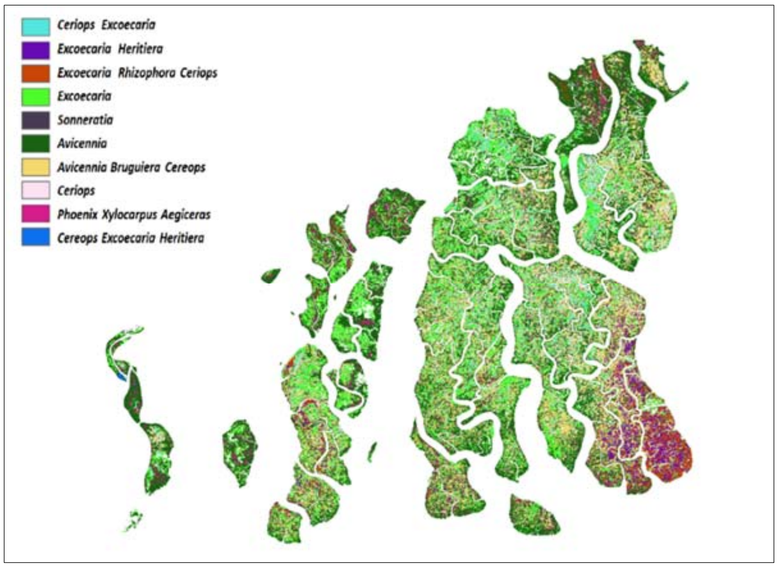
Step 5. Project Future (2050) Spatial Distribution of Mangrove Species for the Indian Sundarbans

Finally, the basemap (2015) of mangroves derived in Step 1, salinity tolerance of various mangrove species computed in Step 3, and projections of location-specific aquatic salinity for 2050 in Step 4 were used to predict the impacts of salinization on mangrove species by 2050.

4. Results

Although earlier studies reported the presence of up to 60 mangrove species in the Indian Sundarbans, the 2015 basemap generated from satellite images in this analysis shows that the forest is populated predominantly by 10 mangrove species and their assemblages (Figure 5).

Figure 5: Basemap of mangrove distribution in the Indian Sundarbans, 2015



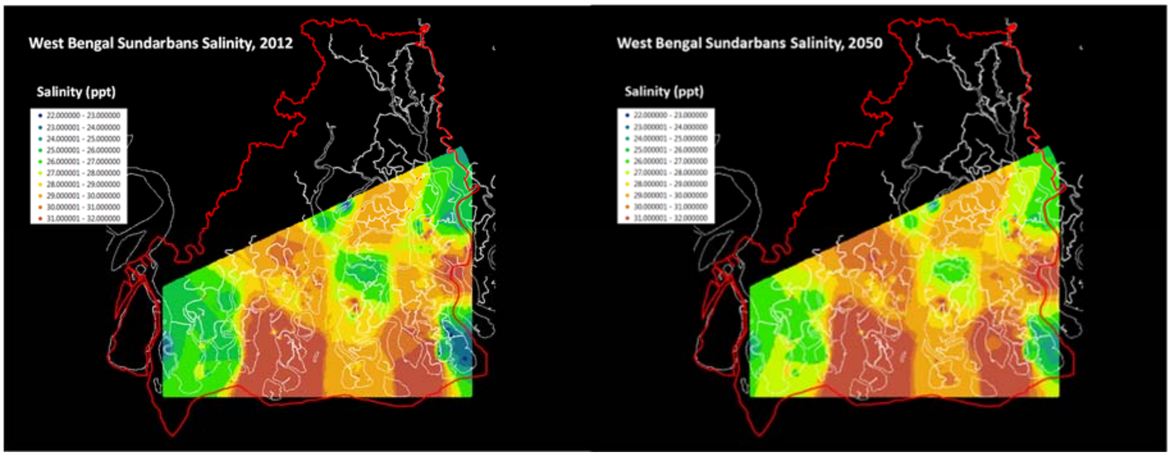
The main mangrove species are listed below:

- *Avicennia alba*, *A. marina*, and *A. officinalis*;
- *Excoecaria agallocha*;
- *Ceriops decandra* and *C. Tagal*;
- *Bruguiera gymnorrhiza* and *B. cylindrical*;
- *Sonneratia apetala*, *S. alba*, *S. griffithii*, and *S. caseolaris*;
- *Heritiera fomes*;
- *Xylocarpus mekongensis* and *X. granatum*;
- *Rhizophora mucronata* and *R. opiculata*;
- *Phoenix paludosa*; and
- *Aegiceras corniculatum*.

Current and Future Aquatic Salinity Profiles for the Indian Sundarbans

Figure 6 shows that current concentrations of maximum salinity in the Indian Sundarbans were already quite high in 2012 and that salinity will increase progressively by 2050.

Figure 6: Maximum aquatic salinity ranges in the Indian Sundarbans



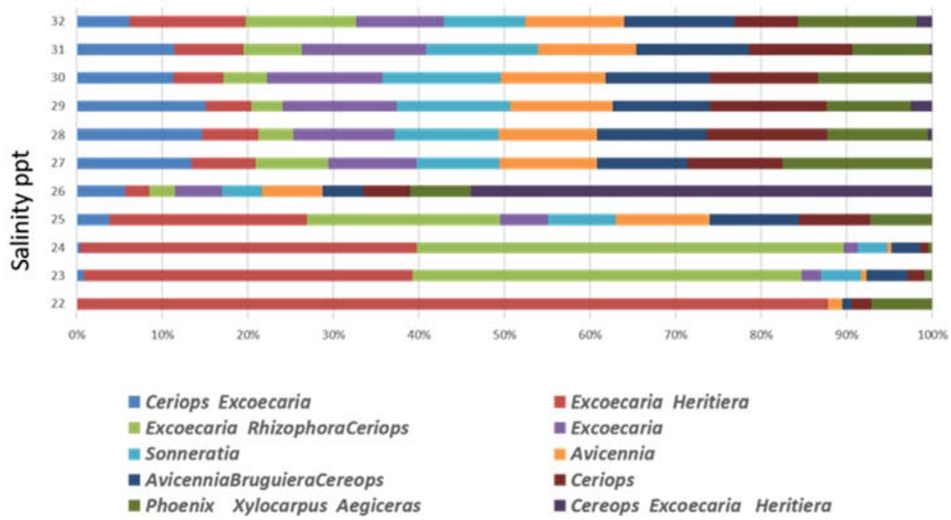
Visual comparison of the two maps allows us to observe the scale of potential change between 2012 and 2050. Over time, salinity appears to spread northward and eastward with the rise in sea level, change in riverine flows, and continued subsidence in the lower Ganges Delta. The transition over this period is pronounced in the southwest coastal, central, and northeastern areas.

Salinity Tolerance of Mangrove Species and Assemblages

From geographic overlays on the 2015 basemap of mangrove species and the corresponding aquatic salinity map, we can observe clustering patterns within several salinity ranges. Figure 7 shows that, in areas with low-to-medium salinity, clustering is evident for *Sonneratia* and *Heritiera* species. In medium-to-high salinity areas, there is pronounced clustering of *Phoenix, Excoecaria, Bruguiera, Xylocarpus, Aegiceras,* and *Rhizophora* species. Finally, in high-salinity areas, *Avicennia* and *Ceriops* species are abundant.[8] These salinity-tolerance estimates derived from the clustering patterns of mangrove species within salinity ranges are critical building blocks of the mangrove transition projection analysis.

[8] These findings are in line with the findings of Barik et al. 2018.

Figure 7: Clustering of mangrove species and assemblages within salinity ranges



Projected Spatial Distribution of Mangrove Species in the Indian Sundarbans, 2050

Figure 8 shows the impact of progressive salinization on the most dominant mangrove species assemblages. As expected, with progressive salinization, the Indian Sundarban landscape will be dominated by salt-tolerant mangrove species and assemblages, including *Avicennia*, *Excoecaria*, *Ceriops*, *Avicennia-Bruguiera-Ceriops* and *Excoecaria-Rhizophora-Ceriops* (Table 1). This change will occur at the expense of freshwater species and assemblages with low-to-medium salt tolerance, including *Sonneratia*, *Excoecaria-Heritiera*, *Excoecaria-Rhizophora-Ceriops*, and *Cereops-Excoecaria-Heritiera*.

Figure 8: Map of mangrove distribution in the Indian Sundarbans, 2050

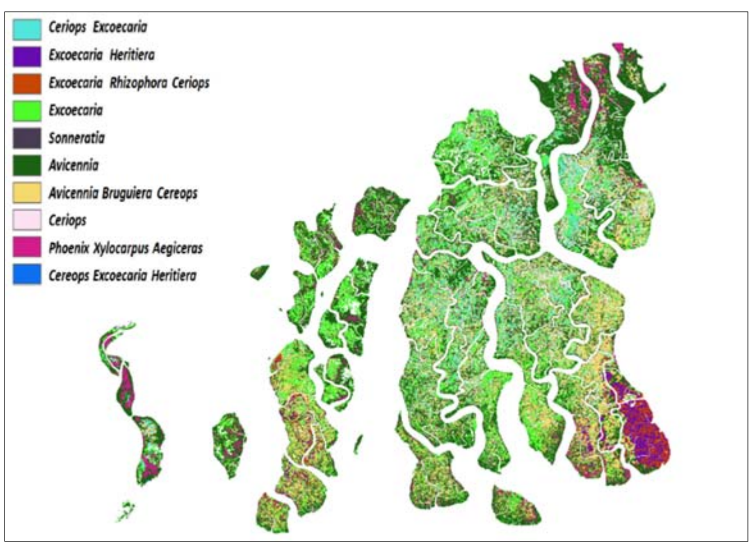
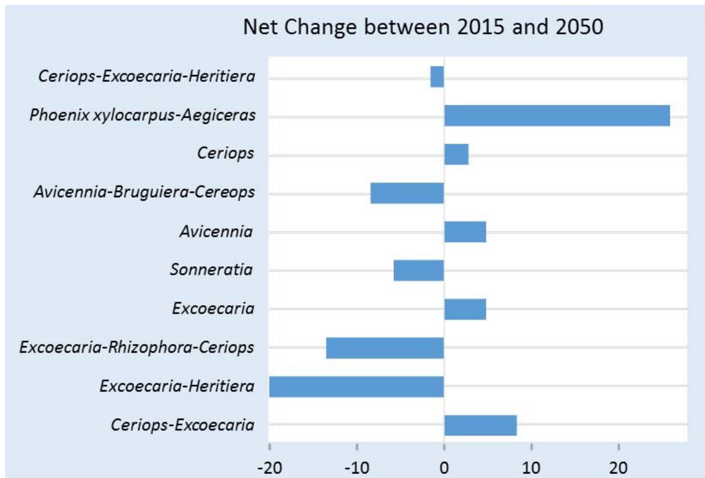


Table 1: Estimated change in area (km^2) for various mangrove species and assemblages, 2015–2050

Mangrove Assemblage, 2015	**Mangrove Assemblage, 2050**									
	Ceriops-Excoecaria	*Excoecaria-Heritiera*	*Excoecaria-Rhizophora-Ceriops*	*Excoecaria*	*Sonneratia*	*Avicennia*	*Avicennia-Bruguiera-Cereops*	*Ceriops*	*Phoenix-Xylocarpus-Aegiceras*	*Ceriops-Excoecaria-Heritiera*
Ceriops-Excoecaria	65.967	0.727	0.819	16.842	0.212	1.130	4.211	0.0054	0.005	0
Excoecaria-Heritiera	0.624	32.206	2.133	4.685	0.252	12.408	14.955	0.514	0.418	0
Excoecaria-Rhizophora-Ceriops	0.092	0.063	299.115	2.525	0.121	11.126	4.910	0.358	2.291	0
Excoecaria	16.262	4.046	25.29	353.500	0.061	6.203	8.616	0.018	0.934	0
Sonneratia	0.243	0.684	4.5	0	35.007	2.885	1.356	0	0.671	0
Avicennia	4.095	0.838	12.978	14.871	0	718.681	0.005	4.986	0.049	0.084
Avicennia-Bruguiera-Cereops	8.619	7.026	29.907	0	0	23.820	338.535	5.543	2.638	0
Ceriops	1.715	0.939	5.814	4.23	0.027	4.478	12.323	148.762	1.871	0
Phoenix-Xylocarpus-Aegiceras	0.017	0.023	1.8	0.579	0.123	6.485	1.256	2.828	47.110	0
Ceriops-Excoecaria-Heritiera	0	0	0.198	0.003	0	0.824	0	0.001	0.379	0.001

Figure 9 shows the absolute gains and losses in area for mangrove species and their assemblages by 2050. As shown, *Excoecaria-Heritiera* will suffer the largest net loss in area, followed by *Excoecaria-Rhizophora-Ceriops*, *Avicennia-Bruguiera-Cereops*, *Ceriops*, *Sonneratia*, and *Ceriops-Excoecaria-Heritiera*. Conversely, *Phoenix xylocarpus-Aegiceras* will see the largest net gain, followed by lesser gains for *Ceriops-Excoecaria*, *Exoecaria*, *Avicennia*, and *Ceriops*.

Figure 9: Migration of mangrove species with progressive aquatic salinization



5. Discussion

A majority of the 4 million people who live in the Indian Sundarban region depend directly or indirectly on the mangrove forest's wide-ranging ecosystem services (e.g., mitigating the impact of natural disasters, trapping suspended sediment, preventing soil erosion, and sequestering carbon). Furthermore, the livelihood dependency of poor communities revolves around a wide array of mangrove-related uses (e.g., fishing, fuelwood collection, timber for building materials, fishing poles, sticks for nets, honey collection, and tourism) (Table 2).

Table 2: Common uses of main mangrove genera in the Indian Sundarbans

Mangrove species	*Timber for building materials*	*Fuel-wood*	*Thatch*	*Medicine*	*Food (fruits, leaves, seeds)*	*Fishing equip-ment*	*Tannin*	*Honey collection*	*Environ-mental functions*	*Fish habitat*
Heritiera fomes	✓	✓		✓				o	o	o
Avicennia alba, A. marina, A. officinalis	✓	o		✓		o		✓	✓	o
Sonneratia apetala, S. alba, S.	✓	o		✓	✓	✓		✓	o	o

griffithii, S. caseolaris										
Excoecaria agallocha	✓			✓				✓	✓	o
Ceriops decandra, C. tagal	✓	✓	✓	✓	✓	o	✓	✓	o	o
Bruguiera gymnorrhiza, B. cylindrica	✓	✓		✓	✓	o	✓		o	o
Rhizophora mucronata, R. apiculate	✓	✓		✓	✓	✓	✓		✓	✓
Xylocarpus mekongensis, X. granatum	✓	o		✓			✓	o	✓	o
Phoenix paludosa	✓	✓	✓				✓		✓	o
Aegiceras corniculatum		✓		✓				✓		o

Note: (✓) indicates information from the literature, and (o) is used to represent expert opinion.

The intertidal region where mangroves are present—the transition zone between freshwater and marine ecosystems—is well-suited for breeding and rearing a variety of fish, crustacean, and mollusk species.[9] Harvesting these species from rivers and creeks provides a major livelihood source for many poor communities, who are especially vulnerable to climate-driven changes in mangrove species composition. The ecosystem's increasing salinity is projected to influence the combination of stenohaline and euryhaline species, thus affecting the food web. It will take a particular toll on economically important fish catches that have specific salinity-tolerance limits (e.g., Parse and Bhangan).

Decline in the growth of forest land and timber species, along with reduced productivity of forest sites, may also impact the livelihood options of poor households. For example, honey collectors, called "Moulis," obtain the first honey of the season from *Aegiceras* and *Acanthus* sp., which fetches a high value, at Rs. 200–250 per kg. Honey collected later in the season, mainly from *Ceriops* and *Avicennia* sp., fetches less (Rs. 80–120 per kg). With changes in mangrove species combinations, the fragrance and viscosity of honey—and thus its price—will vary.

Increasing salinity will also reduce the diversity of mangrove species, which could diminish the attraction of the Sundarbans as a biodiversity hotspot destination. With sea-level rise in a changing climate, declining tourism would also adversely affect the livelihoods of poor people living in the coastal region. Although the wood quality of the *Ceriops-Avicennia* group is widely

[9] The direct relationships between particular mangrove and fish species are still being investigated.

appreciated, salinity ingression may increase due to the altered species combination, which could affect the water table and thus water sources. Women would be especially vulnerable since they spend a significant amount of time collecting fuelwood and drinking water.

6. Concluding Remarks

Despite the widely-acknowledged, treaty-protected ecological status of the Sundarbans, concerns related to growing aquatic salinity have not yet been incorporated into regional management protocols. Over time, eastward meandering of the Ganges and Brahmaputra is reducing freshwater inflows significantly. Because the region is quite flat, strong tidal effects may travel long distances upstream, even at the current sea level. These effects will be exacerbated by continuing sea-level rise. As long as such dynamics continue, efforts to improve local ecological conditions through changes in hydrological regime (e.g., river training and other engineering work) will likely be futile (Potkin 2004). Thus, it appears that engineering attempts to control rising salinity in the Sundarbans are unlikely to succeed.

The Indian Sundarbans is a UNESCO World Heritage Site. Effective conservation management will require establishment of location-specific baseline data for tree stand structures, tree abundance, species richness and diversity, export of nutrients, hydrological patterns, rates of sedimentation, and relative sea-level rise (McLeod and Salm 2006). Such baseline data will permit monitoring of changes in Sundarban mangrove systems over time. Since mangroves depend on fluxes of both daily tides and freshwater, management protocols should include both connectivity between mangrove systems and nearby river sources and maintenance of upland freshwater catchments. Areas should be identified that are likely to survive sea-level rise in a changing climate. Tidal fluctuations, varying pH, and salinity should be monitored to support assisted regeneration and colonization of suitable mangrove species, where necessary. Attempts to restore mangrove areas that are currently degraded should also be undertaken.[10]

Since changes in mangrove stocks induced by rising aquatic salinity are likely to change the prospects for forest-based livelihoods, resources should also be directed to the development of alternative livelihoods for mangrove-dependent households. Sea-level rise will continue beyond 2100, even if greenhouse gas (GHG) emissions are stabilized in the near future.[11] The impacts on globally-important mangrove ecosystems and the socioeconomic implications for vulnerable populations will undoubtedly be an important part of this story. High-resolution

[10] It is worth noting that local women's groups can be engaged in nursery preparation of these salt-tolerant species as part of community-based mangrove restoration activities.

[11] Current scientific estimates are that sea level may rise by 1 m or more in the 21st century (Hansen et al. 2011; Vermeer and Rahmstorf 2009; Pfeffer, Harper, and O'Neel 2008; Rahmstorf 2007; Dasgupta et al. 2009; Brecht et al. 2012). It is feared that sea level may even rise by 3 m or more by 2100, in light of new evidence on ice-cliff instability of the Antarctic (https://www.nature.com/articles/nature17145; http://www.nature.com/news/antarctic-model-raises-prospect-of-unstoppable-ice-collapse-1.19638; https://climatefeedback.org/evaluation/antarctica-doomsday-glaciers-could-flood-coastal-cities-grist-eric-holthaus/).

spatial assessments of such problems have been scarce. This research represents an attempt to narrow the knowledge gap for coastal West Bengal. We hope that these analyses will promote more widespread efforts to develop conservation and sustainable development policies that incorporate rising salinity, changes in mangrove dynamics, and their impacts on the welfare of poor communities.

References

Alongi, D. M. 2002. "Present State and Future of the World's Mangrove Forests." *Environmental Conservation* 29(3): 331–49.

———. 2008. "Mangrove Forests: Resilience, Protection from Tsunamis and Responses to Global Climate Change." *Estuarine, Coastal and Shelf Science* 76(1): 1–13.

Barik, J., A. Mukhopadhyay, T. Ghosh, S. K. Mukhopadhyay, S. M. Chowdhury, and S. Hazra. 2018. "Mangrove Species Distribution and Water Salinity: An Indicator Species Approach to Sundarban." *Journal of Coastal Conservation* 22(2): 361–8.

Barry, P. 2001. "EO-1/Hyperion Science Data User's Guide." Redondo Beach, CA: TRW Space, Defense & Information Systems.

Bhadra, T., A. Mukhopadhyay, and D. Hazra. 2017. "Identification of River Discontinuity Using Geo-Informatics to Improve Freshwater Flow and Ecosystem Services in Indian Sundarban Delta." In *Environment and Earth Observation*, 137–52. Cham, Switzerland: Springer.

Blasco, F., P. Saenger, and E. Janodet. 1996. "Mangroves as Indicators of Coastal Change." *Catena* 27(3–4): 167–78.

Brecht, H., S. Dasgupta, B. Laplante, S. Murray, and D. Wheeler. 2012. "Sea-Level Rise and Storm Surges: High Stakes for a Small Number of Developing Countries." *The Journal of Environment & Development* 21(1): 120–38.

Cole, C. V., and P. P. Vaidyaraman. 1966. "Salinity Distribution and Effect of Freshwater Flows in the Hooghly River." In *Proceedings of Tenth Conference on Coastal Engineering*, 1312–434, Tokyo, September.

Dasgupta, S., B. Laplante, C. Meisner, D. Wheeler, and J. Yan. 2009. "The Impact of Sea Level Rise on Developing Countries: A Comparative Analysis." *Climatic Change* 93: 379–88.

Dasgupta, S., M. Huq, Z. H. Khan, M. M. Z. Ahmed, N. Mukherjee, M. F. Khan, and K. Pandey. 2014. "Vulnerability of Bangladesh to Cyclones in a Changing Climate: Potential Damages and Adaptation Cost." *Climate and Development* 6: 96–110.

Dasgupta, Susmita, Farhana Akhter Kamal, Zahirul Huque Khan, Sharifuzzaman Choudhury, and Ainun Nishat. 2015a. "River Salinity and Climate Change: Evidence from Coastal Bangladesh." In *Asia and the World Economy: Actions on Climate Change by Asian Countries*, eds. John Whalley and Jiahua Pan, 205–42. World Scientific Press.

Dasgupta, Susmita, Md. Moqbul Hossain, Mainul Huq, and David Wheeler. 2015b. "Climate Change and Soil Salinity: The Case of Coastal Bangladesh." *Ambio* 44(8): 815–26.

Dasgupta, S., I. Sobhan, and D. Wheeler. 2017. "Impact of Climate Change and Aquatic Salinization on Mangroves Species in the Bangladesh Sundarbans." *Ambio* 46(6): 680–94.

———. 2018. "Sea-Level Rise and Species Conservation in Bangladesh's Sundarbans Region." *Journal of Management and Sustainability* 8(1): 1.

Datt, B., T. R. McVicar, T. G. Van Niel, D. L. Jupp, and J. S. Pearlman. 2003. "Preprocessing EO-1 Hyperion Hyperspectral Data to Support the Application of Agricultural Indexes." *IEEE Transactions on Geoscience and Remote Sensing* 41(6): 1246–59.

Duggin, M. J., and C. J. Robinove. 1990. "Assumptions Implicit in Remote Sensing Data Acquisition and Analysis." *Remote Sensing* 11(10): 1669–94.

Ellison, J. C., and D. R. Stoddart. 1991. "Mangrove Ecosystem Collapse during Predicted Sea Level Rise: Holocene Analogues and Implications." *Journal of Coastal Research* 7: 151–65.

Erwin, K. L. 2009. "Wetlands and Global Climate Change: The Role of Wetland Restoration in a Changing World." *Wetlands Ecology and Management* 17: 71–84.

Farooq, S., and H. Govil. 2014. "Mapping Regolith and Gossan for Mineral Exploration in the Eastern Kumaon Himalaya, India Using Hyperion Data and Object Oriented Image Classification." *Advances in Space Research* 53(12): 1676–85.

Gilman, E., H. Van Lavieren, J. C. Ellison, V. Jungblut, L. Wilson, F. Areki, G. Brighouse, J. Bungitak, et al. 2006. *Pacific Island Mangroves in a Changing Climate and Rising Sea*. Regional Seas Report and Studies No. 179. Nairobi: UNEP.

Gopal, B., and M. Chauhan. 2006. "Biodiversity and Its Conservation in the Sundarban Mangrove Ecosystem." *Aquatic Sciences* 68(3): 338–54.

Hansen, J., M. Sato, P. Kharecha, and K. V. Schuckmann. 2011. "Earth's Energy Imbalance and Implications." *Atmospheric Chemistry and Physics* 11(24): 13421–449.

Islam, S. N., and A. Gnauck. 2008. "Mangrove Wetland and Ecosystems in Ganges-Brahmaputra Delta in Bangladesh." *Frontiers of Earth Science in China* 2(4): 439–48.

IWM (Institute of Water Modeling). 2003. *Sundarban Biodiversity Conservation Project: Surface Water Modeling*. Final Report. Dhaka: Institute of Water Modeling, Ministry of Environment and Forests, Government of Bangladesh.

Lange, G.-M., S. Dasgupta, T. Thomas, S. Murray, B. Blankespoor, K. Sander, and T. Essam. 2010. *Economics of Adaptation to Climate Change-Ecosystem Services*. World Bank Discussion Paper No. 7. Washington, DC: World Bank.

McLeod, E., and R. V. Salm. 2006. *Managing Mangroves for Resilience to Climate Change*, 64. Gland: IUCN.

Nandy, S., and S. P. S. Kuswaha. 2011. "Study on the Utility of IRS 1D LISS-III Data and the Classification Techniques for Mapping of Sundarban Mangroves." *Journal of Coastal Conservation* 15(1): 123–37.

Naskar, K. R. 1988. "Economic Potentialities of the Tidal Mangrove Forests of Sundarbans in India." *Journal of Indian Society of Coastal Agricultural Research* 6(2): 149–57.

Petersen, L., and S. Shireen. 2001. *Soil and Water Salinity in the Coastal Area of Bangladesh*. Dhaka: Bangladesh Soil Resources Development Institute.

Pfeffer, W. T., J. T. Harper, and S. O'Neel. 2008. Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise." *Science* 321: 1340–43.

Potkin, A. 2004. "Watering the Bangladesh Sundarbans." In T*he Ganges Water Dispersion: Environmental Effects and Implications*, ed. M. M. Q. Mirza, 163–76. Dordrecht: Kluwer Academic Publishers.

Rahmstorf, S. 2007. "A Semi-Empirical Approach to Projecting Future Sea-Level Rise." *Science* 315: 368–70.

Rao, A. N. 1986. "Mangrove Ecosystems of Asia and the Pacific." *In Technical Report of the UNDP/UNESCO Research and Training Pilot Programme on Mangrove Ecosystems in Asia and the Pacific* (RAS/79/002), 1–48.

Semeniuk, V. 1994. "Predicting the Effect of Sea Level Rise on Mangroves in Northwestern Australia." *Journal of Coastal Research* 10: 1050–76.

SRDI (Soil Resources Development Institute). 2000. *Soil Salinity in Bangladesh 2000*. Dhaka: Soil Resources Development Institute.

SRDI (Soil Resources Development Institute). 2010. *Soil Salinity in Bangladesh 2010*. Dhaka: Soil Resources Development Institute.

UK DEFR (United Kingdom Department of Environment, Food and Rural Affairs). 2007. *Investigating the Impact of Relative Sea-Level Rise on Coastal Communities and Their Livelihoods in Bangladesh*. Dhaka: Institute of Water Modeling and Center for Environment and Geographic Information Services.

UNEP (United Nations Environment Programme). 1994. *Assessment and Monitoring of Climate Change Impacts on Mangrove Ecosystems*. UNEP Regional Seas Reports and Studies No. 154. Nairobi: UNEP.

Vermeer, M., and S. Rahmstorf. 2009. “Global Sea Level Linked to Global Temperature.” *Proceedings of the National Academy of Sciences* 106: 21527–32.

Annex: Processing of Landsat 8 OLI

Gain and bias corrections of satellite data through radiometric calibration are prerequisites for the classification and detection of change from multi-temporal images (Duggin and Robinove 1990). Therefore, Landsat 8 data products were first rescaled to Top of Atmosphere (TOA) radiance and TOA spectral reflectance, using the rescaling coefficient factor provided in the metadata.

The OLI data were converted to TOA radiance, using the following conversion equation:

$$L_\lambda = M_L \times Q_{cal} + A_L, \quad (1)$$

where L_λ equals TOA radiance (Watts/m^2 x srad x µm), M_L is the band-specific multiplicative rescaling, Q_{cal} is the quantized and calibrated standard product pixel values (DN), and A_L is equivalent to the band-specific additive rescaling factor.

The OLI data were converted to TOA reflectance, using the following conversion equation:

$$\rho`_\lambda = M_\rho \times Q_{cal} + A_\rho, \quad (2)$$

where $\rho`_\lambda$ equals TOA planetary reflectance without correction for solar angle, M_ρ equals the band-specific multiplicative rescaling factor, Q_{cal} is the quantized and calibrated standard product pixel values (DN), and A_ρ equals the band-specific additive rescaling factor.

TOA reflectance was then corrected with the solar zenith angle, expressed as follows:

$$\rho_\lambda = \frac{\rho`_\lambda}{\mathrm{Cos}\,(\theta_{SZA})}, \quad (3)$$

where ρ_λ equals TOA reflectance and ϑ_{SZA} is the Solar Zenith angle.