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Impact of Climate Change and Aquatic Salinization on Mangrove Species and Poor Communities in the Bangladesh Sundarbans

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Abstract

This paper investigates possible impacts of climate change on the poor communities of the Bangladesh Sundarbans via changes in aquatic salinity and mangrove species. The implications for poor communities are assessed by computing changes in high-value mangrove species for the five sub-districts in the Sundarbans. The results of the impact analysis indicate highly varied patterns of gain and loss across the five sub-districts. Overall, however, the results indicate that salinity-induced mangrove migration will have a strongly regressive impact on the value of timber stocks because of the loss of the highest value timber of *Heretiera fomes*. In addition, augmented potential for honey production is likely to increase conflicts between humans and wildlife in the region.

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Impact of Climate Change and Aquatic Salinization on Mangrove Species and Poor Communities in the Bangladesh Sundarbans

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1. Introduction

The Sundarbans is a tidal-wetland forest delta with an approximate area of 10,200 sq. km along the Bay of Bengal,[1] spanning coastal segments of Bangladesh and India. It is the largest remaining contiguous mangrove forest in the world,[2] and one of the richest ecosystems. The region is known for its exceptional biodiversity, which includes 350 species of vascular plants, 250 fish species, 8 amphibians, 58 reptiles, 300 birds and 42 mammals, along with numerous species of phytoplankton, fungi, bacteria, zooplankton, invertebrates and molluscs (Gopal and Chauhan 2006). The Sundarbans also harbors numerous threatened species, including the endangered Royal Bengal Tiger, several species of endangered dolphins, a critically endangered river terrapin, the vulnerable estuarine crocodile, Indian flap-shelled turtle, peacock soft-shelled turtle, and the near-threatened Indian python. The Sundarbans is also an important breeding ground for indigenous and marine fish species (e.g., *Tenualosa ilisha*), and cetaceans such as the Ganges and Irrawady dolphins (GoB 2010). The area is internationally recognized under the Ramsar Convention and is a UNESCO World Heritage site.[3]

The importance of the Sundarbans ecosystem is also associated with its valuable ecological services, including: (1) trapping of sediment and land formation; (2) protection of millions of human lives and assets in coastal Bangladesh and West Bengal (India) from cyclones; (3) acting as a breeding ground and nursery for indigenous and marine fish, as well as other aquatic life; (4) production of wood; (5) supplies of food and building materials; (6) production of oxygen; (7) recycling of waste; and (8) sequestration of carbon. (GoB 2010).

[1] The Sundarbans is at the confluence of the Ganges and Brahmaputra Rivers stretching from the Bhagirathi-Hooghly River in the west to the Padma-Meghna River in the east, and extending southward into the Bay of Bengal. Approximately 40 percent of the forest ecoregion lies within the Indian state of West Bengal (about 4,200 sq. km) and the remainder is in Bangladesh (about 6,000 sq. km). (World Bank 2014b).
[2] The second largest is only about one-tenth of the Sundarbans' size (Agarwala et al. 2003).
[3] UNESCO declared the Indian portion of the forest a World Heritage Site in 1987, and the Bangladesh portion of the forest was declared a separate World Heritage site in 1997.

Although the Sundarbans' ecological importance and uniqueness are recognized by Bangladesh, India and the international community, and its conservation is an obligation under international conventions and treaties, the region is currently threatened by a number of natural factors and human actions. The area is still in active formation as its rivers change their course. Eastward meandering of the Ganges and Brahmaputra Rivers over time is affecting sedimentation and reducing freshwater inflows significantly. In addition, water supplies, sedimentation, and the region's topography and hydrology have all been affected by human actions, such as construction of upstream dams, embankments to protect land from tides, over-exploitation of mangrove timber, urban and industrial pollution, and mangrove clearing for agriculture and aquaculture. Local human-induced losses will probably continue, and climate change is likely to aggravate current problems.

Climate change poses a number of threats to the Sundarbans, including rise in sea level, rise in air and water temperature, and change in the frequency and intensity of precipitation and storms (Alongi 2008). Among these threats, increased saltwater intrusion from sea level rise may pose one of the greatest challenges. (For example, see Dasgupta et al. 2015a, b, c, d; SRDI 2010, UK DEFR 2007; IWM 2003; Peterson and Shireen 2001; SRDI 2000; Karim et al. 1990.) Healthy mangroves need daily fluxes from both ocean and fresher water. The Sundarbans is already facing a serious shortage of fresh water during the dry season (October to May) because some major distributaries of the Ganges feeding Sundarbans 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. The associated increase in aquatic salinization will inevitably change the hydrological regime of the Sundarbans and alter its forest ecology.

These changes may have significant implications for the forest-based livelihoods of millions of poor inhabitants in the Sundarbans and adjacent areas. 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 by assessing the impact of aquatic salinization on the spatial distribution of mangrove species, with particular attention to the potential consequences for poor communities in the Sundarbans region.

The focus of our analysis is on the Bangladesh Sundarbans,[4] as the potential impact of salinity on the region has become a major concern for the Government of Bangladesh and affiliated research institutions. Recently the Bangladesh Climate Change Resilience Fund (BCCRF) Management Committee has highlighted salinity intrusion as a critical part of adaptation to climate change. Prior research on this issue has been conducted or co-sponsored by the Ministry of Environment and Forests (World Bank 2000) and two affiliated institutions: the Center for Geographic and Environmental Information Services (Hassan and Shah 2006) and the Institute of Water Modeling (IWM 2003; UK DEFR 2007).

Various projections of soil and water salinity for the Bangladesh Sundarbans have suggested significant risks for residents' welfare.[5] Sundarbans communities are among the poorest of the poor in Bangladesh, and their livelihoods will be significantly affected by spreading and

[4] Approximately, 60 percent of the Sundarbans is in Bangladesh, covering about 6,000 sq. km in certain districts of Khulna, Satkhira and Bagerhat districts.

[5] Previous research on salinization in coastal Bangladesh has employed a variety of methods (see for example Nobi and Das Gupta 1997; Aerts et al., 2000; IWM 2003; CEGIS 2006 and Bhuiyan and Dutta 2011). Many of these studies have simulated salinity change in rivers and estuaries using hydraulic engineering models and have compared the results with actual measures. In the most comprehensive study to date, Dasgupta et al. (2015a) have used 27 alternative climate change scenarios to project salinity trends in coastal rivers to 2050, with a model that links the spread and intensity of salinity to changes in the sea level, temperature, rainfall, and altered riverine flows from the Himalayas. The study provides new estimates of location-specific river salinity through 2050.

intensifying aquatic salinity with climate change. Understanding household choices will also be critical, since households may respond to localized threats of salinization and inundation by relocating some or all members to areas where expected earnings and survival probabilities are higher (Dasgupta et al, 2014c). Previous studies have assessed the implications of salinization for vegetation patterns in the region (For example, see Iftekhar and Saenger 2008; Hoque et al. 2006), but they have not provided high-resolution spatial estimates of expected changes and their implications for poor communities. This paper attempts to contribute by extending the previous work in both dimensions.

The remainder of the paper is organized as follows. Section 2 introduces the mangrove species of the region and maps their spatial distribution. Drawing on prior work by Dasgupta, et al. (2015a), Section 3 combines a digital map of aquatic salinity with the mangrove distribution map to develop estimates of the salinity tolerance range of each mangrove species. In Section 4, we project future aquatic salinity in the region using 27 scenarios from Dasgupta et al. (2015a) that combine projections from three IPCC climate scenarios, three global circulation models, and three assumptions about the rate of land subsidence in the lower Ganges Delta. Then we combine the salinity projections with our estimated species salinity tolerance ranges to produce spatial distribution scenarios for mangroves in 2050. Section 5 describes the economic and ecological value of various mangrove species and translates our results to projected changes for the five *upazila*s in the Sundarbans mangrove region -- Dacope, Koyra, Mongla, Sarankhola and Shyamnagar --and assesses the potential poverty implications. Section 6 summarizes and concludes the paper.

2. Mangrove Species in the Sundarbans

The Sundarbans region in Bangladesh is populated predominantly by seven mangrove species (see Table 1).[6]

Table 1: Bangladesh Sundarbans mangrove species

Scientific Name	Vernacular Name
Avicennia alba, marina, officinalis	Baen
Excoecaria agallocha	Gewa
Ceriops decandra	Goran
Bruguiera gymnorrhiza	Kankra
Sonneratia apetala	Keora
Xylocarpus mekongensis	Passur
Heritiera fomes	Sundri

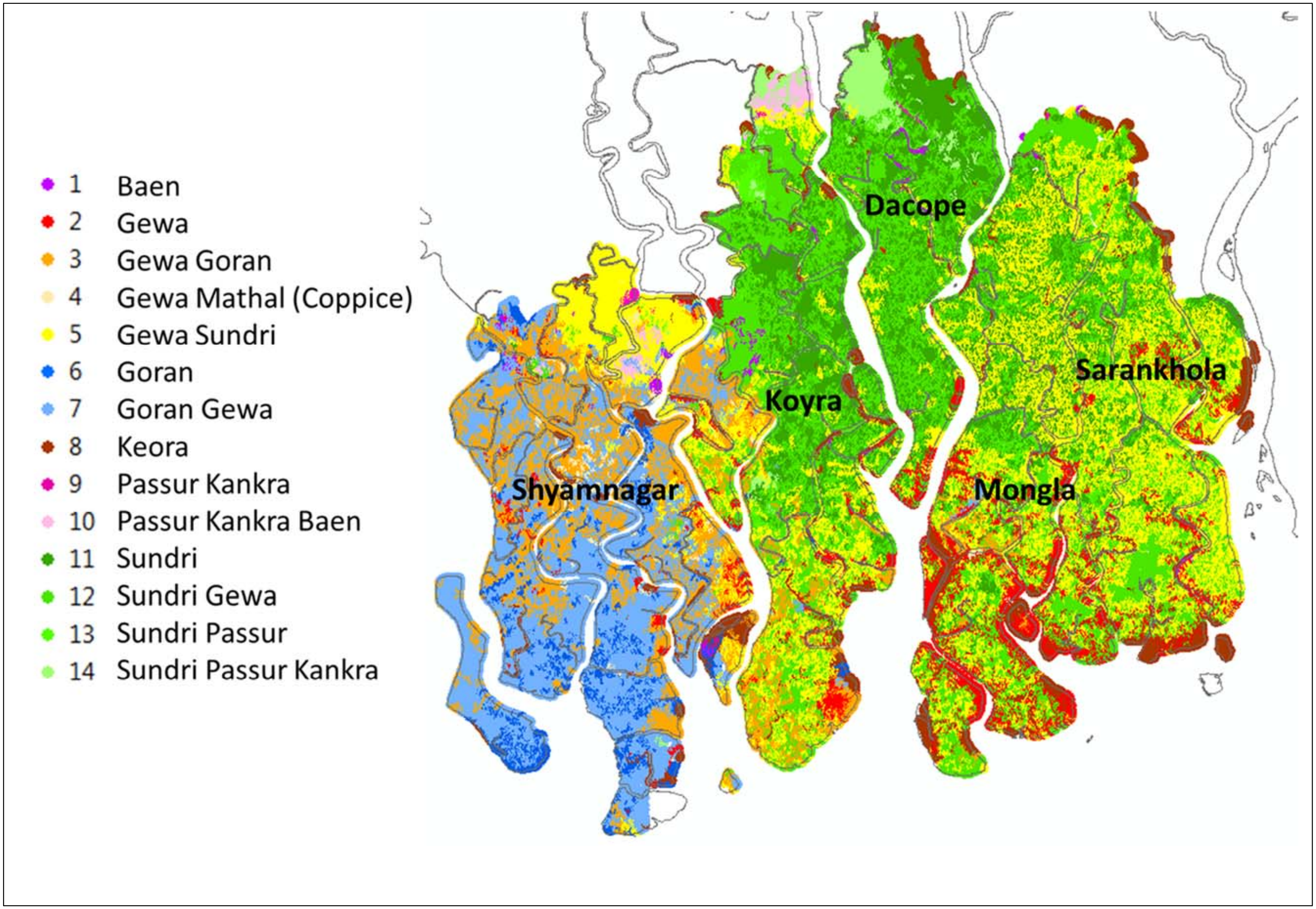
Source: Aziz and Paul (2015)

In order to understand the geographic distribution of these various species, we started with a geographic overlay of Bangladesh Sundarbans forest with *upazila* maps constructed from an administrative shapefile provided by the Government of Bangladesh. The Sundarbans mangrove region includes five *upazila*s in Khulna Division: Dacope and Koyra in Khulna District; Mongla and Sarankhola in Bagerhat, and Shyamnagar in Satkhira. Figure 1 displays a high-resolution map of the distribution of Sundarbans mangrove species in 2013.[7] The map reveals concentrations of *Ceriops decandra* (Goran) in southern and western Shyamnagar; *Excoecaria agallocha* (Gewa) in eastern Shyamnagar, western Koyra and southern Mongla; and *Heritiera fomes* (Sundri) in Koyra, Dacope and northern Mongla. Between these areas of concentration lie mixed patterns dominated by the first species entries in the legend of Figure 1.

[6] About 99 percent of the forest area is accounted for by these seven mangrove species. The region also includes scattered habitat for 20 other tree species. Forest inventories conducted at different times have concluded that a significant area of Sundarbans has mixed varieties of mangrove species, with species proportions varying with site conditions. Forest types are classified by dominant species (GoB 2010; Hussain and Acharya 1994).

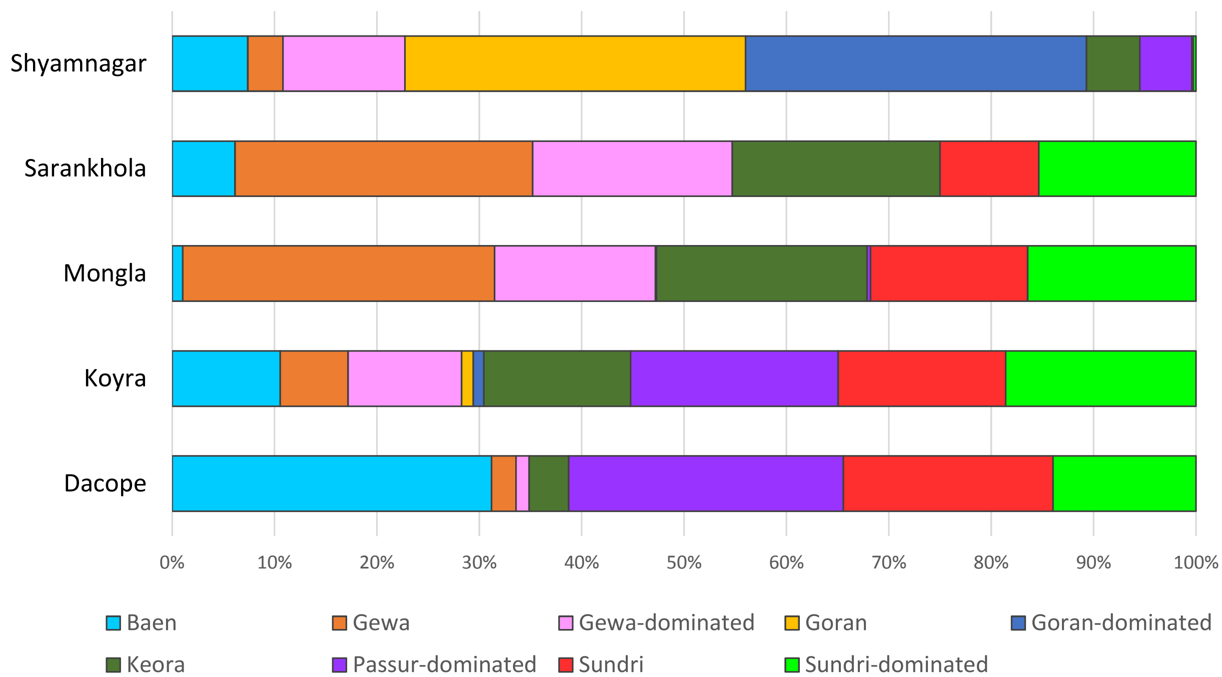
[7] This map has been provided by Department of Forest, Bangladesh.

Figure 1: Mangrove species distribution, 2013



Notable mixes include *Ceriops decandra* (Goran) - *Excoecaria agallocha* (Gewa) and *Excoecaria agallocha* (Gewa) - *Ceriops decandra* (Goran) in most of Shyamnagar, and *Excoecaria agallocha* (Gewa) - *Heritiera fomes* (Sundri) and *Heritiera fomes* (Sundri) - *Excoecaria agallocha* (Gewa) in northeast Shyamnagar and northwest Koyra. Figure 2 displays species shares by *upazila* as an aid to identifying clusters for individual species. *Avicennia alba*, *marina*, *officinalis* (Baen) is concentrated in Dacope (51.1%), *Excoecaria agallocha* (Gewa) in Mongla (52.9%), *Ceriops decandra* (Goran) in Shyamnagar (97.7%), and *Sonneratia apetala* (Keora) in Koyra and Mongla (28.7% and 35.7%, respectively). *Heritiera fomes* (Sundri), the most valuable species, is relatively evenly spread across Dacope (33.6%), Koyra (32.7%) and Mongla (26.7%).

Figure 2. Distribution of mangrove species by *upazila*

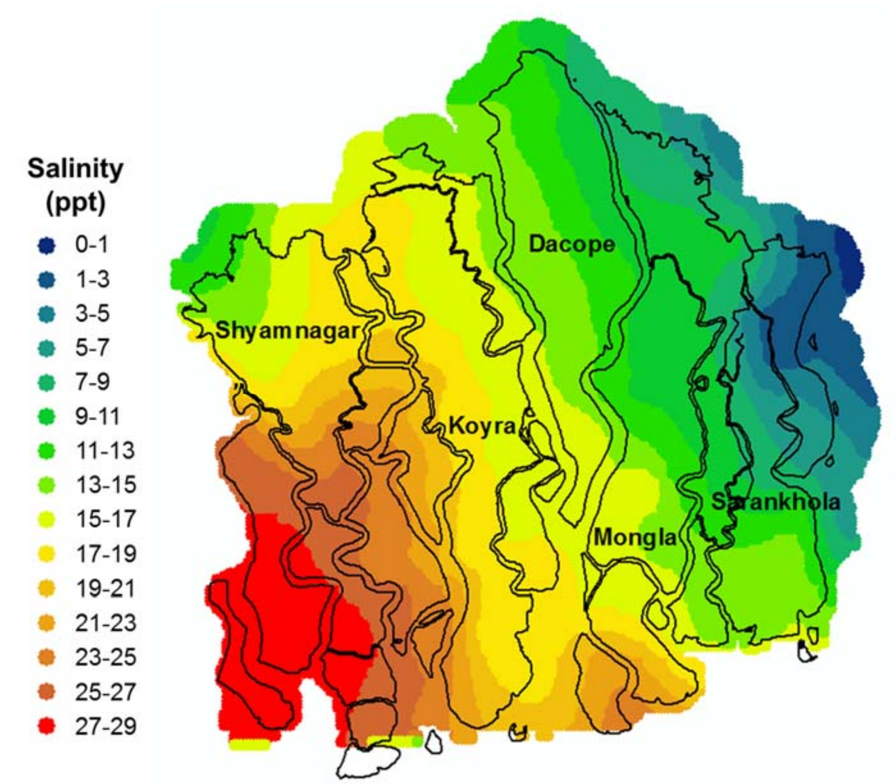


Our findings are in general agreement with the salinity tolerances of mangrove species documented in the report of the IUCN Wetlands Programme (Hussain and Acharya 1994) and the forest inventory of the Bangladesh Sundarbans (Chaffey, Miller and Sandom 1985).

3. Estimating Salinity Ranges for Mangrove Species

To determine salinity tolerance ranges for mangrove species and mixes, we combine the distribution data illustrated in Figure 1 with high-resolution aquatic salinity maps developed by Dasgupta, et al. (2015a). Their research has produced salinity estimates for seven months in 2012: January - June and December. Seven-month mean salinity (Figure 3) exhibits an extremely broad range, from near-marine salinity (27-29 ppt) in southwest Shyamnagar to fresh water (0-1 ppt) in northeast Sarankhola.

Figure 3. Sundarbans region: estimated aquatic salinity, 2012



Source: Dasgupta, et al. (2014a)

Geographic overlays of salinity maps in Figure 3 with the mangrove species displayed in Figure 1 reveal a broad spatial correlation pattern in Shyamnagar, Koyra and Dacope: apparent domination for *Ceriops decandra* (Goran) in the salinity range 23-29 ppt, *Excoecaria agallocha* (Gewa) mixes with *Ceriops decandra* (Goran) and *Heritiera fomes* (Sundri) in 17-21, and *Heritiera fomes* (Sundri) in 11-17.

Although these observations provide a useful overview, our high-resolution information permits more precise estimation of salinity tolerance ranges. Our mangrove database identifies 14 mangrove types (species and mixed species) in 8.44 million pixels for the region. We assign each mangrove pixel to the nearest salinity pixel, calculate total pixels for each integer salinity value and mangrove type, and use the totals to compute incidence probabilities for mangrove types across salinity values. We drop marginal occurrences beyond the 90th percentile to ensure robust projections

Table 2 corroborates the previous observations about mangrove spatial distributions, while providing much more detail about the relative incidence of mangrove species across salinity intervals.[8] Among individual species, clustering is pronounced for *Avicennia alba, marina, officinalis* (Baen) (in the salinity range 12-14 ppt), *Excoecaria agallocha* (Gewa) (14-16*)*, *Ceriops decandra* (Goran) (27-28) *and Heritiera fomes* (Sundri) (14-17), while *Sonneratia apetala* (Keora) is more evenly distributed across a broad salinity range. Salinity ranges for mixed groups reflect the ranges of their constituent species (e.g., *Excoecaria agallocha* (Gewa) - *Ceriops decandra*

[8] In Table 2, we use bold print to identify key focal species for our analysis. The column for each species records the percent of its range that is observed at each salinity measure.

(Goran) and *Ceriops decandra* (Goran) - *Excoecaria agallocha* (Gewa); *Excoecaria agallocha* (Gewa) - *Heritiera fomes* (Sundri) and *Heritiera fomes* (Sundri) - *Excoecaria agallocha* (Gewa).

Table 2: Sundarbans mangroves: estimated incidence by salinity interval

Salinity (ppt)	Baen	Gewa	Gewa Goran	Gewa Mathal	Gewa Sundri	Goran	Goran Gewa	Keora	Passur Kankra	Passur Kankra Baen	Sundri	Sundri Gewa	Sundri Passur	Sundri Passur Kankra
2								**0.01**						
3	**0**	**0**	0	0	0.23	**0**	0	**0.37**	0	0	**0.90**	0.22	0	0
4	**0**	**0**	0	0	0.98	**0**	0	**0.02**	0	0	**1.33**	0.69	0	0
5	**0**	**0**	0	0	1.66	**0**	0	**0.48**	0	0	**1.03**	0.72	0	0
6	**0**	**3.07**	0	0	1.61	**0**	0	**1.23**	0	0	**1.03**	0.92	0	0
7	**0**	**2.46**	0	0	1.72	**0**	0	**0.72**	0	0	**0.58**	0.91	0	0
8	**0**	**1.40**	0	0	2.77	**0**	0	**0.72**	0	0	**0.99**	1.07	0	0
9	**1.12**	**0.52**	0	0	5.60	**0**	0	**4.37**	0	0	**3.80**	3.79	0.20	0
10	**0.53**	**0.93**	0	0	8.52	**0**	0	**2.37**	5.44	0	**7.89**	3.53	0.83	0
11	**0.17**	**1.22**	0	0	6.72	**0**	0	**2.77**	0	0	**9.80**	2.96	1.54	3.18
12	**12.34**	**1.65**	0	0	4.36	**0**	0	**3.54**	9.07	0	**9.11**	3.88	3.43	6.45
13	**25.59**	**3.30**	0.19	0	5.05	**0**	0	**3.60**	11.68	0	**6.40**	5.09	0.84	41.22
14	**16.13**	**10.42**	0.24	0	6.94	**0**	0	**8.07**	6.46	0.49	**10.05**	13.39	1.82	21.29
15	**5.61**	**15.16**	2.25	2.03	9.23	**1.05**	0.32	**8.21**	1.81	44.75	**11.53**	17.62	10.21	5.26
16	**2.06**	**14.47**	0.63	0.29	4.62	**0.09**	0.49	**12.56**	19.39	17.57	**12.76**	11.41	64.95	16.79
17	**1.59**	**6.45**	0.89	0	5.46	**1.66**	0.37	**5.06**	0	0	**14.83**	9.69	3.00	0
18	**5.58**	**5.42**	3.24	0.68	5.66	**1.89**	0.84	**7.34**	0	0	**0**	7.39	2.02	0
19	**8.54**	**6.55**	5.37	0.20	6.54	**0.38**	0.65	**4.03**	1.81	0	**0**	5.74	3.99	0
20	**9.61**	**4.79**	5.88	3.47	5.97	**0.69**	0.77	**3.89**	41.5	4.38	**0**	3.20	0	0
21	**2.43**	**5.19**	6.73	5.91	5.75	**0.68**	1.41	**4.82**	0	8.74	**0**	0	0	0
22	**0**	**5.92**	7.21	2.10	4.70	**0.62**	1.48	**6.77**	0	7.61	**0**	0	0	0
23	**0**	**5.14**	8.66	4.98	0	**0.54**	3.34	**4.48**	0	11.37	**0**	0	0	0
24	**0**	**0**	10.52	5.64	0	**2.36**	6.83	**2.56**	0	0	**0**	0	0	0
25	**0**	**0**	9.25	19.01	0	**10.33**	10.02	**3.93**	0	0	**0**	0	0	0
26	**0**	**0**	12.35	36.16	0	**3.45**	8.99	**0**	0	0	**0**	0	0	0
27	**0**	**0**	15.53	18.08	0	**29.91**	31.69	**0**	0	0	**0**	0	0	0
28	**0**	**0**	11.06	0	0	**46.36**	32.79	**0**	0	0	**0**	0	0	0

4. Projections of Future Mangrove Distributions

4.1 Projecting Salinity in 2050

Using high-resolution digital maps of aquatic salinity and mangroves, we have estimated salinity tolerance ranges and clustering patterns within those ranges for 14 mangrove species and species mixes. In this section, we explore alternative salinity futures and the associated mangrove distributions. Our aquatic salinity scenarios are drawn from Dasgupta, et al. (2015a), who quantify the prospective relationship between climate-induced changes in sea level, temperature, rainfall, and riverine flows from the Himalayas, and the spread and intensity of aquatic salinization in the coastal zone. Their research takes account of projected land subsidence in the Ganges Delta, as well as alternative levels of upstream freshwater withdrawal.

They develop 27 scenarios for 2050 that incorporate three AR4 global emissions scenarios B1, A1B, A2)[9] ; two estimates of sea level rise by 2050 (27 cm for scenario B1, 32 cm for A1B

[9] Basic elements of the three scenarios are as follows:

B1: Rapid economic growth with convergence among regions; global population that peaks in mid-century and declines thereafter; rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies.

A1B: Rapid economic growth with convergence among regions; global population that peaks in mid-century and declines thereafter; rapid introduction of new and more efficient technologies; energy from mixed fossil and renewable sources.

A2: Non-convergent economic development; continuously increasing population; heterogeneous technologies and energy sources.

and A2); three global circulation models (IPSL-CM4, MIROC3.2, ECHO-G)[10]; and three annual subsidence rates for land in the lower Ganges Delta (2, 5 and 9 mm/year).[11]

Figure 4 illustrates the scale of potential change by combining our 2012 salinity map with the maximum change result for 2050 (AR4 A2 scenario, IPSL global circulation model, 9 mm/year subsidence in the lower Ganges Delta). Two patterns are particularly striking in Figure 4. First, higher salinity spreads northward and eastward as the sea level rises, riverine flows change and subsidence continues in the lower Ganges Delta. Second, the transition from 2012 to 2050 is most pronounced in Koyra and northern Shyamnagar.

Figure 4 illustrates the scale of potential change by combining our 2012 salinity map with the maximum change result for 2050 (AR4 A2 scenario, IPSL global circulation model, 9 mm/year subsidence in the lower Ganges Delta).

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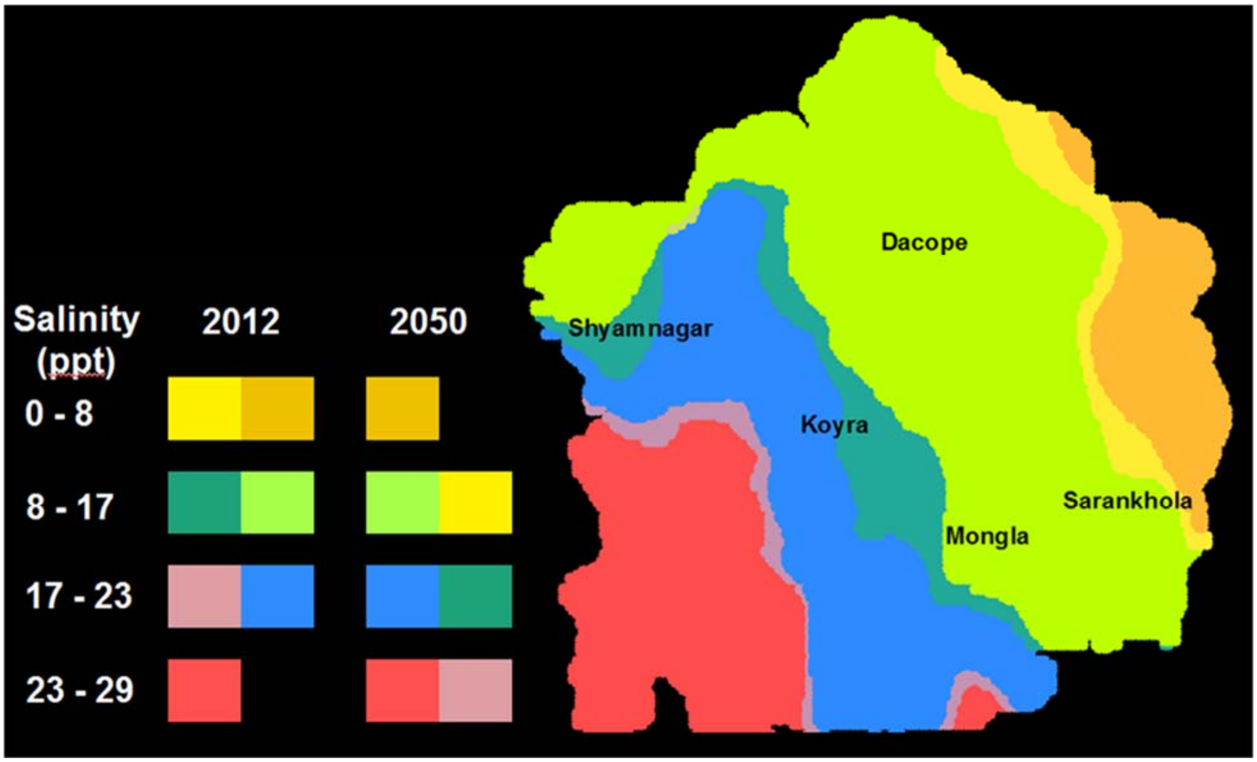
[10] Model implementing institutions are as follows:

IPSL-CM4:	Institut Pierre Simon Laplace, France;
MIROC3.2:	Center for Climate System Research, University of Tokyo, National Institute for Environmental Studies, Japan, Frontier Research Center for Global Change, Japan;
ECHO-G:	Meteorological Institute of the University of Bonn, Germany, Model and Data Group, Max Planck Institute for Meteorology, Hamburg, Germany, Korea Meteorological Administration.

In their salinity modeling exercise, Dasgupta et al. (2015a) started with the temperature and rainfall projections for the territory of Bangladesh from 9 GCMs. Models were then ranked from low to high based on their median projections. Finally, three GCMs (IPS-CM4L, MIROC3.2, and ECHO-G) with the highest, intermediate and lowest ranks and the corresponding projections were used to capture the uncertain extent of climate change.

[11] The Ganges Delta in Bangladesh is still in an active, dynamic state. Therefore, it is critical to include projection of land subsidence of the lower Bengal delta (the Ganges Delta in Bangladesh) in simulating future climate scenarios. Physical impacts of relative mean sea-level rise are caused by a combination of sea-level rise scenarios associated with global warming and vertical land movement (subsidence or accretion). At present there is an intense controversy in Bangladesh regarding the estimates and projections of land subsidence in the coastal region (see Dasgupta et al. 2015). In light of the widely varying estimates, the hydrological modeling for our analysis was run for three alternative scenarios of land subsidence: 2 mm per year, 5 mm per year, and 9 mm per year.

Figure 4: Salinity ranges, 2012 and 2050 (AR4 A2, GCM IPSL, Subsidence 9 mm/year)



In Figure 4, color-coded rows in the legend identify salinity ranges in 2012 and 2050. The first row shows that in 2012, salinity in the range 0 - 8 ppt characterizes the areas colored tan and brown in the eastern region. By 2050, advancing salinity shrinks the 0 - 8 ppt range to the brown region alone. In a similar vein, salinity in the range 8 - 17 ppt is found in the areas colored dark and light green in 2012. By 2050, increasing salinity causes an eastward shift of this salinity range. The western (dark green) part moves up to the range 17-23 ppt, while the tan area in the east (previously in the range 0 - 8 ppt) moves into the range 8 - 17 ppt.

Two patterns are particularly striking in Figure 4. First, higher salinity spreads northward and eastward as the sea level rises, riverine flows change and subsidence continues in the lower

Ganges Delta. Second, the transition from 2012 to 2050 is most pronounced in Koyra and northern Shyamnagar.

4.2 Projecting Mangrove Species Migration Through 2050

We estimate the effects of salinization on mangrove migration by combining the estimates of salinity tolerance ranges in Table 2 with our 27 aquatic salinity scenarios. For each of the 8.44 million pixels in our map, we identify candidate mangrove types whose salinity tolerance range includes the pixel's projected salinity in 2050. We assume that the currently-resident species will continue occupying the pixel if projected salinity remains within its incidence range. Where this is not the case, we select transition-appropriate candidate species with the highest likelihood score: incidence probability for the pixel's projected salinity (from Table 2), divided by the distance to the candidate species' nearest habitat in 2013. The likelihood score incorporates two predictive factors: a species' current locational intensity at the pixel's projected salinity, and the species' proximity to the pixel, which proxies its conformity with unobserved local conditions in the pixel's neighborhood.[12]

To illustrate the latter factor, consider species A and B that have identical incidence probabilities for a pixel's projected salinity. Species A has current habitat within 5 km of the pixel, while the closest habitat for B is 200 km away. This disparity suggests that unobserved local conditions favor A.

[12] We have tested three weighting methodologies for this exercise: linear distance, distance squared (which gives more weight to proximity), and the square root of distance (which gives less weight). The spatial projection results are effectively identical in all cases, so we confine our presentation to the results for linear distance. The other results are available from the authors on request.

We also use historical and scientific information to select transition-appropriate species for particular cases. *Sonneratia apetala* (Keora) is known to colonize only mudflats in newly-emergent areas, but all of our scenarios incorporate some measure of subsidence. We therefore delete *Sonneratia apetala* (Keora) from the list of transition candidates. We assume that *Sonneratia apetala* (Keora) remains in its currently-inhabited pixels if their projected salinity falls within *Sonneratia apetala* (Keora)'s incidence range; elsewhere it is replaced by appropriate transition candidates.

We also eliminate transition candidacy for *Excoecaria agallocha* (Gewa) Mathal (coppice), which presents a special case historically. This vegetation type emerged in previously-exploited areas, as *Excoecaria agallocha* (Gewa) mangroves were harvested for paper mills and coppices were regenerated from the root stock. Such harvesting no longer occurs, so future stands of *Excoecaria agallocha* (Gewa) - Mathal (coppice) will only reflect current stands, minus areas where it is replaced by other species because projected salinity exceeds its upper incidence limit.

We rely on prior knowledge of transition dynamics to modify lists of potential replacements for three mangrove types: *Heritiera fomes* (Sundri), *Heritiera fomes* (Sundri) - *Xylocarpus mekongensis* (Passur), and *Heritiera fomes* (Sundri) - *Xylocarpus mekongensis* (Passur) - *Bruguiera gymnorrhiza* (Kankra). None of these types is likely to be replaced directly by *Excoecaria agallocha* (Gewa) - *Ceriops decandra* (Goran), *Ceriops decandra* (Goran), or *Ceriops decandra* (Goran) - *Excoecaria agallocha* (Gewa). And we have pruned potential replacement lists accordingly.

4.3 Illustrative Projection Results

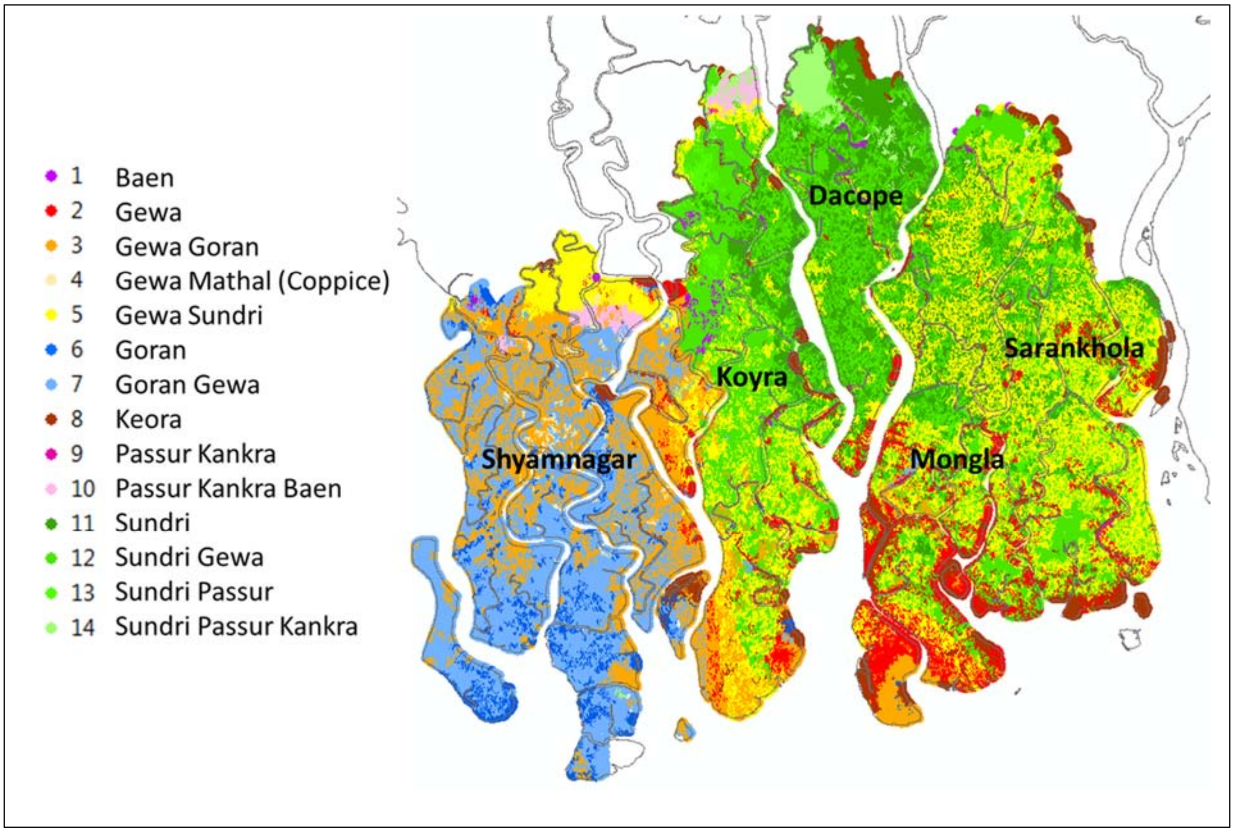
Figure 5 illustrates our projection results using the maximal case (AR4 A2, GCM IPSL, subsidence 9 mm/year) because it provides the clearest view of potential change. Comparison of

Figure 5 with Figure 4 provides a useful overview of progressive salinization's impacts on the most populous mangrove types. *Ceriops decandra* (Goran) and *Ceriops decandra* (Goran) *Excoecaria agallocha* (Gewa) advance to the north and east in Shyamnagar; *Excoecaria agallocha* (Gewa), *Excoecaria agallocha* (Gewa) - *Ceriops decandra* (Goran) and *Excoecaria agallocha* (Gewa) - *Heritiera fomes* (Sundri) shift eastward in Koyra and expand in southern Mongla; *Heritiera fomes* (Sundri) retreats almost entirely from central and western Koyra, replaced mostly by *Heritiera fomes* (Sundri) - *Excoecaria agallocha* (Gewa) in areas not newly-dominated by *Excoecaria agallocha* (Gewa) - *Heritiera fomes* (Sundri).

Table 3: Sundarbans mangrove area: percent change, 2013 - 2050, by mangrove type and scenario

			Mangrove Type													
AR4	GCM	Subs (mm/ yr)	Baen	Gewa	Gewa Goran	Gewa Mathal (Coppice)	Gewa Sundri	Goran	Goran Gewa	Keora	Passur Kankra	Passur Kankra Baen	Sundri	Sundri Gewa	Sundri Passur	Sundri Passur Kankra
A1B	IPSL	9	2.4	19.8	22.5	-9.1	-6.4	5.5	6.7	-11.2	-45.1	38.8	-24.2	-4.6	10.3	-18.0
A2	IPSL	9	2.2	20.0	22.3	-9.1	-6.7	5.5	6.7	-11.2	-44.0	40.3	-23.1	-4.7	8.8	-16.4
B1	IPSL	9	-3.3	20.4	21.4	-6.9	-6.4	5.4	6.5	-11.1	-44.2	42.3	-23.0	-4.6	7.6	-15.5
A2	ECHO-G	9	-1.3	20.9	21.7	-8.6	-6.3	4.3	6.0	-11.1	-44.2	39.4	-21.8	-4.9	6.9	-13.5
A1B	IPSL	5	-5.0	22.1	19.0	-6.9	-5.9	5.2	6.1	-10.5	-28.9	51.2	-21.8	-4.7	6.9	-12.7
A1B	ECHO-G	9	-1.3	19.9	22.2	-8.6	-6.9	5.5	6.7	-11.2	-44.2	39.4	-21.7	-4.9	6.8	-13.5
B1	ECHO-G	9	-4.4	20.5	21.3	-6.9	-6.6	5.4	6.5	-11.1	-44.2	44.0	-21.5	-5.0	5.2	-9.3
A2	MIROC	9	-4.2	20.1	22.1	-8.6	-7.0	5.5	6.7	-11.2	-44.2	39.8	-21.3	-5.1	6.2	-9.3
A2	IPSL	5	-5.2	22.1	19.0	-6.9	-6.0	5.2	6.1	-10.5	-29.6	51.3	-21.2	-4.8	5.5	-11.4
A1B	MIROC	9	-1.6	19.8	22.2	-8.6	-7.0	5.5	6.7	-11.2	-44.2	39.9	-21.2	-5.1	6.2	-11.7
B1	MIROC	9	-4.5	20.4	21.2	-6.9	-6.6	5.4	6.5	-11.1	-44.2	45.8	-21.0	-5.2	4.8	-8.9
B1	IPSL	5	-5.6	22.3	18.3	-6.9	-5.7	5.2	6.0	-10.3	-29.6	46.4	-20.8	-4.8	5.4	-8.9
A2	ECHO-G	5	-6.6	22.1	18.9	-6.9	-6.1	5.2	6.1	-10.5	-35.0	51.7	-20.2	-5.2	4.0	-6.7
A1B	MIROC	5	-7.7	21.9	18.8	-6.9	-6.0	5.2	6.1	-10.5	-35.0	50.5	-20.0	-5.1	3.9	-6.5
B1	ECHO-G	5	-5.8	21.9	18.1	-6.9	-5.7	5.2	6.0	-10.3	-35.0	46.3	-20.0	-4.9	3.9	-6.5
B1	MIROC	5	-5.8	21.8	18.1	-6.9	-5.8	5.2	6.0	-10.3	-35.0	46.3	-19.7	-5.0	3.9	-6.5
A1B	IPSL	2	-5.7	22.4	17.2	-6.9	-5.5	5.1	5.7	-10.0	-29.6	49.5	-19.4	-4.8	3.8	-7.3
A2	IPSL	2	-5.8	22.2	17.1	-6.9	-5.5	5.1	5.7	-10.0	-35.0	49.5	-19.3	-4.9	3.6	-6.7
B1	IPSL	2	-6.2	22.8	16.1	-6.9	-5.2	5.1	5.5	-9.9	-35.5	49.2	-18.8	-4.7	4.1	-6.7
A2	ECHO-G	2	-6.2	21.9	17.1	-6.9	-5.6	5.1	5.6	-10.0	-35.4	50.4	-18.7	-4.9	3.9	-6.1
A1B	ECHO-G	2	-6.4	21.9	17.1	-6.9	-5.6	5.1	5.6	-10.0	-35.5	50.4	-18.7	-4.9	4.0	-6.0
A2	MIROC	2	-7.0	21.9	16.9	-6.9	-5.5	5.1	5.6	-10.0	-35.5	50.5	-18.5	-4.9	3.9	-5.8
A1B	MIROC	2	-6.9	21.9	16.8	-6.9	-5.5	5.1	5.6	-10.0	-35.5	50.5	-18.5	-4.9	3.9	-5.8
B1	ECHO-G	2	-7.0	23.0	16.0	-6.9	-5.3	5.1	5.5	-9.9	-35.5	49.3	-18.3	-4.8	4.0	-6.0
B1	MIROC	2	-7.0	22.7	15.9	-6.9	-5.2	5.1	5.5	-9.9	-35.5	49.3	-18.2	-4.8	3.9	-5.8
A1B	ECHO-G	5	-10.8	22.8	13.5	0.0	-4.7	4.2	5.0	-9.8	-12.5	44.9	-14.4	-5.0	5.5	-5.7
A2	MIROC	5	-10.2	22.2	13.3	-0.1	-4.2	4.5	4.7	-9.8	-8.0	33.1	-12.1	-5.5	3.3	-5.7

Figure 5: Mangrove distributions, 2050



4.4 General Assessment of Mangrove Projections

We generalize our results by projecting the distribution of mangrove types for all 27 scenarios. Table 3 is sorted in ascending order by percent change for *Heritiera fomes* (Sundri), the most valuable species. All scenarios project declines for *Heritiera fomes* (Sundri), ranging from 24.2% to 12.1%. The declines are generally largest for 9 mm/year subsidence, followed successively by 5 mm/year and 2 mm/year. We also find large declines for *Xylocarpus mekongensis* (Passur) - *Bruguiera gymnorrhiza* (Kankra) (from 45.1% to 8.0%) and large increases for *Excoecaria agallocha* (Gewa) (19.8% to 23.0%), *Excoecaria agallocha* (Gewa) - *Ceriops decandra* (Goran) (13.3% to 22.5%) and *Xylocarpus mekongensis* (Passur) - *Bruguiera gymnorrhiza* (Kankra) - *Avicennia alba, marina, officinalis* (Baen) (33.1% to 51.7%), while projected increases are significantly smaller for *Ceriops decandra* (Goran) and *Ceriops decandra* (Goran) - *Excoecaria agallocha* (Gewa). Our projections for *Heritiera fomes* (Sundri) and *Ceriops decandra* (Goran) are in general agreement with estimated changes by Hoque et al. (2006), Potkin (2004); and Blasco and Aizpuru (2002).[13]

5. Implications for Poor Communities in Sundarbans *Upazila*s

The Sundarbans contributes significantly to both the economy of southwestern Bangladesh and the national economy (Potkin 2004), and forest-based livelihoods have been important in the region. In the past, the Sundarbans was an important source of timber, pulp, firewood, reeds, *Nypa fruticans*, Phoenix Fronds, honey, bee wax, fish, crab and shrimp. In 1989 the Forest Department imposed a moratorium on the felling of trees and collection of firewood. The remaining timber[14] has potential value, however, and our projections indicate that salinization will further deplete the stock of *Heritiera fomes* (Sundri), the most valuable species. Many households remain dependent on collection of golpata (*Nypa fruticans*) leaf for roofing, grass for matting and fodder, reeds for fencing, bee-wax for commercial use, honey, fish and crab for consumption (Uddin et al. 2013; IPAC 2010; Gopal and Cahuhan 2006). All of these activities are likely to be affected as advancing salinization changes the spatial distribution of mangrove ecosystems.

The Sundarbans mangrove region includes five *upazila*s in Khulna Division: Dacope and Koyra in Khulna District; Mongla and Sarankhola in Bagerhat, and Shyamnagar in Satkhira. Many of these *upazila*s are poor compared to the national standard. We identify the poverty status of the

[13] Mukhopadhyay et al. (2015) project future mangrove distributions from recent trends in mangrove migration using an approach based on a Markov chain model and cellular automata. Our approach differs significantly, because we project alternative futures by combining empirical estimates of mangrove species' salinity tolerance ranges with salinity projections developed from several IPCC AR4 climate scenarios, global circulation model projections, and models of riverine flow and land subsidence in the lower Ganges Delta.

[14] Although the ban on felling trees in the Sundarbans is likely to remain, estimated Annual Allowable Cuts ranging from 54,000 m^3 to approximately 143,000 m^3 of Sundri were reported in the Integrated Resource Management Plan of the Forest Department of Government of Bangladesh in 2010 (GoB 2010).

Sundarban *upazila*s using 2010 poverty incidence estimates provided by the World Bank (2014a) and 2011 population estimates from the Bangladesh Bureau of Statistics. Following World Bank (2014a), we use two standards to determine poverty incidence: the upper poverty line, for households whose food expenditures are at or below the food poverty line established by the Bangladesh Bureau of Statistics;[15] and the lower poverty line, for extremely poor households whose total expenditures are at or below the food poverty line.

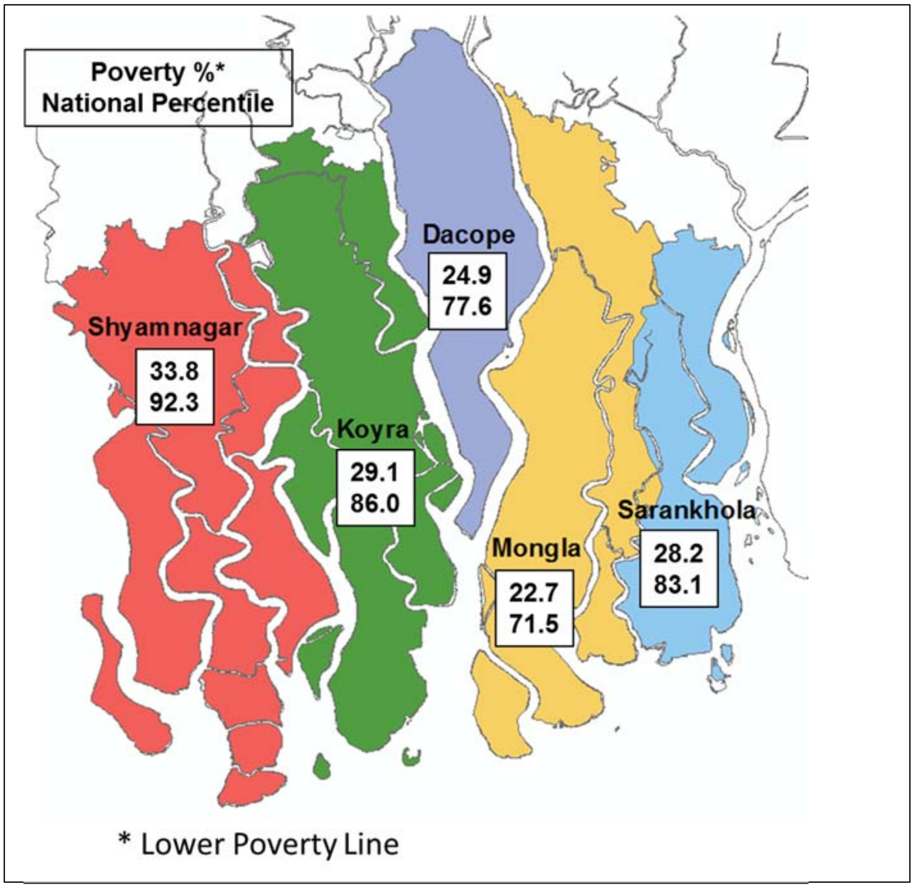
Table 4 and Figure 6 provide summary statistics for the five *upazila*s. Although all five are poor by national standards, their national percentiles vary from 71.5 to 92.3 for lower-line poverty and 77.0 to 91.0 for upper-line poverty. Koyra and Shyamnagar are the poorest (by both standards) and most populous. Koyra's lower-line and upper-line poverty incidences -- 29.1% and 49.1% -- are in the national 86th and 89th percentiles, respectively. Its lower- and upper-line poverty populations are 56,400 and 95,200. Shyamnagar's lower- and upper-line poverty incidences are in the national 92nd and 91st percentiles, with poverty populations of 107,600 and 159,800.

Table 4: Poverty status of Sundarbans *upazila*s

	Lower Poverty Line			Upper Poverty Line		
Upazila	% Poor	National Percentile	Population ('000)	% Poor	National Percentile	Population ('000)
Mongla	22.7	71.5	31.0	41.9	77.0	57.2
Dacope	24.9	77.6	37.9	44.5	82.2	67.8
Sarankhola	28.2	83.1	33.6	48.0	88.1	57.2
Koyra	29.1	86.0	56.4	49.1	89.2	95.2
Shyamnagar	33.8	92.3	107.6	50.2	91.0	159.8

[15] See Report of the Household Income and Expenditure Survey/HIES 2010. Bangladesh Bureau of Statistics, Government of Bangladesh.

Figure 6: Sundarbans *upazila*s: poverty status (lower poverty line)



We assess the implication of projected mangrove migration for poor communities by computing changes at the *upazila* level for 27 climate scenarios. Table 5 summarizes the results for five dominant mangrove species. Here it is worth recalling that all five *upazila*s are poor by national standards, but Shyamnagar and Koyra are the poorest and most populous (Table 4). For *Heritiera fomes* (Sundri), the most valuable[16] species overall, the negative impact is concentrated in Koyra, with a median decline of 58.0%. However, this is at least partly offset by significant increases in *Avicennia alba*, *marina*, *officinalis* (Baen) (45.6%), *Excoecaria agallocha* (Gewa) (20.0%) and *Ceriops decandra* (Goran) (20.0%). In contrast, Shyamnagar has very large declines

[16] The estimated price of Sundri-equivalent-timber BDT 41,890/ m^3, and the price of other species is BDT.2,375/m^3 (Data Source: Economic and Financial Analysis of the Ganges Barrages Study Project).

in *Avicennia alba, marina, officinalis* (Baen) (71.0%), *Excoecaria agallocha* (Gewa) (67.3%) and *Sonneratia apetala* (keora) (68.1%) with negligible offsetting gains for other valuable species. Overall, the disproportionate losses of *Heritiera fomes* (Sundri) in Koyra and three key species in Shyamnagar indicate that salinity-induced mangrove migration will have a strongly regressive impact on the value of standing timber stocks in the region.

Our results also suggest some potentially-countervailing effects. For example, many poor households collect honey[17] and wax during the summer season from March to June (Krishnamurty 1990; Chakrabarti 1986). Field research has indicated that among the various mangrove species, honey bees in the Sundarbans prefer *Excoecaria agallocha* (Gewa), *Avicennia alba, marina, officinalis* (Baen), *Ceriops decandra* (Goran), *Heritiera fomes (*Sundri), *Sonneratia apetala* (Keora) and *Bruguiera gymnorrhiza* (Kankra) (Chakrabarti, 1987).[18] Hence, the change in mangrove species in favor of *Avicennia alba, marina, officinalis* (Baen), *Excoecaria agallocha* (Gewa), *Ceriops decandra* (Goran), and *Sonneratia apetala* (keora) is likely to increase overall honey production. However, the impacts will not be evenly distributed across *upazila*s. Table 5 suggests that the poorest *upazila*, Shyamnagar, will experience significant declines in honey production from *Avicennia alba, marina, officinalis* (Baen), *Excoecaria agallocha* (Gewa) and *Sonneratia apetala* (keora). On the other hand, Koyra will benefit from an increase in *Avicennia alba, marina, officinalis* (Baen), *Excoecaria agallocha* (Gewa) and *Ceriops decandra* (Goran), and Mongla will benefit from an increase in *Excoecaria agallocha* (Gewa).

[17] According to experts in Bangladesh, potential honey production is between 3,000 and 5,000 tons per annum if the potential is fully exploited. At present, the price is Tk. 125 to Tk. 135 per kg for honey collected from Sundarbans with rudimentary sieving. The estimated total value of honey production from the Sundarbans is between Tk. 375 million and Tk. 675 million per annum if the full potential of honey production is exploited.

[18] In the Sundarbans, bees display the following preference percentages for making honeycombs: Excoecaria agallocha (Gewa) (39%), Avicennia alba, marina, officinalis (Baen) (16%), Ceriops decandra (Goran) (11%), Garjan (10%), Heritiera fomes (Sundri) (9%), Sonneratia apetala (keora) (5%), and Bruguiera gymnorrhiza (Kankra) (4%). See Chakrabari (1987).

While increased honey collection can be beneficial, we should stress that this activity is fraught with hazards from twice-daily tidal inundations and attacks by man-eating tigers,

Table 5: Median changes in key mangrove species by *upazila*, 27 scenarios

	Median % Change				
Upazila	*Avicennia alba, marina, officinalis* (Baen)	*Excoecaria agallocha* (Gewa)	*Ceriops decandra* (Goran)	*Sonneratia apetala* (keora)	*Heritiera fomes* (Sundri)
Dacope	0	0	0	0	0
Koyra	45.6	20.0	20.0	-0.3	-58.0
Mongla	0	47.4	(a)	0	-2.3
Sarankhola	0	0	0	0	0
Shyamnagar	-71.0	-67.3	4.2	-68.1	0

(a) Ceriops decandra (Goran) has an extremely small median increase in Mongla, where the species has a tiny presence in 2013. This would translate to a huge but misleading percent increase.

crocodiles, venomous snakes and sharks.[19] Unfortunately, augmented production of honey is likely to increase conflicts between humans and wildlife.

6. Summary and Conclusions

In this paper, we have used a detailed scenario analysis to assess possible impacts of climate change, sea level rise and land subsidence on aquatic salinity, mangrove species migration and poor communities in the Bangladesh Sundarbans. Our analysis draws on spatially-formatted information from Dasgupta et al. (2015a), including aquatic salinity in 2012, and 27 projections for 2050, developed from combinations of three IPCC climate change scenarios (B1, A1B, A2),

[19] The available statistics indicates that thousands of honey collectors have been killed by tigers, crocodiles and snakes since human habitation of the Sundarbans began. It is believed that approximately 80 people are killed every year by tigers alone.

three global circulation models (IPSL-CM4, MIROC3.2, ECHO-G) and three assumptions about the rate of subsidence in the Ganges Delta (2, 5 and 9 mm/year).

Our results cover salinity-induced migration patterns for 14 mangrove types: both sole species -- *Avicennia alba, marina, officinalis* (Baen), *Excoecaria agallocha* (Gewa), *Ceriops decandra* (Goran), *Bruguiera gymnorrhiza* (Kankra), *Sonneratia apetala* (keora), *Xylocarpus mekongensis* (Passur), *Heritiera fomes* (Sundri) -- and combinations of those species.

Using the most recent digital maps of aquatic salinity and mangrove distributions, we estimate incidence probabilities by unit salinity interval for each mangrove type. Then we combine estimated incidence probabilities with information on current species locations and our 27 salinity scenarios to project the distribution of mangrove types in 2050. We find significant overall losses for *Heritiera fomes* (Sundri) and *Xylocarpus mekongensis* (Passur) *Bruguiera gymnorrhiza* (Kankra), along with substantial gains for *Excoecaria agallocha* (Gewa), *Excoecaria agallocha* (Gewa) *Ceriops decandra* (Goran) and *Xylocarpus mekongensis* (Passur) *Bruguiera gymnorrhiza* (Kankra) *Avicennia alba, marina, officinalis* (Baen). Projected gains are modest for *Ceriops decandra* (Goran) and *Ceriops decandra* (Goran) *Excoecaria agallocha* (Gewa).

We overlay the results with an administrative map of the Sundarbans region and compute changes in mangrove types for the five *upazila*s in the region. To assess potential poverty impacts, we combine our results with upazila poverty populations identified using two bounds: an upper poverty line, for households whose food expenditures are at or below the food poverty line established by the Bangladesh Bureau of Statistics; and a lower poverty line, for extremely poor households whose total expenditures are at or below the food poverty line. Our calculations cover 27 salinity scenarios for 2050.

We find highly-varied patterns of gain and loss for the 14 mangrove types across the five *upazila*s, with particularly interesting results for five species that have significant economic and ecological value: *Heritiera fomes* (Sundri), *Avicennia alba, marina, officinalis* (Baen), *Excoecaria agallocha* (Gewa), *Ceriops decandra* (Goran) and *Sonneratia apetala* (keora). For *Heritiera fomes* (Sundri), the most valuable species overall, the negative impact is concentrated in Koyra, with a median decline of 58.0%. However, this is at least partly offset by significant increases in *Avicennia alba, marina, officinalis* (Baen), *Excoecaria agallocha* (Gewa) and *Ceriops decandra* (Goran). In contrast, Shyamnagar has very large declines in *Avicennia alba, marina, officinalis* (Baen), *Excoecaria agallocha* (Gewa) and *Sonneratia apetala* (Keora), with negligible offsetting gains in other valuable species. In summary, our results suggest that migration of mangrove species driven by aquatic salinization will have the greatest negative impacts on the poorest *upazila*s via loss of standing timber value and honey production, as well as increased risk of human-wildlife conflicts.

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. At present, the water from the Ganges which flows through its distributary, the Gorai River, is the only major source of freshwater for the Sundarbans. The Gorai is almost empty during the dry season (December to May), and tidal effects cause intrusion of saline water through several major rivers -- the Baleswar, Jamuna, lower Meghna, Malancha, Pussur, Sibsa, and Tnetulia. The region is very flat, so strong tidal effects at times travel up to 200 km 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 hydrological regime changes (e.g., river training and other engineering work) will probably be futile (Potkin 2004). Hence, engineering attempts to control rising salinity in the Sundarbans do not seem likely to succeed.

The Sundarbans is a UNESCO World Heritage Site, internationally recognized under the Ramsar Convention, and effective conservation management will require establishment of location-specific baseline data for tree stand structures, tree abundance, species richness and diversity, the export of nutrients, hydrological patterns, rates of sedimentation and relative sea-level rise (see McLeod and Salm (2006) in the IUCN-Nature Conservancy Report on Managing Mangroves for Resilience to Climate Change). Such baseline data will permit monitoring of changes in the Sundarbans mangrove systems over time. Since mangroves depend on fluxes of both daily tides and fresher water, management protocols should include both connectivity between mangrove systems and nearby river sources, and maintenance of upland fresh water catchments. Areas that are likely to survive sea level rise in a changing climate should be identified (See Dasgupta et al. 2016b for a methodology.) Tidal fluctuations, varying pH and salinity should be monitored, to support additional planting of suitable mangrove species where necessary. Attempts to restore mangrove areas that are currently degraded should also be undertaken.

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.

Worldwide, low-lying coastal regions will be at increasing risk from inundation, salinization and other potential impacts because sea level rise will continue beyond 2100 even if greenhouse gas emissions are stabilized in the near future.[20] Impacts on globally-important mangrove ecosystems and the socioeconomic implications will undoubtedly be an important part of this story. High-resolution spatial assessments of these problems have been scarce, and this paper represents an attempt to narrow the knowledge gap for coastal Bangladesh. We hope that analyses such as this one 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.

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

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