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REPORT

Climate change and soil salinity: The case of coastal Bangladesh

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Abstract This paper estimates location-specific soil salinity in coastal Bangladesh for 2050. The analysis was conducted in two stages: First, changes in soil salinity for the period 2001–2009 were assessed using information recorded at 41 soil monitoring stations by the Soil Research Development Institute. Using these data, a spatial econometric model was estimated linking soil salinity with the salinity of nearby rivers, land elevation, temperature, and rainfall. Second, future soil salinity for 69 coastal sub-districts was projected from climate-induced changes in river salinity and projections of rainfall and temperature based on time trends for 20 Bangladesh Meteorological Department weather stations in the coastal region. The findings indicate that climate change poses a major soil salinization risk in coastal Bangladesh. Across 41 monitoring stations, the annual median projected change in soil salinity is 39 % by 2050. Above the median, 25 % of all stations have projected changes of 51 % or higher.

Keywords Climate change · Coastal areas · Soil salinity · Bangladesh

INTRODUCTION

The potential impacts of climate change on coastal regions include progressive inundation from sea-level rise, heightened storm damage, loss of wetlands, and increased salinity from saltwater intrusion. Worldwide, about 600 million people currently inhabit low-elevation coastal zones that will be affected by progressive salinization (CIESIN 2010; Wheeler 2011). Recent research suggests that the sea level may rise by one meter or more in the twenty first century, which would increase the vulnerable population to about one billion by 2050 (Rahmstorf 2007; Pfeffer et al. 2008; Dasgupta et al. 2009; Vermeer and Rahmstorf 2009; Hansen and Sato 2011; Brecht et al. 2012).

While most research has focused on inundation and losses from heightened storm surges, increased salinity from saltwater intrusion may actually pose the greatest threat to livelihoods and public health through its impacts on agriculture, aquaculture, infrastructure, coastal ecosystems, and the availability of fresh water for household and commercial use. Understanding the physical and economic effects of salinity diffusion and planning for appropriate adaptation will be critical for long-term development and poverty alleviation in countries with vulnerable coastal regions (Brecht et al. 2012).

Bangladesh provides an excellent setting for investigation of these issues, because it is one of the countries most threatened by sea-level rise and saltwater intrusion. In Bangladesh, about 30% of the cultivable land is in coastal areas where salinity is affected by tidal flooding during the wet season, direct inundation by storm surges, and movement of saline ground and surface water during the dry season (Haque 2006; Dasgupta et al. 2014a). In consequence, the potential impact of salinity has become a major concern for the Government of Bangladesh and the affiliated research institutions. Recently, the Bangladesh Climate Change Resilience Fund (BCCRF) Management Committee has highlighted salinity intrusion in coastal Bangladesh as a critical issue for adaptation to climate change. In its National Adaptation Programme of Action,[1] the Government of Bangladesh has assigned particularly high priority to projects related to adaptation to increased salinity. The temporal and geographic pattern of

[1] Available online at http://unfccc.int/resource/docs/napa/ban01.pdf.

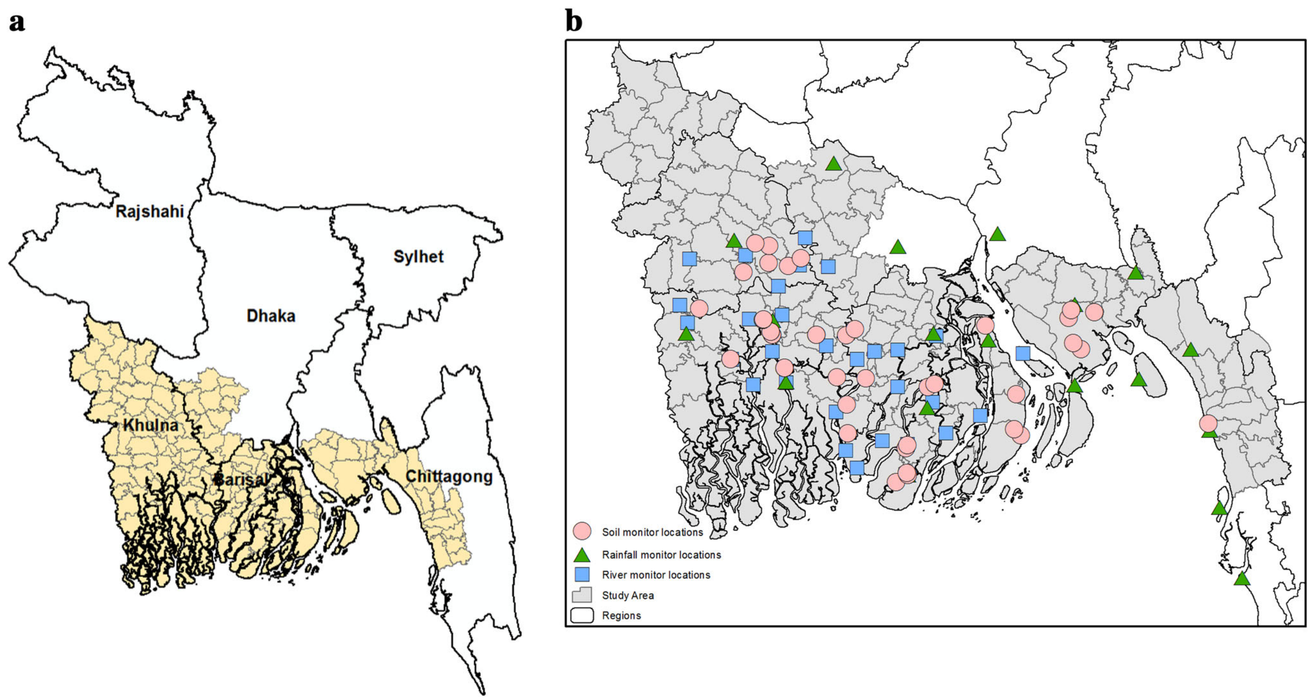

Fig. 1 **a** Study regions and *upazila*s in Bangladesh. **b** Location of soil, river monitoring stations and BMD weather stations in the study area

appropriate adaptive investments will depend critically on the expected intensity and diffusion rate of salinization in different locations.

In previous studies in Bangladesh, researchers simulated salinity change in rivers and estuaries using hydraulic engineering models and compared the results with actual measures (Nobi and Das Gupta 1997; Aerts et al. 2000; Bhuiyan and Dutta 2011). In the most comprehensive study to date, Dasgupta et al. (2014a) extended recent salinity trends in coastal rivers to 2050 with a projection model that links the spread and intensity of salinity to changes in sea level, temperature, rainfall, and altered riverine flows from the Himalayas. While the Dasgupta study (Dasgupta et al. 2014a) provides new estimates of future river salinity for alternative scenarios of climate change, no comparable assessment of soil salinity has been undertaken until now. This research attempts to fill the gap by predicting soil salinity in coastal Bangladesh through 2050.

The present analysis was conducted in two stages. In the first stage, changes in soil salinity in coastal Bangladesh for the period 2001–2009 were assessed using salinity information recorded at 41 soil monitoring stations by the Soil Research Development Institute (SRDI). Using these data, a spatial econometric model was estimated linking soil salinity with the salinity of nearby rivers, land elevation, temperature, and rainfall. In the second stage, future soil salinity for 69 coastal sub-districts was projected from climate-induced changes in river salinity and projections of rainfall and temperature based on the time trends for 20 Bangladesh Meteorological Department weather stations in the coastal region. The findings indicate that climate change poses a major soil salinization risk for coastal Bangladesh.

MATERIALS AND METHODS

Study area

The study area comprises 140 sub-districts (*upazilas*) in four regions of southern Bangladesh: Barisal (38 upazilas), Chittagong (30), Dhaka (13), and Khulna (59). As shown in Fig. 1, the study area spans the southern coastal regions of Bangladesh, with extensions to permit assessment of current and future salinity further inland.

The dataset includes monthly soil salinity measures from 41 stations for the period 2001–2009, provided by the Bangladesh Soil Research Development Institute[2]; water salinity measures from 29 stations for 2000–2008, provided by Dasgupta et al. (2014a), elevation data from DIVA-GIS[3]; and monthly temperature and rainfall data from 20 BMD weather stations for 1990–2010.[4]

[2] The data on soil salinity have not previously been available for empirical research.

[3] CGIAR-SRTM data with 3 s resolution, aggregated to 30 seconds by DIVA-GIS. Available online at http://www.diva-gis.org/gdata.

[4] BMD temperature and rainfall data have been provided by the Bangladesh Agricultural Research Council. Temperature data are

The monitoring stations for soil salinity, river salinity, and weather are located in different places, at varying distances from one another (see Fig. 1). However, the analysis requires spatial juxtaposition of soil salinity, river salinity, temperature, and rainfall measures at soil monitoring locations. The analysis incorporates river salinity measures for all stations within 30 km of each soil salinity monitor. Relative diffusion impacts are captured using weights for river stations that are inversely proportional to their squared distances from the soil stations. For weather stations, the analysis uses observations for the station that is closest to each soil salinity monitor.

Figure 2 presents average monthly station soil salinity measures for 2001–2009, color-coded in five groups for visual comparison. Soil salinity is particularly high in the Khulna coastal region. The water from the Ganges River, which flows through its tributary, the Gorai River, is the only major source of freshwater for the Khulna region. The offtake of the Gorai is almost nil during the dry season (November–May). The salinity level at the Bay of Bengal during the dry season is also comparatively high; and saline water intrudes via tidal effects through the major rivers: the Baleswar, Jamuna, lower Meghna, Malancha, Pussur, Sibsa, and Tnetulia. The topography of the region is very flat; strong tidal effects sometimes travel 200 km upstream from the coast.

Visual comparison of soil salinity measures with readings from the river stations (Fig. 2, Panel a vs. Panel b) indicates some spatial correlation, particularly in the concentration of high salinity in central Khulna. However, Fig. 2 also reveals some marked differences. For example, the soil salinity measures in Barisal are relatively higher than their riverine counterparts. Hence, river salinity alone cannot be used as a proxy for soil salinity.

Methodology

The analysis was conducted in two stages. In the first stage, a spatial econometric model incorporating determinants of soil salinity was specified and estimated. In the second stage, location-specific future soil salinity was projected from the climate-induced changes in its determinants.

Stage 1: Econometric analysis of determinants of soil salinity

The econometric projection model for this exercise incorporates several determinants of soil salinity. Land-based measures should be related to salinity in nearby rivers via annual flooding and water table infusion. Logically, infusion effects and salinity should decline with elevation. In addition, dilution from precipitation should produce a negative relationship between soil salinity and rainfall. Finally, measured soil salinity rises with temperature because the measure is based on electrical conductivity, which is greater at higher temperatures (Rhoades et al. 1999).

The estimation model is specified as follows:

$$S_{\mathrm{Lit}} = \beta_0 + \beta_1 E_i + \beta_2 S_{\mathrm{R}it} + \beta_3 R_{it} + \beta_4 T_{it} + \varepsilon_{it}. \quad (1)$$

Prior expectations: $\beta_1, \beta_3 < 0$; $\beta_2, \beta_4 > 0$, where for period t, $S_{\mathrm{L}it}$ measured soil salinity (dS/m) at land station i, E_i elevation (m) of station i, $S_{\mathrm{R}it}$ distance-weighted measured salinity (ppt) at river stations within 30 km of land station i, R_{it} measured rainfall (mm) at the Bangladesh Meteorological Department (BMD) weather station nearest to land station i, T_{it} Maximum monthly temperature (°C) at the BMD weather station nearest to land station i, ε_{it} Random, spatially autocorrelated error term with station and time components.

To test the robustness of the model, the exercise uses six methods to estimate (1): two basic estimators (OLS, with and without dummy variables for monitoring stations), two panel estimators [random (RE) and fixed effects (FE)], and two spatial econometric estimators (random and fixed effects). Panel estimation employs the standard xtreg estimator in Stata. Spatial econometric estimation employs the xsmle estimator in Stata, developed by Belotti et al. (2014), drawn from studies by Elhorst (2010), Lee and Yu (2010), Cameron et al. (2011) earlier work by Kelejian and Prucha (1998), Anselin (2001, 2002), Kelejian et al. (2004), Kelejian and Prucha (2006) Kapoor et al. (2007), Barrios et al. (2010).

The results, presented in Table 1, are robust and stable across all six estimators. All parameters have the expected signs, and all estimates have very high levels of significance. Collinearity forces exclusion of elevation from the three fixed-effects estimators. In the other estimators ((1), (3) and (5)), the effect of elevation is clear. Across the 41 monitors in the dataset, elevation varies from 3 to 11 m. In the most theoretically appropriate estimate (5), measured electrical conductivity (a standard proxy for salinity) declines by 0.665 dS/m with each 1-m increase in elevation, ceteris paribus. The spatial fixed-effects (FE) estimator (6) has been chosen for projection, since it incorporates the most appropriate specification of the error term. In (6), measured soil salinity increases by 0.326 dS/m for each increase of 1 part per thousand (ppt) in distance-weighted salinity measured by nearby river monitors. Rainfall has the predicted dilution effect: Measured soil salinity decreases by 0.003 dS/m for each one-millimeter increase in monthly rainfall. The predicted impact of

Footnote 4 continued
available online at http://www.barc.gov.bd/ym_temp.php; rainfall data at http://www.barc.gov.bd/ym_rainfall.php.

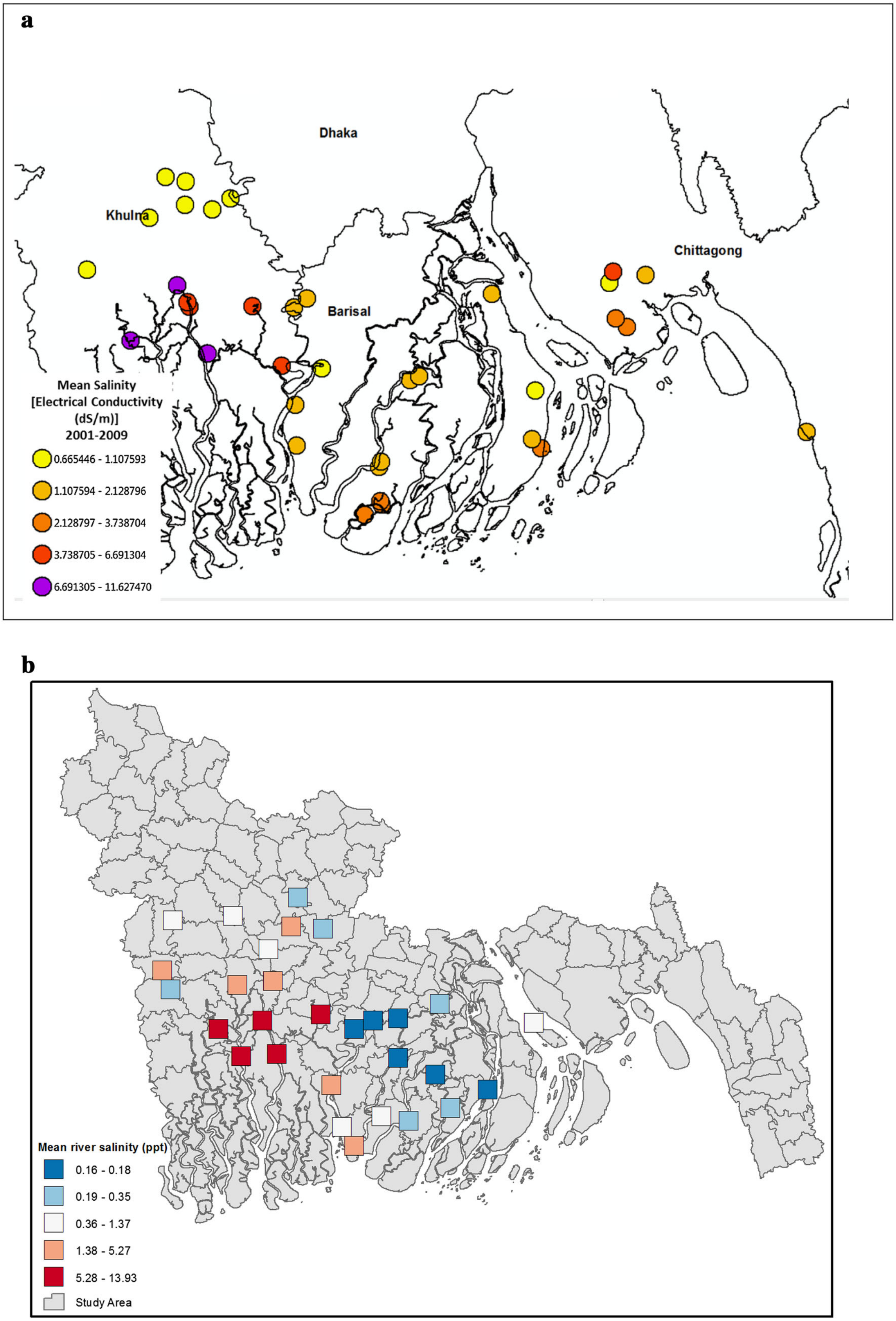

Fig. 2 **a** Mean salinity measures for land stations (dS/m): 2001–2009. **b** Mean salinity measures for river stations (ppt): 2001 and 2008

Table 1 Regression results: soil salinity monitors

	(1) OLS	(2) FE	(3) Panel, RE	(4) Panel, FE Panel, RE	(5) Spatial	(6) Spatial Panel, FE
Dependent variable: land station measure of soil salinity						
Elevation	−0.476 (16.42)**		−0.584 (4.68)**		−0.665 (4.04)**	
River salinity	0.682 (29.90)**	0.323 (15.18)**	0.339 (15.92)**	0.323 (15.18)**	0.334 (13.34)**	0.326 (12.73)**
Rainfall	−0.002 (9.96)**	−0.003 (13.80)**	−0.003 (13.69)**	−0.003 (13.80)**	−0.003 (12.37)**	−0.003 (15.36)**
Temperature	0.162 (7.59)**	0.245 (13.83)**	0.242 (13.59)**	0.245 (13.83)**	0.249 (13.52)*	0.249 (12.74)**
Constant	0.922 (1.38)	−4.42 (7.44)	−0.387 (0.40)	−3.990 (7.43)**		
Obs	4428	4428	4428	4428	4428	4428
R^2	0.30	0.55	0.27	0.22	0.26	0.53
Stations	41	41	41	41	41	41

Absolute value of *t* statistics in parentheses

* Significant at 5 %; ** Significant at 1 %

Table 2 Robust panel regression estimates: temperature and rainfall at 20 BMD weather stations, 1990–2010

	Trend	*t* statistic	Regression *F* statistic	BMD weather stations	Monthly observations
Temperature	0.0034	21.93**	$F(240, 4799) = 197.15$	20	5040
Log rainfall	–0.00058	4.50**	$F(240, 4775) = 379.89$	20	5016

temperature on electrical conductivity is also strongly reflected in the results: Measured soil salinity increases by 0.249 dS/m for each 1 °C increase in maximum monthly temperature.

Stage 2: Future projection of determinants of soil salinity

Employing model (1) for forecasting future soil salinity requires projected salinity measures for each river station and projected rainfall and temperature for each weather station.

The projections for river stations use the river salinity projections of Dasgupta et al. (2014a). Long-term rainfall and temperature have been projected using data from 20 coastal region BMD weather stations for the period 1990–2012.[5] The temperature analysis estimates a time trend in a panel regression that includes both station fixed effects and station-specific monthly variations. The rainfall analysis uses the same approach but performs the estimation for log rainfall to ensure positive projections in drier months. Robust regression is employed to ensure against any additional outlier effects. The full results are not reported here, since the regressions include 11 monthly dummies, 19 weather station dummies, and 209 interactions of the monthly and weather station dummies, as well as the time trend.[6] Table 2 presents the estimates of primary interest: monthly time trends for temperature and rainfall.

To illustrate the implications, Fig. 3 presents annual means for monthly temperature and rainfall at the Bangladesh Meteorological Department's Patuakhali station in central Barisal (displayed on the map in Fig. 3, Panel a). The projections for Patuakhali are representative of projections for all 20 BMD stations in the database.

In 1990, all stations in Chittagong except Chandpur recorded high annual rainfall intensities (200–350 mm/month), while most stations in Barisal, Dhaka, and Kulna recorded medium intensities (150–200 mm/month). By 2030, the projections indicate a major shift toward lower rainfall in all three western districts, while stations in Chittagong shift from 200–350 to 150–200 mm/month. By 2050, expected rainfall for almost all stations in Khulna and Dhaka is low (100–150 mm/month); stations in Barisal are divided between low and medium rainfall; and all the formerly high-rainfall stations in Chittagong have shifted to medium rainfall.

5 Monthly mean rainfall and maximum temperature in 1990 and 2001 for all 20 stations, as well as projections for 2050 are available from the authors upon request.

6 Full results are available from the authors on request.

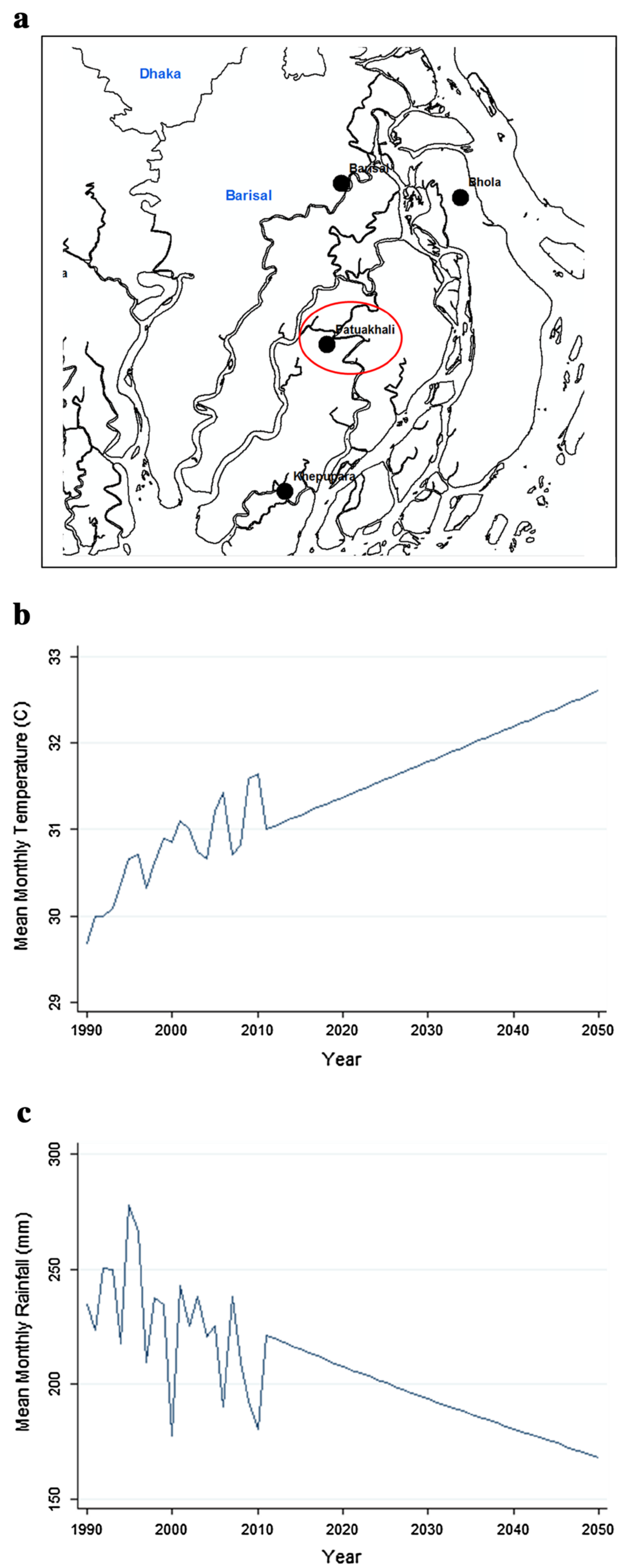

Fig. 3 Recorded and projected temperature and rainfall, BMD Patuakhali station. **a** Station location. **b** Temperature, 1990–2050. **c** Rainfall, 1990–2050

RESULTS

Soil salinity projections

The analysis develops projections for soil salinity measures at each of the 41 monitoring stations by combining the estimates for model (1) with the previously described projections for river salinity, temperature, and rainfall. As noted previously, inclusion of temperature provides a correction for the effect of temperature on electrical conductivity. Inclusion of rainfall provides a correction for the diluting effect of precipitation on measured salinity. The implications of the estimates are illustrated using the fixed-effects spatial estimates in Table 1, column (6). Tables 3 and 4 present salinity measures for 2001, 2009, 2050 (using projected exogenous variables), and projected percent changes from 2009 to 2050. We incorporate three measures that reflect important dimensions of variation: (1) median salinity (Table 3), which captures the central tendency in annual salinity; (2) maximum salinity (Table 4—Panel a) during the dry season (November–April), which permits assessment of seasonally intense salinity on important dry-season crops, particular HYV boro rice; and (3) maximum salinity (Table 4—Panel b) during the flooding season (July–September), which permits assessment of seasonally intense salinity on important crops, particularly paddy-irrigated aman rice.

The distribution statistics for percent changes in salinity from 2009 to our high projection scenarios in 2050 indicate that many areas in the coastal region of Bangladesh will have very significant increases in soil salinity during the coming decades. For median annual salinity, 41 monitoring stations have median, third-quartile and 90th-percentile changes of 39.2, 50.7, and 55.0 %, respectively. The corresponding statistics are 13.1, 24.0, and 28.2 % for dry season maxima and 36.6, 49.5, and 64.8 % for wet season maxima. Overall, the results suggest that increases in median annual salinity readings will be accompanied by a narrowing of the seasonal spread, as wet season maximum grow more rapidly than dry season maxima.

Figure 4 adds a geographic dimension to the projections. Once again, monitoring stations are color-coded using standardized ranges for soil salinity in 2001, 2009, and 2050: Blue (0–0.75 dS/m); Green (0.75–1.50); Yellow (1.50–2.25); Orange (2.25–4.50); Red (4.50–6.00); and Purple (6.00 +). In 2001, Khulna has the greatest variance among the four regions, with northern stations uniformly Blue and central stations heavily Red and Purple. Stations in Barisal vary from Blue to Orange, while stations in Chittagong vary from Green to Red.

Table 3 Soil salinity, annual medians: 2001, 2009, 2050

No.	District	Upazila	Union	Latitude	Longitude	Annual Median Salinity (dS/m)				
						(1) 2001	(2) 2009	(3) 2050 (Low)	(4) 2050 (High)	% Change (2) → (4)
1	Patuakhali	Kalapara	Nilganj	21.94578	90.17050	3.7	4.4	5.0	5.4	23.6
2	Patuakhali	Kalapara	Kalapara Paurashava	21.98330	90.23330	3.2	3.8	4.4	4.9	27.6
3	Patuakhali	Kalapara	Kalapara Paurashava	21.99386	90.22681	2.7	3.3	4.0	4.4	31.7
4	Barguna	Amtali	Amtali Paurashava	22.12138	90.22292	1.6	2.1	2.8	3.2	49.4
5	Barguna	Amtali	Amtali Paurashava	22.13909	90.22922	1.3	1.9	2.5	3.0	55.0
6	Bhola	Charfesson	Betua	22.19045	90.81819	3.1	3.8	4.4	4.8	27.5
7	Pirojpur	Mathbaria	Sapleza	22.20042	89.92107	1.1	2.7	3.4	3.7	35.0
8	Bhola	Charfesson	Aslampur	22.22229	90.78430	2.1	2.8	3.4	3.8	37.1
9	Chittagong	Sadar	Patenga	22.24992	91.79086	2.1	2.1	3.3	3.6	72.8
10	Pirojpur	Mathbaria	Tushkhali	22.34908	89.91582	1.5	2.4	2.9	3.2	35.1
11	Bhola	Tazumuddin	Shambhupur	22.40176	90.79628	1.1	1.9	2.5	2.9	54.0
12	Patuakhali	Dumki	Lebukhali	22.44016	90.33809	1.7	1.9	2.5	2.9	53.2
13	Patuakhali	Dumki	Lebukhali	22.45449	90.37039	1.7	1.9	2.5	2.9	53.1
14	Pirojpur	Bhandaria	Nudmulla	22.48384	90.01342	1.0	1.3	1.9	2.2	73.2
15	Bagerhat	Morrelganj	Boloibunia	22.49153	89.86618	5.3	6.0	6.6	6.9	14.4
16	Bagerhat	Mongla	Burirdanga	22.53708	89.59258	9.6	10.7	11.5	11.7	8.6
17	Bagerhat	Mongla	Burirdanga	22.53764	89.59447	9.3	10.4	11.1	11.3	9.1
18	Khulna	Paikgacha	Paikgacha Paurshava	22.58453	89.31239	10.5	12.7	13.0	13.0	1.8
19	Noakhali	Sadar		22.63512	91.13185	2.4	3.3	3.9	4.3	29.7
20	Noakhali	Subarnachar	Char Jubilee	22.66566	91.09137	3.2	3.6	4.3	4.7	29.3
21	Pirojpur	Nazirpur	sekhmatia	22.70739	89.91236	1.9	2.6	3.4	3.7	39.9
22	Khulna	Batiaghata	Batiaghata	22.70764	89.52872	5.5	7.0	8.1	8.3	19.1
23	Khulna	Batiaghata	Batiaghata	22.70847	89.52878	5.5	7.0	8.1	8.3	19.2
24	Khulna	Batiaghata	Jalma	22.71006	89.75828	3.6	6.6	8.9	9.6	46.6
25	Khulna	Batiaghata	Jalma	22.71022	89.75833	3.3	6.3	8.7	9.4	48.3
26	Khulna	Batiaghata	Batiaghata	22.72508	89.52161	4.4	6.0	7.1	7.3	22.5
27	Khulna	Batiaghata	Batiaghata	22.72594	89.52150	4.9	6.4	7.5	7.8	20.9
28	Pirojpur	Nazirpur	Nazirpur	22.73853	89.95810	2.1	2.5	3.1	3.5	40.6
29	Bhola	Bhola Sadar	Illisha	22.75565	90.63653	1.7	2.1	2.8	3.2	55.7
30	Khulna	Dumuria	Gutudia	22.78700	89.48219	10.2	11.9	12.9	13.2	10.5
31	Khulna	Dumuria	Gutudia	22.78789	89.48300	10.6	12.3	13.4	13.6	10.2
32	Noakhali	Sadar		22.79693	91.06693	1.3	1.8	2.5	2.8	59.3
33	Noakhali	Sadar	Noakhali Paurashava	22.82500	91.20087	2.2	2.7	3.4	3.7	39.2
34	Noakhali	Subarnachar	Char Bata	22.83716	91.08100	4.9	5.4	6.1	6.4	19.7
35	Jessore	Keshabpur	Sagardari	22.84428	89.15143	0.8	1.7	2.4	2.4	42.2
36	Jessore	Abhoynagar	Noapara Paurshava	23.03539	89.38065	1.0	1.5	2.1	2.2	41.5
37	Narail	Kalia	Babra Hachla	23.06582	89.61078	1.1	1.5	2.1	2.3	54.7
38	Narail	Sadar	Singasolpur	23.08159	89.51141	1.0	1.5	2.1	2.2	50.7
39	Narail	Lohagara	Kotakul	23.10675	89.67736	1.1	1.5	2.1	2.3	52.0
40	Narail	Sadar		23.16893	89.51302	1.1	1.5	2.0	2.1	43.4
41	Narail	Sadar	Tularampur	23.18428	89.44060	1.1	1.5	2.0	2.1	39.8

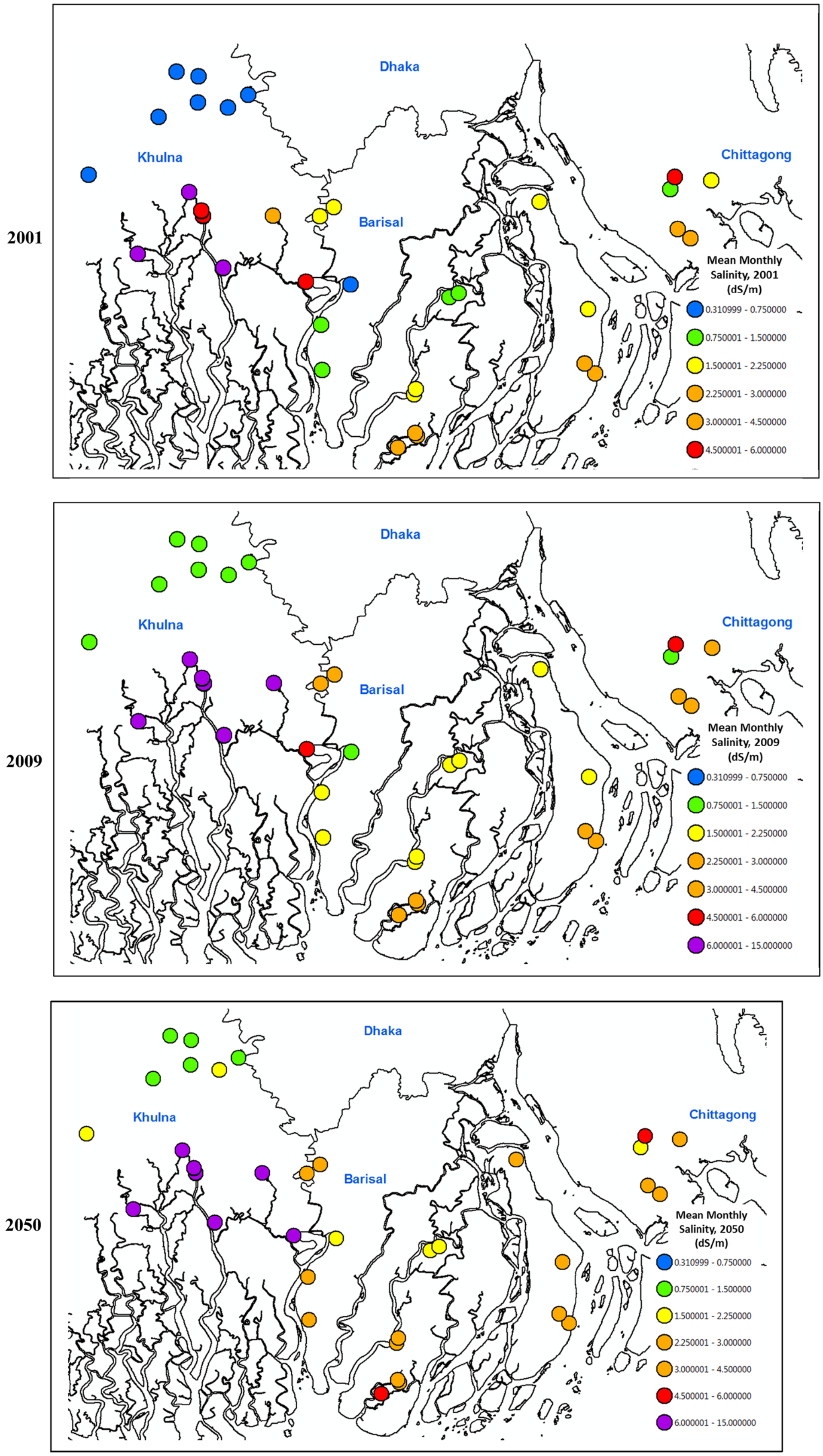

Fig. 4 Observed and projected soil salinity measures: 2001, 2009, 2050

Table 4 Soil salinity, dry and wet season monthly maxima: 2001, 2009, 2050

District	Upazila	Union	Latitude	Longitude	Panel a Dry season maximum monthly salinity (dS/m)					Panel b Wet season maximum monthly salinity (dS/m)				
					(1) 2001	(2) 2009	(3) 2050 (Low)	(4) 2050 (High)	% Change (2) → (4)	(5) 2001	(6) 2009	(7) 2050 (Low)	(8) 2050 (High)	% Change (6) → (8)
Patuakhali	Kalapara	Nilganj	21.94578	90.17050	5.1	5.4	5.8	6.2	15.2	3.6	3.8	4.2	4.7	23.9
Patuakhali	Kalapara	Kalapara Paurashava	21.98330	90.23330	4.6	4.8	5.2	5.6	17.7	3.2	3.3	3.8	4.2	27.9
Patuakhali	Kalapara	Kalapara Paurashava	21.99386	90.22681	4.1	4.3	4.7	5.1	19.8	2.7	2.8	3.3	3.8	32.7
Barguna	Amtali	Amtali Paurashava	22.12138	90.22292	2.9	3.0	3.4	3.8	26.3	1.6	1.8	2.3	2.7	52.1
Barguna	Amtali	Amtali Paurashava	22.13909	90.22922	2.7	2.8	3.1	3.6	28.2	1.4	1.6	2.1	2.5	59.0
Bhola	Charfesson	Betua	22.19045	90.81819	4.7	4.5	5.0	5.4	20.5	2.5	3.2	3.9	4.4	34.3
Pirojpur	Mathbaria	Sapleza	22.20042	89.92107	2.7	3.9	4.3	4.6	19.3	1.1	1.2	1.7	2.1	78.1
Bhola	Charfesson	Aslampur	22.22229	90.78430	3.7	3.5	4.0	4.4	26.2	1.5	2.3	3.0	3.4	49.0
Chittagong	Sadar	Patenga	22.24992	91.79086	3.1	2.7	3.6	3.9	45.2	1.9	1.8	2.6	3.0	69.5
Pirojpur	Mathbaria	Tushkhali	22.34908	89.91582	2.8	4.3	4.5	4.9	13.5	1.6	1.3	2.5	2.8	113.4
Bhola	Tazumuddin	Shambhupur	22.40176	90.79628	2.8	2.5	3.0	3.4	36.1	0.5	1.2	1.9	2.3	87.9
Patuakhali	Dumki	Lebukhali	22.44016	90.33809	2.7	2.7	3.1	3.5	27.7	1.9	1.9	2.0	2.4	26.0
Patuakhali	Dumki	Lebukhali	22.45449	90.37039	2.8	2.7	3.1	3.5	27.7	1.9	1.9	2.0	2.4	26.0
Pirojpur	Bhandaria	Nudmulla	22.48384	90.01342	2.1	2.4	2.8	3.1	27.8	1.2	1.2	1.3	1.6	34.4
Bagerhat	Morrelganj	Boloibunia	22.49153	89.86618	7.1	8.6	9.0	9.2	7.0	5.6	5.2	6.2	6.5	23.3
Bagerhat	Mongla	Burirdanga	22.53708	89.59258	13.1	17.3	17.8	18.0	3.8	10.8	10.6	11.7	11.9	12.2
Bagerhat	Mongla	Burirdanga	22.53764	89.59447	12.6	16.8	17.3	17.5	4.0	10.4	10.2	11.3	11.5	12.8
Khulna	Paikgacha	Paikgacha Paurshava	22.58453	89.31239	11.6	17.1	17.0	17.1	−0.1	9.9	12.4	12.6	12.6	1.8
Noakhali	Sadar		22.63512	91.13185	4.2	3.9	4.4	4.8	23.2	1.8	2.5	3.2	3.6	41.7
Noakhali	Subarnachar	Char Jubilee	22.66566	91.09137	4.5	4.3	4.7	5.0	17.7	2.6	3.3	3.8	4.1	26.2
Pirojpur	Nazirpur	sekhmatia	22.70739	89.91236	3.5	5.1	5.4	5.7	12.5	2.0	2.4	3.1	3.4	43.7
Khulna	Batiaghata	Batiaghata	22.70764	89.52872	7.8	11.9	12.5	12.7	7.2	5.7	7.2	8.3	8.5	18.4
Khulna	Batiaghata	Batiaghata	22.70847	89.52878	7.8	11.9	12.5	12.7	7.2	5.7	7.2	8.3	8.5	18.4
Khulna	Batiaghata	Jalma	22.71006	89.75828	9.4	17.2	18.4	19.2	11.5	3.9	7.5	9.8	10.6	40.6
Khulna	Batiaghata	Jalma	22.71022	89.75833	9.1	16.9	18.2	18.9	11.7	3.6	7.3	9.6	10.3	41.9
Khulna	Batiaghata	Batiaghata	22.72508	89.52161	6.5	10.4	11.0	11.3	8.3	4.6	6.1	7.2	7.4	22.0
Khulna	Batiaghata	Batiaghata	22.72594	89.52150	6.9	10.9	11.5	11.7	8.0	5.0	6.5	7.6	7.9	20.5
Pirojpur	Nazirpur	Nazirpur	22.73853	89.95810	3.4	3.9	4.5	4.9	24.0	2.0	2.2	2.8	3.1	36.6
Bhola	Bhola Sadar	Illisha	22.75565	90.63653	3.3	2.6	3.2	3.6	37.5	1.7	1.7	2.4	2.8	64.8
Khulna	Dumuria	Gutudia	22.78700	89.48219	11.8	15.7	16.3	16.5	5.0	10.3	11.9	12.9	13.1	10.5

Table 4 continued

District	Upazila	Union	Latitude	Longitude	Panel a Dry season maximum monthly salinity (dS/m)					Panel b Wet season maximum monthly salinity (dS/m)				
					(1) 2001	(2) 2009	(3) 2050 (Low)	(4) 2050 (High)	% Change (2) → (4)	(5) 2001	(6) 2009	(7) 2050 (Low)	(8) 2050 (High)	% Change (6) → (8)
Khulna	Dumuria	Gutudia	22.78789	89.48300	12.3	16.2	16.7	17.0	4.9	10.7	12.3	13.3	13.5	10.1
Noakhali	Sadar		22.79693	91.06693	2.7	2.4	2.8	3.2	31.0	0.8	1.5	2.0	2.3	59.0
Noakhali	Sadar	Noakhali Paurashava	22.82500	91.20087	3.6	3.3	3.8	4.1	22.5	1.7	2.4	2.9	3.2	36.2
Noakhali	Subarnachar	Char Bata	22.83716	91.08100	6.3	6.0	6.4	6.8	12.6	4.3	5.0	5.5	5.9	17.1
Jessore	Keshabpur	Sagardari	22.84428	89.15143	1.8	3.7	4.1	4.2	13.1	0.6	1.3	1.9	2.0	56.8
Jessore	Abhoynagar	Noapara Paurshava	23.03539	89.38065	1.8	3.1	3.2	3.3	5.1	1.1	1.3	1.8	1.9	44.9
Narail	Kalia	Babra Hachla	23.06582	89.61078	1.9	3.2	3.4	3.6	10.5	1.2	1.5	2.1	2.3	52.1
Narail	Sadar	Singasolpur	23.08159	89.51141	1.8	3.1	3.2	3.4	9.2	1.1	1.5	2.0	2.2	49.5
Narail	Lohagara	Kotakul	23.10675	89.67736	1.9	3.2	3.3	3.4	9.4	1.2	1.5	2.1	2.2	49.4
Narail	Sadar		23.16893	89.51302	1.9	3.0	3.0	3.2	5.9	1.2	1.4	1.9	2.0	43.0
Narail	Sadar	Tularampur	23.18428	89.44060	1.9	3.0	3.0	3.1	4.5	1.2	1.4	1.9	2.0	40.4

By 2009, a general pattern of salinity increase is already apparent: All stations in northern Khulna have increased from Blue to Green; nearly all stations in Barisal (one exception) are Yellow or Orange; and stations in Chittagong have become heavily Orange as well. The shift continues through 2050, with some stations in north Khulna changing to Yellow, most stations becoming Purple in central Khulna, most stations in Barisal becoming Orange (and one changing to Red), and the sole Green station in Chittagong becoming Yellow.[7]

DISCUSSION

Resources for adaptation to climate change will remain scarce, and mobilizing a cost-effective response will require an integrated spatial analysis of salinity diffusion, its socioeconomic impacts, and the costs of adaptation and remediation. Previous research has initiated such analysis with sporadic measurements of soil salinity in coastal areas (SRDI 1998a, b, 2000, 2010), and local survey-based research that suggests significant agricultural productivity losses from rising soil salinity (Karim et al. 1990; Rahman and Ahsan 2001; Petersen and Shireen 2001; Hassan and Shah 2006; Mahmood et al. 2010; Thomas et al. 2013). To our knowledge, no previous research has developed spatially explicit estimates of recent and future trends in soil salinity throughout Bangladesh's coastal region. Our research fills this gap, indicating widespread significant increases for annual, dry season, and wet season soil salinity.

In order to assess the socioeconomic implications, another econometric analysis was recently conducted to forecast the impacts of rising soil salinity on the output of high-yielding variety (HYV) rice in coastal Bangladesh. The results indicate output declines of 15.6 % in nine upazilas where soil salinity will exceed 4 deciSiemens per meter before 2050.[8] Without new coping strategies, the predicted changes will produce significant income declines from HYV rice production in many areas, including a 10.5 % loss in Barisal region and a 7.5 % loss in Chittagong region (Dasgupta et al. 2014b).

Bangladesh is one of the countries that are most vulnerable to climate change and sea-level rise. Although climate-related increases in salinity from saltwater intrusion in coastal areas have been highlighted as a serious problem, systematic studies of spatiotemporal impacts are

[7] The analysis excludes one geographically isolated station from Fig. 2 to make the clustered icons easier to view. This station, Patenga, is further south on the coast of Chittagong. It is Yellow in 2001 and 2009, and changes to Orange in 2050.

[8] Our findings coincide with the salinity threshold established by technical experimentation (Suryanarayanan 2010).

scarce in Bangladesh. This paper has attempted to fill the gap with projections of soil salinity in 2050 for 69 *upazilas* in coastal Bangladesh. The findings suggest that climate change poses a major soil salinization risk for coastal Bangladesh. They indicate that across 41 monitoring stations, median changes by 2050 in annual, dry season, and wet season soil salinity will be 39.2, 13.1, and 36.6 %, respectively. As shown in Table 4, many areas will have significantly greater increases. For example, many areas in Barisal, Chittagong, and Khulna Districts will have very large increases in soil salinity during the coming decades. The results have sobering implications for HYV rice production in coastal Bangladesh. Many upazilas have already suffered significant losses, which will be compounded by further salinity increases in the coming decades. This inexorable process will continue as long as the sea continues to rise and salinity increases in coastal rivers. No prospect for near-term relief is apparent, since rising global greenhouse gas emissions continue to propel rapid climate change and melting of the polar ice caps.

Finally, we hope that the analytical framework and estimates presented in this paper will be useful for the Government of the People's Republic of Bangladesh in preparation of location-specific coastal adaptation plans as climate change continues.

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