# Mangrove Spatial Distribution in the Indian Sundarbans: Predicting Salinity-Induced Migration in a Changing Climate

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## Abstract

This study contributes to understanding the physical and economic impacts of progressive, climate-driven aquatic salinization on the spatial distribution of mangrove species in the Indian Sundarbans, which accounts for about two-fifths of the 10,200 km<sup>2</sup> tidal-wetland forest delta. To estimate future mangrove distribution, a five-step analysis was undertaken, using high-resolution spatial assessments. A current (2015) basemap and overlays of salinity tolerance for major mangrove species and their assemblages and projected location-specific aquatic salinity for 2050 were used to predict salinity-induced migration. The results show gain-and-loss patterns, with salt-tolerant species predominating at the expense of freshwater species. These changes are likely to reduce the flow of ecosystem services, adversely affecting the livelihood options of poor people in adjacent areas. Effective management will require establishing baseline data for monitoring system changes over time, protocols for maintaining species health, and support for mangrove regeneration and restoration. Resources should also be directed to alternative livelihoods for mangrove-dependent households. The study recommends an integrated policy approach, focused on rising salinity, changes in mangrove dynamics, and the welfare of mangrove-dependent communities.

**Keywords:** aquatic salinization, climate change, high-resolution assessment, mangrove-dependent livelihood, mangrove migration, spatial distribution, Sundarbans

## 1. Introduction

The mangrove ecosystems of the Sundarbans—the world's largest remaining contiguous mangrove forest situated along coastal segments of Bangladesh (60 percent) and India (40 percent) in the Bay of Bengal—are at increasing risk from the impacts of climate-driven sea-level rise. In this 10,200 km<sup>2</sup> tidal-wetland forest delta, as in other globally important mangrove forests, sea-level rise may even threaten the survival of mangrove species. In the past, mangroves have shown considerable resilience to sea-level fluctuations (Alongi, 2002, 2008; Gilman et al., 2006; Erwin, 2009); however, their future rate of adaptation and migration may not keep pace (Ellison & Stoddart, 1991; Semeniuk, 1994; United Nations Environment Programme, 1994; McLeod & Salm, 2006; Lange et al., 2010). In the case of the Sundarbans, the extent of permanent inundation is uncertain since sedimentation is still occurring in the active Ganges-Brahmaputra Delta. That said, climate-driven sea-level rise will inevitably have significant implications for the many poor people who depend on the mangrove forest for their livelihoods. (Note 1)

#### 1.1 Challenges to Healthy Mangroves in the Sundarbans

In the Sundarbans, the two greatest threats to the health of mangroves in a changing climate are progressive aquatic salinization and shortage of nutrients from freshwater flows (Dasgupta, Kamal, Khan, Choudhury, & Nishat, 2015a; Dasgupta, Hossain, Huq, & Wheeler, 2015b; Institute of Water Modeling, 2003; Peterson & Shireen, 2001; Soil Resources Development Institute, 2000, 2010; United Kingdom Department of Environment, Food & Rural Affairs, 2007). It is expected that alteration of riverine flows from the Himalayas, combined with sea-level rise, will intensify salinity intrusion as climate change continues (Dasgupta et al., 2015a, b; Dasgupta et

al., 2014). This increase in aquatic salinization, in turn, is projected to alter the region's hydrological regime and forest ecology (Barik et al., 2018; Dasgupta, Sobhan, & Wheeler, 2017). Freshwater shortage during the dry season (October–May) is already a serious issue, owing to the decline of some of the major distributaries of the Ganges that feed the Sundarbans. These changes have significant implications for adaptively managing the mangrove forests.

## 1.2 Study Aim and Focal Area for Analysis

Planning for appropriate adaptation, including the development of conservation and sustainable development policies that incorporate rising salinity, changes in mangrove dynamics, and the welfare impacts on poor communities, requires a better understanding of the physical and economic effects of salinity diffusion in the region. To date, high-resolution spatial assessments have been scarce. This study contributes to narrowing this knowledge gap by analyzing the impact of aquatic salinization on the spatial distribution of mangrove species.

The focus of the analysis is the Indian Sundarbans in coastal West Bengal, which accounts for about two-fifths  $(4,200 \text{ km}^2)$  of the mangrove wetlands. The Sundarbans Biosphere Reserve in West Bengal encompasses a 9,630 km<sup>2</sup> area, consisting of a core zone  $(1,700 \text{ km}^2)$  and development  $(5,300 \text{ km}^2)$ , managed  $(2,400 \text{ km}^2)$ , and restoration  $(230 \text{ km}^2)$  zones (Nandy & Kuswaha, 2011). The Harinbhanga River (known as the Raymangal, Kalindi, & Ichhamati in northern areas) demarcates the reserve's international border with Bangladesh. The Indian Sundarbans is said to possess the world's richest tropical mangrove formation (Naskar, 1988). (Note 2)

Although ecologically resilient, mangrove species in the Indian Sundarbans are highly sensitive to hydrological changes (Blasco, Saenger, & Janodet, 1996), particularly the salinity profile of the adjacent water column or soils. Sea-level rise, driven by climate change and subsidence, is perhaps the greatest threat to mangrove health (McLeod & Salm, 2006). Because of siltation at off-take, most of the region's rivers are now tidal-fed, having lost their connection with source rivers, which perennially supplied freshwater from glacier melt. Today their estuarine character is maintained only by monsoon runoff (Bhadra, Mukhopadhyay, & Hazra, 2017; Cole & Vaidyaraman, 1966; Gopal & Chauhan, 2006). In recent decades, human-induced hydrologic alterations in the upper reaches of the Bhagirathi Hooghly River and the Ganges-Brahmaputra-Meghna system have also affected freshwater flow. (Note 3) In the foreseeable future, the region is likely to experience further changes in its salinity profile due to saltwater intrusion from sea-level rise. (Note 4)

## 2. Method

To obtain a broader understanding of how progressive, climate-driven aquatic salinization can be expected to affect the future distribution of mangrove species in the Indian Sundarbans, a five-step method was used. These steps are detailed in the subsections below.

#### 2.1 Generate a Mangroves Basemap from Satellite Data

Step 1 was to generate a high-resolution basemap of the current (2015) spatial distribution of mangrove species in the Indian Sundarbans. The basemap was prepared using Landsat 8 Operational Land Imager (OLI), sentinel, and hyperspectral data from Hyperion (Figure 1), along with field survey data, in the multi-step procedure described below. (Note 5)



Figure 1. Map showing hyperspectral scenes coverage over mangrove forested areas of the Sundarbans

## 2.1.1 Field Survey

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

## 2.1.2 Spectral Profile Generation for Mangrove Species

Second, spectral profiles of the mangrove species were generated from hyperspectral imagery from Hyperion. Out of 242 bands of Hyperion images, 67 were eliminated (i.e., water-vapor absorption bands and those for overlapping regions or without data) (Barry, 2001; Datt, McVicar, Van Niel, Jupp, & Pearlman, 2003). (Note 6) The remaining 175 calibrated bands underwent visual and statistical examination, and signal-to-noise ratios were determined for all. At this stage, de-striping and atmospheric corrections were made, which provided calibrated image spectra of the species (Figure 2). (Note 7).



Figure 2. 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 3). Absorption and peak reflectance detected from the spectral profile indicated the characteristics of each species. All remaining Hyperion images were classified with those detected spectral signatures using the Spectral Angle Mapper (SAM) in ENVI<sup>TM</sup>.



Figure 3. Spectra generated using the hyperspectral imagery and field survey samples

#### 2.1.3 Image Rescaling and Classification Process

Third, Landsat 8 OLI images were rescaled to Top of Atmosphere (TOA) radiance and TOA spectral reflectance, using the rescaling coefficient factor provided in the metadata (Appendix A). (Note 8) The corrected Landsat OLI images were then classified using an unsupervised process (with 200 classes), immediately followed by a knowledge-based classification process, 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 other 41 ground-control points was later used to finalize the knowledge engine and accuracy assessment of the classified mangrove maps.

#### 2.1.4 Ground-Truthing the Images

Finally, field data on the mangrove species and their assemblages were used to ground-truth the images. The classified images were shared with Sundarbans mangrove experts, and, based on their field experience, the images were revised. Subsequent re-testing of the mangrove species map showed that the level of accuracy had increased to 70 percent (Figure 4).



Figure 4. Map showing sampling points formangrove species identification in the Sundarbans

#### 2.2 Generate a Baseline Aquatic Salinity Profile for the Region

Step 2 was to generate a baseline aquatic salinity profile for the Indian Sundarbans. A high-resolution spatial point file covering four years (2012–15) was created from the best available, location-specific monitored salinity data, using a multi-step process. (Note 9) Because salinity information for the Indian Sundarbans is quite limited, the analysis drew from the most comprehensive study to date on salinity impacts for the Bangladesh Sundarbans (an area of about 6,000 km<sup>2</sup>) in order to generate a broader picture of current and future salinity for the region (Dasgupta, Sobhan, & Wheeler, 2018). (Note 10)

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 sparse observations for others. A fixed-effects (FE) regression was then estimated, expressed as follows:

$$\ln S_{it} = \beta_0 + \sum_{j=1}^N \beta_j D S_j + \sum_{k=2}^{12} \gamma_k D M_k + \delta y + \varepsilon_{it} , \qquad (1)$$

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

## 2.3 Estimate Salinity Tolerance of Mangrove Types

Step 3 computed the salinity tolerance ranges for the relevant mangrove species and mixed species. This was done using the geographic overlays of base mangrove distributions derived in Step 1, combined with the high-resolution, spatial aquatic salinity profile developed in Step 2.

## 2.4 Project Future (2050) Location-specific Aquatic Salinity for the Region

Step 4 estimated future aquatic salinity for the Indian Sundarbans. A projection model using high-resolution point data was first developed for the Bangladesh Sundarbans. For each point, the *SP* ratio (salinity in 2012 divided by salinity in 2050) and the *SM* ratio (salinity in 2012 divided by the maximum salinity in 2012 for all points) were computed. The *SP* is distributed (0, 1). Fractional logit was then 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 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.

## 2.5 Project Future (2050) Spatial Distribution of Mangrove Species for the Region

Step 5 estimated the impacts of progressive aquatic salinization by 2050 for mangrove species in the Indian Sundarbans. This was done using the 2015 basemap derived in Step 1, the salinity tolerance of various mangrove species computed in Step 3, and the location-specific aquatic salinity projected for 2050 in Step 4.

## 3. Results

The 2015 basemap generated from satellite images in this analysis shows that just 10 mangrove species and their assemblages predominate in the Indian Sundarbans. These are 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 (Figure 5).



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

## 3.1 Current and Future Aquatic Salinity Profiles for the Region

The results show 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).



Figure 6. Maximum aquatic salinity ranges in the Indian Sundarbans, 2012 and 2050

By visually comparing the two maps in Figure 6, one can observe the scale of potential change between 2012 and 2050. Over time, salinity spreads northward and eastward with the ongoing rise in sea level, change in riverine flows, and subsidence in the lower Ganges Delta. As shown, the transition is quite pronounced in southwestern coastal, central, and northeastern areas.

#### 3.2 Salinity Tolerance of Mangrove Species and Assemblages

From geographic overlays on the 2015 basemap and the corresponding aquatic salinity map, one can observe species clustering patterns by salinity range. These salinity-tolerance estimates are critical building blocks for analyzing the projected mangrove transition. The findings show clustering of *Sonneratia* and *Heritiera* species in areas with low-to-medium salinity; *Phoenix, Excoecaria, Bruguiera, Xylocarpus, Aegiceras,* and *Rhizophora* species in areas with medium-to-high salinity; and *Avicennia* and *Ceriops* species in high-salinity areas (Figure 7). (Note 11)



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

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

Figure 8 shows that, with progressive salinization, salt-tolerant mangroves will dominate the landscape of the Indian Sundarbans. These species and their assemblages include *Avicennia, Excoecaria, Ceriops, Avicennia-Bruguiera-Ceriops*, and *Excoecaria-Rhizophora-Ceriops*. 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* (Appendix B).



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

Figure 9 shows how progressive, climate-driven aquatic salinization is expected to impact mangrove migration by 2050. As shown, *Phoenix xylocarpus-Aegiceras* will see the largest net gain, followed by lesser gains for *Ceriops-Excoecaria*, *Exoecaria*, *Avicennia*, and *Ceriops*. Conversely, *Excoecaria-Heritiera* will suffer the largest net loss in area, with smaller losses for *Excoecaria-Rhizophora-Ceriops*, *Avicennia-Bruguiera-Cereops*, *Sonneratia*, and *Ceriops-Excoecaria-Heritiera*.



Figure 9. Absolute area gains and losses for mangrove species and assemblages, 2015-50

#### 4. Discussion and Recommendations

The mangrove forests of the Indian Sundarbans provide a wide array of ecosystem services and household uses (Table 1). Most of the 4 million people who live in the coastal region depend on the mangrove forests for their livelihoods (e.g., fishing, honey collection, and tourism) and daily needs (e.g., water and fuelwood collection).

Mangrove species	Timber for building materials	Fuel- wood	Thatch	Medicine	Food (fruits, leaves, seeds)	Fishing equip- ment	Tannin	Honey collection	Environ- mental functions <sup>a</sup>	Fish habitat
Heritiera fomes	$\checkmark$	$\checkmark$		$\checkmark$				0	0	0
Avicennia alba, A. marina, A. officinalis	✓	0		$\checkmark$		0		$\checkmark$	$\checkmark$	0
Sonneratia apetala, S. alba, S. griffithii, S. caseolaris	√	0		$\checkmark$	✓	$\checkmark$		√	0	0
Excoecaria agallocha	$\checkmark$			√				$\checkmark$	$\checkmark$	0
Ceriops decandra, C. tagal	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	0	$\checkmark$	$\checkmark$	0	0
Bruguiera gymnorrhiza, B. cylindrical	√	$\checkmark$		$\checkmark$	✓	0	$\checkmark$		0	0
Rhizophora mucronata, R. aniculate	$\checkmark$	$\checkmark$		$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$		$\checkmark$	$\checkmark$
Xylocarpus mekongensis, X. granatum	√	0		$\checkmark$			$\checkmark$	0	√	0
Phoenix paludosa Aegiceras comiculatum	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$			$\checkmark$	$\checkmark$	$\checkmark$	0 0

#### Table 1. Ecosystem services and common uses of mangrove species in the Indian Sundarbans

*Note*.  $(\checkmark)$  indicates information from the literature, and (o) is used to represent expert opinion.

<sup>a</sup>. Examples include trapping suspended sediment, preventing soil erosion, sequestering carbon, and mitigating the impact of natural disasters.

Traditionally, the intertidal zone where mangroves are found has been well-suited for breeding and rearing a variety of fish, crustacean, and mollusk species. (Note 12) But progressive aquatic salinization is expected to impact the food web, taking its toll on economically important fish catches with specific salinity-tolerance limits. Also, with changes in mangrove species combinations, honey collectors ("Moulis") may not fetch as high a price due to variations in the honey's fragrance and viscosity. In addition, reduced diversity of mangrove species could diminish tourism in the region. Furthermore, altered species combinations could increase salinity ingression, affecting the water table and thus water sources; women would shoulder a greater burden since they spend more hours collecting fuelwood and drinking water.

Engineering attempts to control rising salinity in the Indian Sundarbans are unlikely to succeed. Concerns over increasing aquatic salinity have not yet been incorporated into regional management protocols despite the Sundarbans' treaty-protected ecological status, which is widely acknowledged. Eastward meandering of the Ganges and Brahmaputra Rivers has already reduced freshwater inflows significantly. Even at the current sea level, strong tides may travel long distances upstream since the land is quite flat. Continuing sea-level rise will only exacerbate such tidal effects. As long as these dynamics continue, efforts to improve local ecological conditions through changes in hydrological regime (e.g., river training) will likely prove futile (Potkin, 2004).

The Indian Sundarbans is a UNESCO World Heritage site, and effective conservation management will require establishing baseline data for monitoring system changes over time, management protocols to maintain mangrove health, and support for mangrove regeneration and restoration. Location-specific baseline data is needed for tree-stand structures, tree abundance, species richness and diversity, export of nutrients, hydrological patterns, rates of sedimentation, and relative sea-level rise (McLeod & Salm, 2006). Management protocols should include connectivity between mangrove systems and nearby river sources, as well as maintenance of upland freshwater catchments. Also, areas that are likely to survive climate-driven sea-level rise should be identified. In addition, monitoring of tidal fluctuations, varying pH, and salinity is needed to support regeneration and colonization of suitable species, where necessary. Furthermore, restoration of currently degraded areas should be undertaken. (Note 13)

Sea-level rise will continue beyond 2100, even if greenhouse gas emissions are stabilized in the near future. The impacts on globally-important mangrove ecosystems and the socioeconomic implications for vulnerable populations are substantial, suggesting that resources should also be directed to developing alternative livelihoods for mangrove-dependent households. It is hoped that this research will promote more widespread efforts to develop conservation and sustainable development policies that integrate rising salinity, changes in mangrove dynamics, and the welfare impacts on poor communities.

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#### Notes

Note 1. Current scientific estimates are that sea level may rise by 1 m or more in this century, globally affecting some 1 billion people by 2050 (Hansen et al., 2011; Vermeer & Rahmstorf, 2009; Pfeffer, Harper, & O'Neel, 2008; Rahmstorf, 2007; Dasgupta et al., 2009; Brecht et al., 2012); a rise of 3 m or more by 2100 is feared 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/

Note 2. Rao (1987) reported that the Indian mangroves consisted of 60 species, while Naskar (1988) reported 35 true mangroves and Blasco, Saenger, & Janodet (1996) reported 58 species.

Note 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 fell from 3,700 m<sup>3</sup> per second to 364 m<sup>3</sup> 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).

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

Note 5. 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 are September 10, 2011, November 23, 2014, and November 13, 2016 and the path/row is 138/45. Hyperion images have 242 bands that include both 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.

Note 6. 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.

Note 7. 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 & Govil, 2014). Atmospheric correction was performed using the FLAASH package available in ENVI<sup>TM</sup>.

Note 8. 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 & Robinove, 1990).

Note 9. At present, there is no geo-coded database on aquatic or soil salinity for the Indian Sundarbans. Data was compiled from field measurements taken by the Nature Environment & Wildlife Society (NEWS) and World Wildlife Fund-India (WWF-India).

Note 10. This study 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&ThisCco de=BGD

Note 11. These findings are in line with those of Barik et al., 2018.

Note 12. The direct relationships between particular mangrove and fish species are still being investigated.

Note 13. Community-based mangrove restoration activities could engage local women's groups in nursery preparation of salt-tolerant species.

#### Appendix A

#### **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 & 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:

$$L_{\lambda} = M_L \ge Q_{cal} + A_L, \tag{A-1}$$

where  $L_{\lambda}$  equals TOA radiance (Watts/m<sup>2</sup> 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:

$$\rho'_{\lambda} = M_{\rho} \ge Q_{cal} + A_{\rho}, \tag{A-2}$$

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

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

$$\rho_{\lambda = \frac{\rho_{\lambda}}{\cos\left(\theta_{\text{SZA}}\right)}},\tag{A-3}$$

where  $\rho_{\lambda}$  equals TOA reflectance and  $\theta_{SZA}$  is the solar zenith angle.

## Appendix **B**

# Estimated Change in Area (km<sup>2</sup>) for Various Mangrove Species and Assemblages, 2015–2050

Mangrove	Mangrove species and assemblages, 2050									
species and	Ceriops-	Excoecaria-	Excoecaria-	Excoecaria	Sonneratia	Avicennia	Avicennia-	Ceriops	Phoenix-	Ceriops-
assemblages,	Excoecaria	Heritiera	Rhizophora-				Bruguiera-		Xylocarpus-	Excoecaria-
2015			Ceriops				Cereops		Aegiceras	Heritiera
Ceriops-	65.967	0.727	0.819	16.842	0.212	1.130	4.211	0.0054	0.005	0
Excoecaria										
Excoecaria-	0.624	32.206	2.133	4.685	0.252	12.408	14.955	0.514	0.418	0
Heritiera										
Excoecaria-	0.092	0.063	299.115	2.525	0.121	11.126	4.910	0.358	2.291	0
Rhizophora-										
Ceriops										
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-	8.619	7.026	29.907	0	0	23.820	338.535	5.543	2.638	0
Bruguiera-										
Cereops										
Ceriops	1.715	0.939	5.814	4.23	0.027	4.478	12.323	148.762	1.871	0
Phoenix-	0.017	0.023	1.8	0.579	0.123	6.485	1.256	2.828	47.110	0
Xylocarpus-										
Aegiceras										
Ceriops-	0	0	0.198	0.003	0	0.824	0	0.001	0.379	0.001
Excoecaria-										
Heritiera										

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