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Article

The Indian Sundarban Mangrove Forests: History, Utilization, Conservation Strategies and Local Perception

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Abstract: Covering approximately 10,000 km^2 the Sundarbans in the Northern Bay of Bengal is the largest contiguous mangrove forest on earth. Mangroves forests are highly productive and diverse ecosystems, providing a wide range of direct ecosystem services for resident populations. In addition, mangroves function as a buffer against frequently occurring cyclones; helping to protect local settlements including the two most populous cities of the world, Kolkata and Dhaka, against their worst effects. While large tracts of the Indian Sundarbans were cleared, drained and reclaimed for cultivation during the British colonial era, the remaining parts have been under various protection regimes since the 1970s, primarily to protect the remaining population of Bengal tigers (*Panthera tigris* ssp. *tigris*). In view of the importance of such forests, now severely threatened worldwide, we trace the areal change that the Indian Sundarbans have undergone over the last two-and-a-half centuries. We apply a multi-temporal and multi-scale approach based on historical maps and remote sensing data to detect changes in mangrove cover. While the mangroves' areal extent has not changed much in the recent past, forest health and structure have. These changes result from direct human interference, upstream development, extreme weather events and the slow onset of climate change effects. Moreover, we consider the role of different management strategies affecting mangrove conservation and their intersection with local livelihoods.

Keywords: Sundarbans; mangroves; landscape change; human-environment interactions

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1. Introduction

Mangroves are diverse and highly productive ecological communities [1,2], which provide important ecosystem functions [3,4]. Located at the land-sea interface, they protect coastal areas against natural hazards such as cyclones and tsunamis [5–8]; they retain terrestrial sediment and recycle nutrients, thus supporting clear offshore waters, which in turn favors the photosynthetic activity of phytoplankton as well as growth and robustness of coral reefs, seagrass beds and reef fish communities [9]; they serve as an important habitat, nursery and refuge, providing food for countless organisms including humans [4]. These ecosystems are also vital carbon sinks, either storing carbon temporarily within organic peat soils, or as dissolved organic carbon in ocean sediments at greater depths, offsetting climatic-active greenhouse gasses for longer periods [10]. Because of these collective ecosystem services, mangroves are also of great economic value [11–17]. However, owing to both anthropogenic and climatic factors, mangroves the world over are severely threatened, and, with current global annual loss rates of 1%–2%, no such forests may be left by the end of the 21st century, if the current trend continues [18–20].

The aim of this paper is to document changes in the areal extent of the Indian Sundarbans during the last two-and-a-half centuries and to analyze how direct human impacts, developments upstream, slow onset climatic change and extreme weather events have affected the health and structure of this ecosystem. This also includes an in-depth analysis of the effects of local to federal level management strategies [21], underscoring how conservation aligns with development, climate change adaptation, local livelihoods, and the values and meanings that local people attach to the challenge of managing such a complex system. Thus, we aim to provide a better understanding of how policies may be designed, employing instruments such as REDD+ (*R*educing *E*missions from *D*eforestation and Forest *D*egradation) and the CDM (*C*lean *D*evelopment *M*echanism) that have emerged out of the climate governance debate. This requires a reconfiguration of development paradigms and an internalization of anthropogenic and climatic drivers of change and their cumulative impacts on the socio-ecological system.

2. Study Area

The Sundarbans are situated on the delta created by the Ganges, Brahmaputra and Meghna rivers in the Bay of Bengal. It consists of a network of mudflats and islands created by accumulated sediment loads that these rivers carry from their Himalayan headwaters separated by anastomotic channels and tidal waterways (Figure 1). Tidal amplitude within the estuaries is between 3.5 and 4 m, with seasonal variation between 1 and 6 m [22]. The Sundarbans, found within 21°32′ to 22°40′N and 88°05′ to 89°51′E, covers an area of approximately 10,000 km^2, of which 62% lies within Bangladesh and 38% in India [23], and forms the largest contiguous mangrove forest on earth. The region is characterized by a tropical climate with a dry season between November and April and a wet monsoonal period over the rest of the year (Figure 1). The total annual amount of precipitation is between 1500 and 2000 mm. During the monsoon season, tropical cyclones and smaller tidal events regularly hit the area, causing severe flooding and wind damage [24]. Seasonal mean minimum and maximum temperatures vary from 12°C to 24°C and 25°C to 35°C, respectively [25].

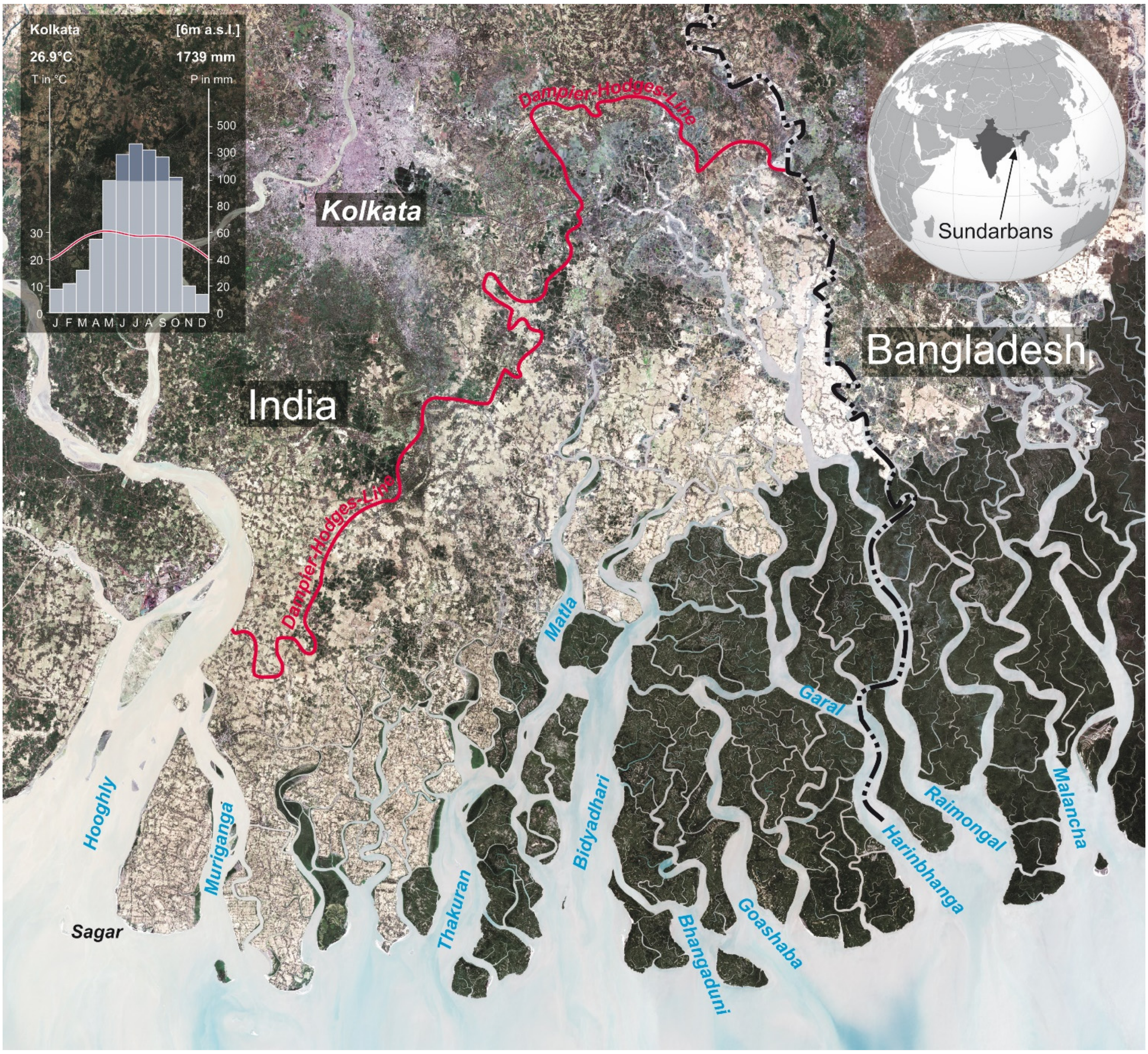

Figure 1. Overview of the Indian Sundarbans. The mangrove forests appear dark green, the surrounding agricultural land is yellowish brown. Settlements appear purple. The Dampier-Hodges-Line marks the boundary of tidal influence and roughly marks the former extent of mangrove forests. Insets show location of the Sundarbans and a climatic diagram of Kolkata representing the climatic conditions of the Sundarbans.

The Sundarban mangroves belong floristically to the Indo-Andaman mangrove province within the species-rich Indo-West Pacific group [26]. According to [27], 24 true mangrove taxa belonging to nine different families are found within the Indian Sundarbans. Several species are endemic such as *Aegialitis rotundifolia*, *Heritiera fomes*, *Sonneratia apetala* or *S. griffithii*. There is kind of a zonation within the Sundarban mangroves, both from land to sea and from east to west. Tectonic uplift in the west and subsidence by sediment compaction and human activities in the east [28–30] in combination with varying freshwater inputs, create different salinity zones—hyposaline in the eastern and western part, where huge rivers deliver meltwater from the Himalayas, and hypersaline in the central part, where the ground is higher and freshwater input from the Matla, Bidyadhari or Harinbhanga rivers is much smaller (in part also because water is retained by dams for diversion). *Avicennia marina*, *A. alba* and *Bruguiera cylindrica* grow in the lower coastal sections while *B. gymnorhiza*, *Ceriops decandra* and *Rhizophora mucronata* are more common upstream. The least salt-tolerant taxa, found in riverine environments and more common to the east, are the eponymous Sundari-tree *Heritiera fomes*, *Excoecaria agallocha* and *Sonneratia caseolaris* [23,31].

Besides the high number of mangrove tree species, accounting for one third of the global total, high biodiversity in the Sundarbans is also represented by other organismic groups with more than 200 additional plant species, more than 400 species of fish, over 300 species of birds, 35 species of reptiles, 42 species of mammals, as well as countless benthic invertebrates, bacteria, fungi, *etc.* [24,32]. While most animals are mangrove visitors rather than mangrove residents, there are a few exceptions, even so not always by choice. To this group belongs the iconic, top predator, the Bengal tiger (*Panthera tigris* ssp. *tigris*) which was eliminated from alternative habitats by man [2]. And even its adopted home has decreased over the past centuries, when large tracts were cleared, drained and reclaimed for agricultural purposes.

The surroundings of the Sundarban mangroves—both in India and Bangladesh—are some of the most densely populated areas in the world. More than half of the population is impoverished on the Indian side and depend heavily on the goods and services that the forests provide [33–35]. According to the classification of [36] provisioning, supporting, cultural, and regulatory services can be distinguished. Mangrove trees are used for timber and construction material (e.g. for houses, boats, traps) as well as for fuel and charcoal production. Apiculture is widespread within the Sundarban mangrove forests and provides honey and wax. Around 2000 people are engaged in beekeeping in the Indian Sundarbans, producing approximately 90% of the total natural honey production in India [23]. In addition, mangrove plants provide tannins for leather production and a wide array of medicinal uses. Whilst crabs, molluscs, shrimps and fish are caught in the ocean and the brackish waters surrounding the mangrove forests, the mangrove proper is the most important source for shrimp larvae supplying the aquacultures. In addition, the mangroves are the nursery ground for many commercially important fish species. Indirect (regulatory) benefits of mangroves for coastal population include erosion control as well as protection from tropical storms and tsunamis. For instance, the relatively low numbers of victims in the Sundarbans area following the 2004 tsunami are related to the buffering capacity of the forests [37]. Furthermore, in May 2009, much of the momentum of cyclone Aila was absorbed by the mangroves, saving the city of Kolkata and other urban sprawls in close vicinity.

3. Data and Methods

A multi-temporal and multi-scale approach, based on historical maps and remote sensing data, was used to detect changes in the mangrove-covered area over a span of over 200 years. Conventional satellite data such as Landsat allowed monitoring land cover changes from the 1970s [38]. Corona images from the early U.S. military reconnaissance survey widened the time span for detecting changes back to the 1960s [39]. Further, two historical maps from the 18th and 19th century were used to delineate the northern boundary of mangrove-covered areas during the British colonial time (Table 1).

Table 1. Historical maps and satellite data employed in this study

Maps	Year	Reference	Scale	
Rennel's Map	1776	[49]	60 Geogr. Miles to 1 Degree	
Hunter's Map	1873	[50]	16 Miles to 1 Inch	
Sensor Type *	**Acquired Data**	**ID**	**Spatial Resolution [m × m²]**	**Spectral Resolution**
Corona KH	1968/02/06	DS1045-2196DA128 DS1045-2196DA129 DS1045-2196DA130 DS1045-2196DA131	2	pan
Landsat 5 TM	1989/01/19	LT41380451989019AAA02	30	VIS, IR
Landsat 7 ETM	2001/01/04	LE71380452001004SGS00	30	VIS, IR
Landsat 7 ETM	2002/04/13	LE71380452002103SGS00 LE71380442002103SGS00	30	pan
Landsat 8 OLI	2014/03/05	LC81380452014064LGN00	30	VIS, IR

* all satellite images were downloaded from http://earthexplorer.usgs.gov/.

Both small-scale maps were georeferenced and the mapped mangrove-covered areas were digitized on screen. The Corona images were co-registered to an orthorectified and mosaicked Landsat ETM scene from 2002 as base image. Two images—covering an area of 20 km × 70 km—of each Corona strip were georeferenced by using more than 100 Ground Control Points within ENVI 5.2. On the panchromatic Corona images the boundary of the mangrove-covered areas were digitized on screen in a geographical information system (GIS) and converted to a raster dataset with a spatial resolution of 30 m × 30 m within ArcGIS 10.1.

All Landsat imageries (processing Level 1T) show a high coherence with a shift of less than 1 pixel, so an additional co-registration was not necessary. Several approaches were developed to map mangrove-covered areas on multi-spectral remote sensing data automatically [22,40–44]. According to [40,45] the most accurate combination of sensor and image processing method is Landsat data and principal component analysis (PCA), using band ratios, if discrimination between mangrove and non-mangrove covered areas is required over a large area. Following this approach, we calculated five normalized difference indices (for vegetation, water and non-vegetated areas) for the calibrated reflectance bands of Landsat data (ENVI 5.2). The indices including the reflectance bands were used as input to a PCA and an unsupervised classification (ISODATA) was performed on a dataset consisting of the first four principal components. The 12 statistical classes were merged to three land cover classes: mangrove, non-mangrove and water. For the change detection analyses, we calculated the differences between the raster dataset derived from the Corona images in 1968, Landsat data from 1989 and 2014. Owing to the manually digitized boundary of the mangrove-covered areas on Corona images, we analyzed only the land loss and land gain between 1968 and 1989. The classified datasets from 1989 and 2014 enabled change detection analyses of mangrove-covered areas as well as land loss and gain.

The remote sensing findings were complemented by socio-economic data and information on management strategies. To understand drivers behind socio-economic constraints, livelihood choices and the nature of socio-ecological interaction, focus group discussions were conducted in three villages from western to eastern Sundarbans between April and September 2014. Expert interviews with forest administrative staff, non-governmental organization (NGO) workers, and international conservation agencies were conducted to understand management protocols, their values, and their perceptions of how social dynamics influence the stability and health of the socio-ecological system.

4. Historical Overview of the Sunderbans' Development

Before the 19th century, Indian Sundarbans were very sparsely settled [46], with only scattered human settlements dating back to the 8th century. A theory of depopulation of the Sundarbans in the middle ages is prominent. Several reasons have been forwarded, and range from earthquakes that led to a sudden subsidence of the land [47], attacks carried out by Portuguese and Arakans [48,49], and a hostile environment [50,51]. The depopulation theory is also found in the state accounts and literature describing the Sundarbans:

> *"…the area was depopulated for all practical purposes. The forest reclaimed the previously inhabited area and when the British East India Company set up their headquarters at Calcutta in 1757, it was at the edge of the forest"* [52]

However, irrespective of debates on the timing of first settlements, permanent human habitation was enabled through the clearing of the forest in low-lying tracts and through the construction of circuit embankments while the delta was still in a state of immaturity [53], a process that started in the late 19th century and continued through to the 20th century. Nevertheless, there is some uncertainty on the nature of settlements and the history of pre-colonial, indigenous reclamation of the region for settlement and cultivation. It is also unclear whether the farming practices were carried out by those who lived in the Sundarbans or whether it was limited to areas connected to the "mainland" that ran up to the fringes of the present city of Kolkata, which was located at the margin of the alluvial plain. The settlement certainly was sparse with *"few or no villages"* and a few houses were scattered along the rice fields [54]. This account is often contested as a Western fascination [55]. However, it might be an indication that the population was migratory in nature, using the land only seasonally for cultivation.

In 1771, British collector general Clod Russell initiated a plan to divide the Sundarbans into plots and to lease them out to prospective landlords for timber extraction and the collection of revenues. These lease-holding landowners encouraged poor farming communities from other parts of Bengal as well as from neighboring states to come and settle in the Sundarbans. These people were put to work clearing the forests and developing the land [54]. This exercise began in 1781, initiated by Tillman Henkel, the then magistrate of the Jessore district, currently in Bangladesh. Rennell's map [49] from 1776 (Figure 2 top left) shows the extension of the mangrove forest just before this forest clearing. According to this map, the mangrove forests extended up to Kolkata at the end of the 18th century. One hundred years later, in 1873 [50], the northern border of the mangrove forest shifted by about 10–20 km at most to the southeast (see Figure 2 top right).

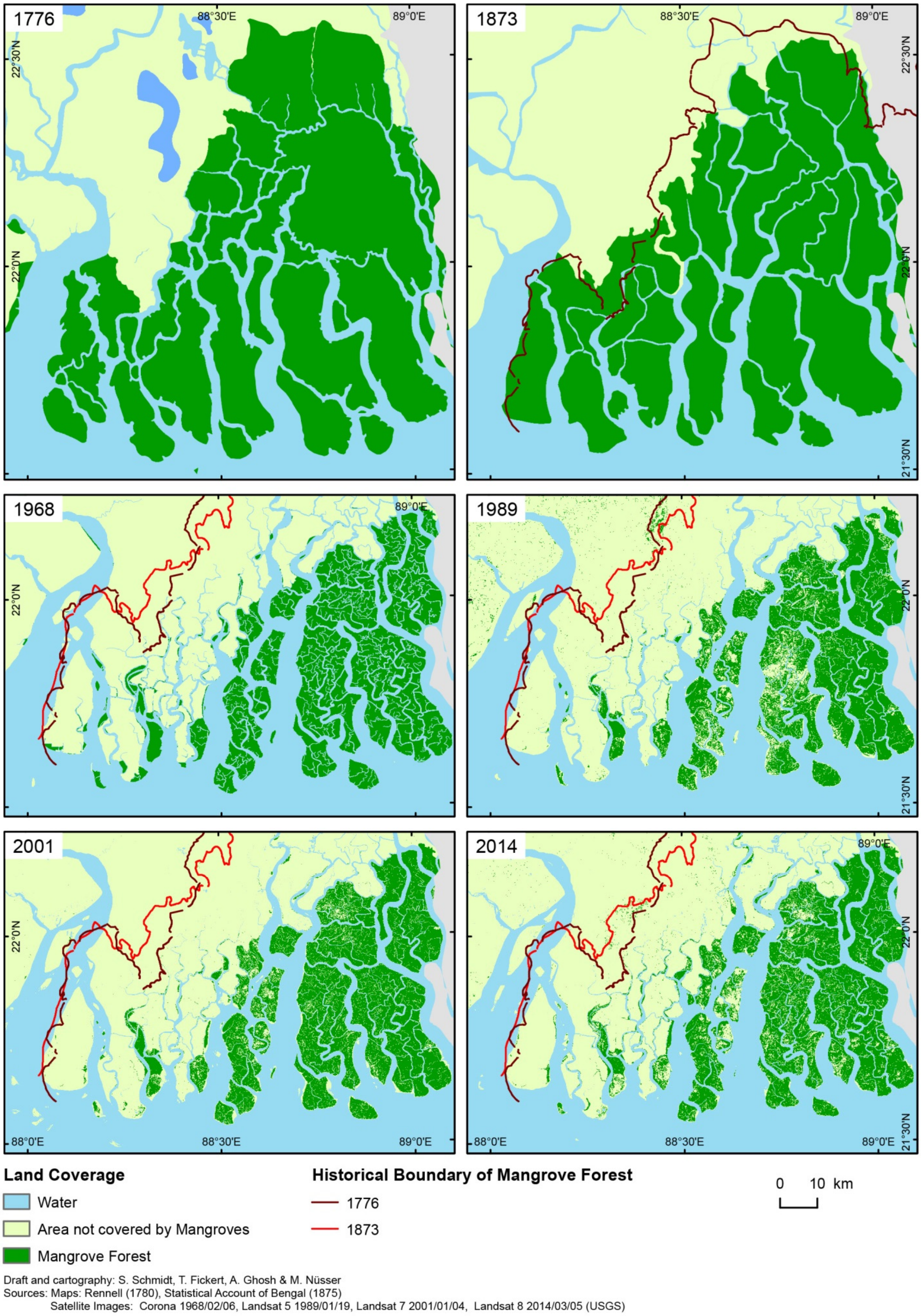

Figure 2. Mangrove extent and cover at various dates between the 18th and 21st century. For data used see Table 1, for change statistics see Table 2.

Table 2. Change statistics of mangrove extent and cover for the last two-and-a-half centuries.

Year of Observation	Mangrove Forest [km²]	Area Change in %	
		relating to previous observation	per decade
1776	6588		
1873	6068	−7.9	−0.8
1968	2307	−62.0	−6.5
1989	1983	−14.0	−6.7
2001	1926	−2.9	−2.4
2014	1852	−3.8	−3.0

Note: due to arguable mapping accuracy of the two historical maps, the figures for these early time slices should be deemed only as rough approximations.

Settlement in the Sundarbans mainly comprised of migrant populations from the adjoining districts of Midnapur, and also from central India, predominantly the marginalized and tribal populations who came in search of work and land and who were initially brought in by the British to construct the embankments [56,57]. As early as 1875/76, the British government set aside all unleased mangrove areas under protection and conservation [58], which after the country's independence was only promulgated in 1972 when the country formulated its wildlife and forest protection legislations [57]. This legal protection presumably supports the present-day extent of the mangrove forests. However, [59] (p. 131) believe that "economic reasons such as high land use conversion costs (due to tidal, saline environment and the presence of the Royal Bengal Tiger […]) have become more important in preventing large-scale destruction of the mangroves than administrative regulations. Moreover very clear demarcation of forest boundaries along rivers and the Bay of Bengal have also contributed to the protection of the forest."

5. Post-Colonial Policies: Legislative Protection and Community Participation

The human population in the Sundarbans increased rapidly in the post-colonial era, especially following the partition of India and Bangladesh. The violent incident of Marichjhapi where over 100 people lost their lives, bears testimony to the mass migration from Bangladesh into Sundarbans, and symbolizes the power struggles between the government and residents of Sundarbans over forest rights [60]. After independence, the population of Indian Sundarbans grew from 1.15 million in 1951 to 4.44 million in 2011 (Figure 3), which led to a growing demand for its resources. Between 1873 and 1968 the mangrove-covered area decreased by about half on account of conversion of forest to agricultural land and settlements (Table 2). The mangrove forest boundary shifted further to the south and the mangroves were cleared between the Hooghly River and the Matla River. The satellite images from 1968 show only small strips of remaining mangroves (Figure 2 middle left).

Since the 1970s, the Indian Sundarban mangroves have been protected under various legal measures which were established primarily to protect and help increase the threatened tiger population. In 1984 a (subordinate) protection of the forests came into law with the establishment of the 1330 km^2 Sundarbans National Park, designated as a UNESCO World Heritage Site in 1987, and a biosphere reserve in 2001, where no human interference is permitted. In addition there are less strictly administered wildlife sanctuaries namely, Sajnekhali (362 km^2), Lothian (38 km^2) and Haliday (6 km^2) and the Sundarbans Reserve Forest, where limited human use is allowed. In total, the protected forest covers an area of about 4260 km^2. Additionally, the government of India established a National Mangrove Committee within the Ministry of Environment and Forests in 1979, with the mandate to manage, protect, and re-afforest the areas. Consequently, despite the high population density, the areal extent of the Indian Sundarban mangrove forest remained more or less stable since the 1960s (Figure 2, Table 2, see also [22,23,41,59]).

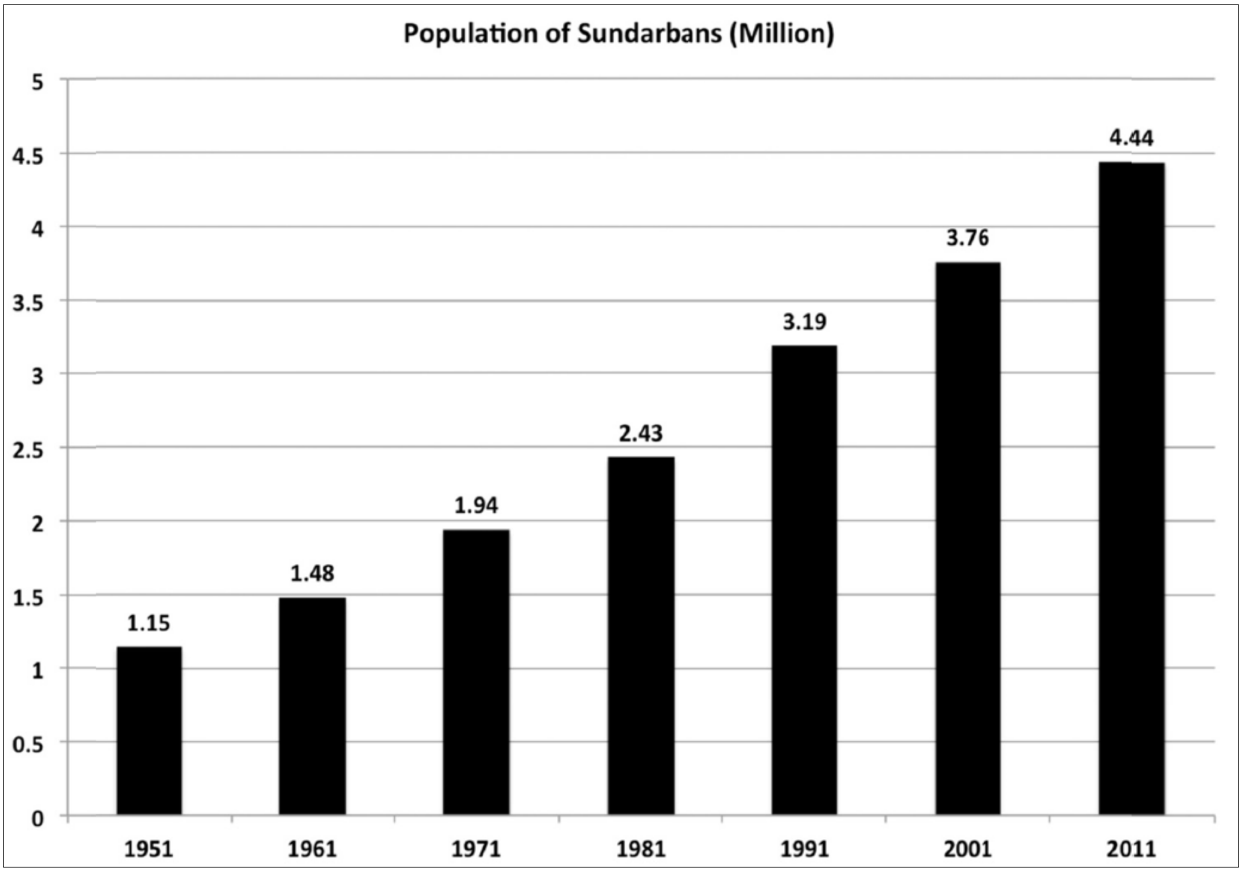

Figure 3. Human population growth in the Indian Sundarbans between 1951 and 2011.

Up until the 1990s the Indian Sundarbans were managed exclusively by the state, and the community was excluded from using it, leading to frequent protests by the local population who claimed use rights [61]. Development support has been neglected, with inadequate power [61] and transportation [57] infrastructure and poor health and education services. Land holding per capita has been small, despite the efforts of government land redistribution programs taking place between 1980 and 1990 [62], whilst the fragmentation of farm plots in subsequent generations has contributed to the marginalization of a large percentage of the population.

With the declaration of the Sundarbans as a World Heritage Site in 1987, the primary objective was given to biodiversity conservation [21], with the Sundarbans also having prestige value for the country. In 2001, the human element was recognized to a degree when the Sundarbans Biosphere Reserve was set up under the Man and the Biosphere Programme (MAB), but the forest department's initiatives towards alternative livelihoods had not yet been formalized [63]. The forest department attempted to introduce some livelihood alternatives in the late 1990s, such as piggeries and mushroom cultivation [63], as well as the managed collection and selling of non-timber forest products (NTFP). The programs were organized through the Joint Forest Management Committees (JFMCs) at the village level and through the Forest Protection Councils (FPCs), but did not yield the desired livelihood outcomes. Household respondents identified the failure of these initiatives as owing to a misalignment with their cultural preferences, as well as because of poor marketing structures and inequitable benefit sharing mechanisms between and amongst the state and the locals. Many respondents claimed that these activities were implemented in a top-down manner, highlighting bureaucratic intransigence [61,64]. Other than by excessive local exploitation and natural hazards, the main underlying reason threatening the future of the Sundarbans is inadequate state governance, as evidenced by disconnected development plans, weak and ineffective enforcement apparatus, poor coordination between the various government agencies, and an unwillingness to include local people in management decisions.

The remote sensing analyses in Figure 4, apart from net land loss, do not reveal any marked change in the forest's extent since the 1960s. While deforestation has not been significant, the forest department has almost always been blamed for overemphasizing protection through FPCs and JFMCs [64]. Many respondents rely on non-timber forest produce, crab, prawn seedlings and fish for their livelihoods, but experience capital losses as forest patrols confiscate their boats or fishing nets, critical to their livelihood. While the forest officers claim to be carrying out their duties and "protecting the forest," the dwellers describe it as an excessive and arbitrary use of power. The low human interference in the forests are differently explained—forest officials describe their efforts as evidence of their efficiency in protecting the forest, whilst people living around the forest cite the increasing risk to life from human-wildlife encounters and the availability of alternatives such as federal income guarantee schemes, in reducing their dependence on forest. However, frictions and conflicts between forest guards and forest dwellers are much too common, according to the accounts of both sides.

The degree of protection varies greatly across forests, as a result creating some confusion for people who access the forest for their livelihoods. While no human activity is allowed in the Sundarbans National Park, limited access to wildlife sanctuaries is allowed whilst reserve forests offer greater access to the people. Much like any other forest in the country, human-wildlife conflicts and illegal extraction in the protected areas have been all too common [65], further serving to alienate local people from taking an active role in the conservation [66] of this commons.

There are several overlapping institutional arrangements and competencies governing the Sundarbans. While the Project Tiger is federally managed, the national park and the wildlife sanctuaries are under the forest departments of the state of West Bengal, who have varying degrees of control in different parts. Additionally, the secretariat of the biosphere reserve, which is the custodian of the entire 9630 km^2 of the Indian Sundarbans, is headed by a director.

The complex interactions between elements of conservation, livelihood security and physical protection of people, coupled with the threat of climatic hazards, calls for additional resources if socially just and equitable benefits are to be accrued from the Sundarbans. Financial proceeds from global mechanisms such as REDD+ and CDM [63], can offer sufficient financial resources by virtue of the Sundarban mangrove's ability to capture carbon at faster rates than tropical forests [10]. However, a REDD+ for the Sundarbans might be vulnerable to a free-rider problem as much as the other REDD+ initiatives have elsewhere. This is why a polycentric approach [67] might be better suited for the Sundarbans as it proposes the development of methods for assessing the benefits and costs of particular strategies.

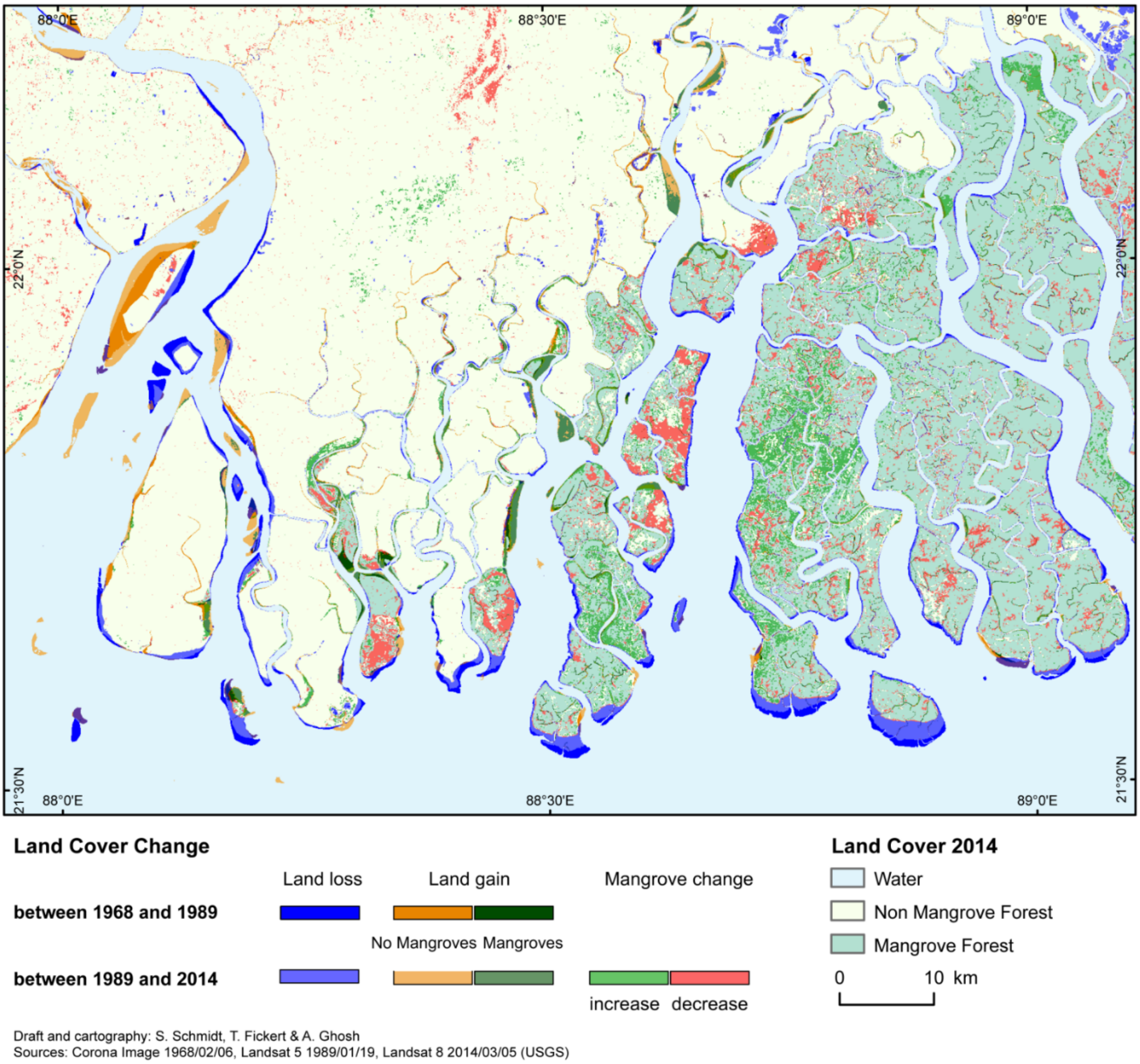

Figure 4. Change detection analyses indicating areas of land loss and land gain between 1968 and 2014 based on Corona and Landsat data; for changes in mangrove extent and cover only the Landsat data were employed; for change statistics see Table 3.

6. Internal Mangrove Dynamics—Climate Change and Human Impacts

While the total mangrove area did not change significantly over the last few centuries, change detection analyses clearly show natural internal mangrove dynamics with small-scale land loss and gain by erosion and accretion of sediments within the tidal channels. Along the Hooghly River channel new islands have developed on the western side, whereas more land has eroded on the east. Ghoramara Island lost almost half of its area between 1968 and 2014 (Figure 4). There is a high turnover rate of aggradation and erosion, which was more or less balanced in the past [65]. Today, however, erosion rates are much higher than aggradation, which is most likely the result of artificial sediment traps upstream by dams and barrages in particular areas (e.g. the Farakka Barrage) and higher discharge through water diversion in other parts of the drainage basin [41,65]. Another concern is the higher amount of meltwater from

Himalayan glaciers, which increases erosion along the estuaries and thus delivers a higher amount of sediments [65,68,69]. Change detection analysis (Figure 4) shows that the new sedimentary deposits along small tidal channels are colonized within a couple of years by light demanding pioneer plant communities which are later replaced by different successional communities due to land rise and modified inundation and salinity conditions [70]. Due to hydrological modifications, with altered flooding and soil salinity conditions, floristic changes can be assumed, which in turn influence the entire food chain within the Sundarban mangrove forests. Furthermore, the increased runoff from the Himalayas reduces soil salinity, and, owing to higher erosion, high siltation causes lower transparency and thus lowers photosynthetic activity of the phytoplankton with adverse consequences on food chains and oxygen production [65,69,71].

Table 3. Change statistics for land loss/gain and mangrove area between 1968 and 2014.

	Differences Between Observations				
	1968–1989 [km²]	1968–2014 [km²]	1989–2001 [km²]	2001–2014 [km²]	1989–2014 [km²]
	Corona and Landsat		Landsat		
Total Land Loss	136	299	74	263	213
Total Land Gain	163	270	219	60	159
No-Mangroves	123	163	204	55	107
Mangroves	40	107	15	5	52
Mangrove Change					
Increase	54		235	137	240
decrease	475		154	220	262

Large-scale changes in mangrove structure as well as coastline are caused by occasional cyclonic disturbances. On 25 May 2009, a tropical cyclone (Aila) hit the Sundarbans in India and Bangladesh with a wind speed of 110 km/hr. Over 8000 people were registered missing and about a million were rendered homeless in the two countries. Approximately 300 people were killed in Sagar Island (for location see Figure 1) alone in the Indian Sundarbans [72]. Impacts on mangrove forests range from defoliation, removal of twigs due to wind throw and breakage of delicate root structures which differed according to the severity of the storm. In the classification (Figure 2 middle right) the passage of one severe tropical cyclone in November 1988 is evident; where low normalized vegetation index values represent reduced ground cover (see also [22]). Mangrove forests generally possess a high resilience to natural disturbances such as tropical storms and tsunamis. According to [22] recovery time in storm disturbed mangrove forests of the Sundarbans is around 25 years. However, following a sequence of recent severe disturbing events, with several cyclones in a row (1988, 1991, Sidr in 2007, Nardis in 2008 and Aila in 2009) and the Asian tsunami of 2004, there is concern that the mangroves' regeneration ability has been weakened. On the Bay of Bengal along the Sundarbans the occurrences of cyclones increased by 26% between 1881 and 2001 [73]. A projection modelling predicts a further increase in the frequency of cyclones, particularly in the late monsoon season [74], as well as a higher intensity of storms in the months of May and June between 2070 and 2100 [75] with the possible outcomes for mangrove structure and vitality being already observable. Thus, the planting of mangrove propagules in large gaps constitutes an important measure for substantial mangrove management if the invasion of non-mangrove taxa and ecosystem conversion is to be avoided [76].

Apart from large cyclones such as Aila, tidal bores and high tides—though a comparatively slow onset is equally destructive—have already started to play havoc on the ecosystem. A tidal bore on 13–15 July 2014 displaced over 50,000 people (recorded by author). Furthermore, over 10,000 dwelling units were completely destroyed and 5000 more were partly damaged. Paddy fields across villages were inundated, at least 15 villages were completely destroyed and intrusion of saline sea water ruined the prospects of agriculture for the next one year or so, whilst sweet-water ponds were contaminated (unpubl. data from the government of West Bengal, department of Panchayat and rural development). These low intensity but relatively high frequency hazards are usually triggered by weather events and the interaction of these events with the local ecosystems.

The increasing intensity of the everyday disasters such as tidal bores has been explained by [74] who points to a further escalation of tidal flows and volumes in the Sundarbans compared to the rest of the eastern coast of India. This is significant as it directly translates into greater destructive abilities of higher sea levels and cyclones but also from otherwise innocuous high tides and regular tidal events throughout the year. The environmental changes under such conditions are expected to be rapid and incremental as has been the case of Sagar [77,78] and Jambudwip [79], one of the fast-eroding islands.

The other important and critical change is sea level rise, owing to global warming, anthropogenic drivers, and land subsidence [65], which eventually affects the mangrove forest and vulnerable, coastal communities. The cumulative effect of this, described as relative mean sea level (RMSL), has risen between 3.14 mm/year [80] and almost 5 mm/year [81] in the Sundarbans, which are much higher than global averages, and threaten to inundate close to a billion people [82].

Sea level rise is a major driver for recent land loss along the coastline [83], which has serious effects on the health of the forests in the Sundarbans. The change detection analyses in Figure 4 shows that the coastline retreat varies, with a maximum of about 2.8 km between 1968 and 2014 for the southern islands. The archipelago has lost 284 km^2 in the past 50 years, whereas accretion has been only 84 km^2 [84]. According to [77,85] the rate of land loss has increased during the first decade of the 21st century from 2.85 km^2 per year to 5.5 km^2. In some cases, such as Jambudwip Island, the total area lost has been over 50% ([79], Figure 4). Sagar Island has shrunk by 15%, and three other islands, Lohachahara, Suparibhanga and Bedford, have completely disappeared, whilst Ghoramara Island has been eroded significantly, displacing scores of people [86].

With RMSL getting higher, land area above water surface will be significantly reduced and the inundated land may no longer support mangroves when the sea level is too high. The low salinity areas will be considerably reduced, causing changes in the abundance patterns of species and the floristic composition in general, with decreases of less salt-tolerant taxa including the economically important tree species *Heritiera fomes* [35]. Cumulative effects of changing weather patterns, tectonic shifts and subsidence have changed the salinity dynamics of the region [65]. Not only has the reduced freshwater supply led to higher river water salinity, but also the aquatic subsystem has significantly altered, resulting in a sharp decline in the commercially important fish in the central tracts [87] of the Sundarbans.

The two most serious anthropogenic impacts on the forest are wastewater pollution from large cities and industry, and a reduction in freshwater supply owing to the construction of upstream embankments for diversion of irrigation water. The most prominent example is the Farakka Barrage, constructed in

1975, which has altered the regional hydrological balance, and has contributed a great deal to differences in freshwater distribution, and to the increased salinization of the soils. Two resultant effects of increased pollution and soil salinization on the Sundarban mangroves is the recent observation of a decrease in canopy closure (see Figure 4), and the prevalence of a top dying disease affecting the formerly dominant and economically most important tree species *Heritiera fomes* [88,89]. Such degradation may have strong negative knock-on effects on the different interrelated components of the Sundarbans' biodiversity [90].

Besides the effects on the vegetation, human action also affects faunal communities, in particular of fishes [65]. High levels of pollution, sediment load, and salinity trigger negative effects on the faunal reproduction and growth, as well disturbing composition and distribution patterns. In the central, more saline, part of the Indian Sundarbans, opportunistic trash fish have increased significantly, while the abundance of commercially important taxa has decreased. In addition, low water quality may also cause a reduction of commercially important fish larvae due to the negative impacts on the quality of their nursery grounds within the forests. Such qualitative and quantitative losses in ecosystem services will have an influence on the Sundarbans as a living environment for human beings, and may result in shifts in profession and/or out-migration of people [35].

Coastal squeeze under rising sea levels [69] may also severely impact the mangrove forest and tiger population. The predicted reduction of habitat by the end of the century may leave less than 20 breeding individuals in the whole of the Sundarbans, which is way below threshold for species maintenance, meaning the tiger will become extinct [91], as two other iconic rhino species have previously: *Rhinoceros sondiacus*, and *R. unicornis* [92].

Indiscriminate construction of circuit embankments [53] to make islands habitable since the British administration, have, over 200 years, altered natural geomorphological processes of delta formation. In many cases the creek beds have risen higher than the low-lying reclaimed areas, turning those areas into vast stretches of permanent marshes that *"seals off the possibility of these tracts ever naturally maturing into lands habitable by humans"* [93] (p. 93). The cumulative impact of altering the geomorphology, and the construction of embankments has led to submergence of large tracts of land in the sea-facing islands, including for those which are non-embanked, and has also led to coastal retro-gradation of more than 10 km in some cases, such as Sagar Island ([94], see also Figure 4). This subsidence of the land can be attributed to the autocompaction of the silt layers as well as to the effects of storm surges that lead to a retreat of the coastline [94,95].

Collapse of these embankments are widespread, though their frequency depends on the type of construction and its interaction with (changing) tidal pressures, cyclonic storms, rising sea level and various tidal events. Every time there is a major breach, human pressure on the ecosystem intensifies; affected households turn to water-based livelihood activities and became directly dependent on the riparian commons [57]. Apart from exposing populations to inundation and destruction of assets, these breaches also lead to an increase in soil salinity, ruining prospects for agriculture, whilst also affecting the floral and faunal diversity of the ecosystem [63].

7. Conclusions

Mangroves are diverse and highly productive ecological communities at the land-sea interface. The Sundarban mangrove forests are the largest in the world. They provide a wide range of important ecosystem services, including: the provision of food and water for millions of its inhabitants; protection against the worst effects of natural hazards, such as with cyclones and tsunamis; the ability to act as a giant long-term carbon sink; the retention of terrestrial sediments; and as a habitat for many species, including for the rare and protected Royal Bengal tiger. The importance of the Sundarbans therefore extends from the local to the global, where different stakeholder objectives attempt to decide its future. During the last two-and-a-half centuries, the Sundarban mangrove ecosystem has been affected by human impact, slow onset climatic change and extreme weather events. Human activities in the inhabited part of the Indian Sundarbans have a greater incremental impact on mangrove forests, salinity increase, relative mean sea level rise and land loss than previously assumed. Protection of mangrove forests is extremely complex and multiscalar because of the interaction of climatic threats, path-dependent development regimes and environmental governance. Enforcement of legal protection is intricately connected to power struggles and by no means a universal virtue [64]. Direct human pressure on these strictly protected forests comes from the extraction of goods and enlarging arable land [58].

While mangroves inherently possess a high resilience to natural disturbances such as tropical storms or tsunamis, the effects of anthropogenic degradation is often irreversible. This is why it is important to reconfigure development plans by including local requirements and to approach the problem through a multiscalar and polycentric manner, instead of looking at conservation and climate change adaptation separately. More effective conservation elicits adaptation co-benefits and vice versa, for example bio-embankments and beach nourishment, which have provided effective protection against coastal erosion along the Netherlands coasts [96,97]. In the Sundarbans, this calls for an interdisciplinary collaboration between natural and social scientists to develop policies addressing conservation and climate change adaptation. The West Bengal government recently announced a number of development measures for the Sundarbans including ecotourism infrastructure [98]. Such developments, if realized, might irreversibly jeopardize the ecosystem, without first addressing the core problems, *i.e.* industrial pollution, upstream diversion schemes, forest clearing, and, importantly, local livelihood needs.

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Author Contributions

All authors conceptualized the frame of this paper. Aditya Gosh and Thomas Fickert wrote the paper; in addition the corresponding author conducted field research on the socio-ecological system of the Sundarbans by expert interviews. Susanne Schmidt performed all GIS analyses. Marcus Nüsser revised the final draft and added insights on human-environmental interactions.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Saenger, P. *Mangrove Ecology, Silviculture and Conservation*; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2002.
2. Hogarth, P.J. *The Biology of Mangroves and Seagrasses*; Oxford University Press: Oxford, UK, 2007; p. 273.
3. Ewel, K.C.; Twilley, R.R.; Ong, J.E. Different kinds of mangrove forests provide different goods and services. *Glob. Ecol. Biogeogr. Lett.* **1998**, *7*, 83–94.
4. Nagelkerken, I.; Blaber, S.J.M.; Bouillon, S.; Green, P.; Haywood, M.; Kirton, L.G.; Meynecke, J.-O.; Pawlik, J.; Penrose, H.M.; Sasekumar, A.; *et al.* The habitat function of mangroves for terrestrial and marine fauna: A review. *Aquat. Bot*. **2008**, *89*, 155–185.
5. Dahdouh-Guebas, F.; Jayatissa, L.P.; di Nitto, D.; Bosire, J.O.; Lo Seen, D.; Koedam, N. How effective were mangroves as a defence against the recent tsunami? *Curr. Biol*. **2005**, *15*, 443–447.
6. Danielsen, F.; Sørensen, M.K.; Olwig, M.F.; Selvam, V.; Parish, F.; Burgess, N.D.; Hiraishi, T.; Karunagaran, V.M.; Rasmussen, M.S.; Hansen, L.B.; *et al.* The Asian Tsunami: A protective role for coastal vegetation. *Science* **2005**, *310*, 643.
7. Kathiresan, K.; Rajendran, N. Coastal mangrove forests mitigated tsunami. *Estuar. Coast. Shelf Sci*. **2005**, *65*, 601–606.
8. Williams, N. Tsunami insight to mangrove value. *Curr. Biol*. **2005**, *15*, 73.
9. Mumby, P.J.; Hastings, A. The impact of ecosystem connectivity on coral reef resilience. *J. Appl. Ecol*. **2008**, *45*, 854–862.
10. Kristensen, E.; Bouillon, S.; Dittmar, T.; Marchand, C. Organic carbon dynamics in mangrove ecosystems: A review. *Aquat. Bot*. **2008**, *89*, 201–219.
11. Costanza, R.; Farber, S.C.; Maxwell, J. The valuation and management of wetland ecosystems. *Ecol. Econ*. **1989**, *1*, 335–361.
12. Costanza, R.; de Groot, R.; Sutton, P.; van der Ploeg, S.; Anderson, S.J.; Kubiszewski, I.; Farber, S.; Turner, R.K. Changes in the global value of ecosystem services. *Glob. Environ. Change* **2014**, *26*, 152–158.
13. Bann, C. *The Economic Valuation of Mangroves: A Manual for Researchers*; International Development Research Centre: Ottawa, ON, Canada, 1997; p. 54.
14. Barbier, E.B. Valuing ecosystem services as productive inputs. *Econ. Policy* **2007**, *49*, 177–229.

15. Walters, B.B.; Rönnbäck, P.; Kovacs, J.M.; Crona, B.; Hussain, S.A.; Badola, R.; Primavera, J.H.; Barbier, E.; Dahdouh-Guebas, F. Ethnobiology, socio-economics and management of mangrove forests: A review. *Aquat. Bot.* **2008**, *89*, 220–236.
16. Salem, M.E.; Mercer, D.E. The economic value of mangroves: A meta-analysis. *Sustainability* **2012**, *4*, 359–383.
17. Russi, D.; ten Brink, P.; Farmer, A.; Badura, T.; Coates, D.; Förster, J.; Kumar, R.; Davidson, N. *The Economics of Ecosystems and Biodiversity for Water and Wetlands*; IEEP: London, UK, 2013; p. 84.
18. Valiela, I.; Bowen, J.L.; York, J.K. Mangrove forests: One of the world's threatened major tropical environment. *Bioscience* **2001**, *51*, 807–815.
19. Ellison, A.M. Macroecology of mangroves: Large scale patterns and processes in tropical coastal forests. *Trees Struct. Funct*. **2002**, *16*, 181–194.
20. Duke, N.C.; Meynecke, J.-O.; Dittmann, S.; Ellison, A.M.; Anger, A.M.; Berger, U.; Cannicci, S.; Diele, K.; Ewel, K.C.; Field, C.D.; *et al.* A world without mangroves. *Science* **2007**, *317*, 41–42.
21. World Bank. *Building Resilience for Sustainable Development of the Sundarbans: Strategy Report*; World Bank Group: Washington, DC, USA, 2014; p. 290.
22. Islam, M.T. Vegetation changes of Sundarbans based on Landsat Imagery analysis between 1975 and 2006. *Landsc. Environ.* **2014**, *8*, 1–9.
23. Spalding, M.; Kainuma, M.; Collins, L. *World Atlas of Mangroves*; Earthscan: London, UK, 2010; p. 319.
24. Gopal, B.; Chauhan, M. Biodiversity and its conservation in the Sundarban mangrove ecosystem. *Aquat. Sci*. **2006**, *68*, 338–354.
25. Banerjee, L.K. Sundarbans. In *Floristic Diversity and Conservation Strategies in India, vol. V, Botanical Survey of India*; Shing, N.P., Shing, K.P., Eds.; Ministry of Environment and Forests: New Delhi, India, 2002; pp. 2801–2829.
26. Duke, N.C. Mangrove floristics and biogeography. In *Tropical Mangrove Ecosystems*; Robertson, A.I., Alongi, D.M., Eds.; American Geophysical Union: Washington, DC, USA, 1992; pp. 63–100.
27. Barik, J.; Chowdhury, S. True mangrove species of Sundarbans delta, West Bengal, Eastern India. *Check List* **2014**, *10*, 329–334.
28. Goodbred, S.L.; Kuehl, S.A. The significance of large sediment supply, active tectonism, and eustasy on margin sequence development: Late Quaternary stratigraphy and evolution of the Ganges—Brahmaputra delta. *Sediment. Geol.* **2000**, *133*, 227–248.
29. Syvitski, J.P.M.; Kettner, A.J.; Overeem, I.; Hutton, E.W.H.; Hannon, M.T.; Brakenridge, G.R.; Day, J.; Vörösmarty, C.; Saito, Y.; Giosan, L.; *et al*. Sinking deltas due to human activities. *Nat. Geosci.* **2009**, *2*, 681–686.
30. Hanebuth, T.J.J.; Kudrass, H.R.; Linstädter, J.; Islam, B.; Zander, A.M. Rapid coastal subsidence in the central Ganges-Brahmaputra Delta (Bangladesh) since the 17th century deduced from submerged saltproducing kilns. *Geology* **2013**, *41*, 987–990.
31. Blasco, F.; Saenger, P.; Janodet, E. Mangroves as indicators of coastal change. *Catena* **1996**, *27*, 167–178.
32. IUCN. *International Union for the Conservation of Nature—Bangaldesh: The Bangladesh Sundarbans: A Photo Real Sojourn*; IUCN Bangladesh Country Office: Dhaka, Bangladesh, 2001.

33. Banerjee, A.K. *Forests of Sundarbans, Centenary Commemoration Volume, West Bengal Forests. Planning and Statistical Cell, Writer's Building*; Calcutta: Bengal, India, 1964; p. 188.
34. Iftekhar, M.S. An overview of mangrove management strategies in three South Asian countries: Bangladesh, India and Sri Lanka. *Int. For. Rev.* **2008**, *10*, 38–51.
35. Shams-Uddin, M.; Shah, M.A.R.; Khanom, S.; Nesha, M.K. Climate change impacts on the Sundarbans mangrove ecosystem services and dependent livelihoods in Bangladesh. *Asian J. Conserv. Biol.* **2013**, *2*, 152–156.
36. De Groot, R.S.; Wilson, M.A.; Boumans, R.M.J. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecol. Econ*. **2002**, *41*, 393–408.
37. Saenger, P. Mangroves: Sustainable management in Bangladesh. In *Tropical Forestry 8, Silviculture in the Tropics*; Günter, S., Weber, M., Stimm, B., Mosandl, R., Eds.; Springer: Berlin, Germany, 2011; pp. 339–347.
38. Lillesand, T.M.; Kiefer, R.W.; Chipman, J.W. *Remote Sensing and Image Interpretation*; John Wiley & Sons: Hoboken, NJ, USA, 2004; p. 704.
39. Dashora, A.; Lohani, B.; Malik, J.N. A repository of earth resource information—CORONA satellite programme. *Curr. Sci. India* **2007**, *92*, 926–932.
40. Green, E.P.; Clark, C.D.; Mumby, P.J.; Edwards, A.J.; Ellis, A.C. Remote sensing techniques for mangrove mapping. *Int. J. Remote Sens.* **1998**, *19*, 935–956.
41. Giri, C.; Pengra, B.; Zhu, Z.; Singh, A.; Tieszen, L.L. Monitoring mangrove forest dynamics of the Sundarbans in Bangladesh and India using multi-temporal satellite data from 1973 to 2000. *Estuar. Coast. Shelf Sci*. **2007**, *73*, 91–100.
42. Lee, T.-M.; Yeh, H.-C. Applying remote sensing techniques to monitor shifting wetland vegetation: A case study of Danshui River estuary mangrove communities, Taiwan. *Ecol. Eng.* **2009**, *35*, 487–496.
43. Kuenzer, C.; Bluemel, A.; Gebhardt, S.; Vo Quov, T.; Dech, S. Remote sensing of mangrove ecosystems: A Review. *Remote Sens.* **2011**, *3*, 879–928.
44. Heumann, B.W. Satellite remote sensing of mangrove forests: Recent advances and future opportunities. *Prog. Phys. Geogr.* **2011**, *35*, 87–108.
45. Gray, D.; Zisman, S.; Corves, C. *Mapping of the Mangroves of Belize*; Technical Report; University of Edinburgh: Edinburgh, UK, 1990; p. 33.
46. Eaton, R.M. Human settlement and colonization in the Sundarbans, 1200–1750. *Agric. Hum. Values* **1990**, *7*, 6–16.
47. O'Malley, L.S.S. *Eastern Bengal District Gazetteers, Khulna*; Calcutta: Bengal, India, 1908; pp. 193–194.
48. Sarkar, S.C. Bengal's southern frontier, 1757 to 1948. *Stud. Hist.* **2012**, *28*, 69–97.
49. Rennel, J. *A Bengal Atlas Containing Maps of the Theatre of War and Commerce on that Side of Hindoostan*; East India Company: London, UK, 1780.
50. Hunter, W.W. *Statistical Account of Bengal, 24 Parganas*; Trübner: London, UK, 1876.
51. Chakrabarty, R. Local people and the global tiger: An environmental history of the sundarbans. *Glob. Environ.* **2009**, *3*, 72–95.
52. Anon. *District Human Development Report, South 24 Parganas*; Development and Planning Department, Government of West Bengal: Kolkata, India, 2010.

53. Chakraborty, S.C. The Sundarbans—Terrain, legends, Gods & myths. *Geogr. Rev. India* **2005**, *67*, 1–11.
54. Hunter, W.W. *Statistical Account of Bengal*; Parganas and Sundarbans: London, UK, 1885.
55. Greenough, P.R. Hunter's drowned land: An environmental fantasy of the Victorian Sundarbans. In *Nature and the Orient: The Environmental History of South and Southeast Asia*; Grove, R.H., Damodaran, V., Sangwan, S., Eds.; Oxford University Press: Delhi, India, 1998, pp. 237–272.
56. Iqbal, I. *The Bengal Delta: Ecology, State and Social Change, 1840–1943*; Palgrave Macmillan: London, UK, 2011; p. 268.
57. Danda, A.A. Surviving in the Sundarbans: Threats and Responses. Ph.D. Thesis, University of Twente, Enschede, The Netherlands, 2007; p. 199.
58. DasGupta, R.; Shaw, R. Changing perspectives of mangrove management in India: An analytical overview. *Ocean. Coast. Manag.* **2013**, *80*, 107–118.
59. Iftekhar, M.S.; Islam, M.R. Degeneration of Bangladesh's Sundarbans mangroves: A management issue. *Int. For. Rev.* **2004**, *6*, 123–135.
60. Jalais, A. The Sundarbans: Whose world heritage site? *Conserv. Soc*. **2007**, *5*, 1–8.
61. Ghosh, A. *Living with Changing Climate—Impact, Vulnerability and Adaptation Challenges in Indian Sundarbans*; Centre for Science and Environment: New Dehli, India, 2012; p. 108.
62. Banerjee, A. Joint forest management in west Bengal. In *Forests People and Power: The Political Ecology of Reform in South Asia*; Springate-Baginski, O., Blaikie, P., Eds.; Routledge: London, UK, 2013; pp. 177–220.
63. Raha, A.K.; Zaman, S.; Sengupta, K.; Bhattacharyya, S.B.; Raha, S.; Banerjee, K.; Mitra, A. Climate change and sustainable livelihood programme: A case study from Indian Sundarbans. *J. Ecol.* **2013**, *107*, 335–348.
64. Sivaramakrishnan, K. Crafting the public sphere in the forests of West Bengal: Democracy, development, and political action. *Am. Ethnol.* **2000**, *27*, 431–461.
65. Raha, A.; Das, S.; Banerjee, K.; Mitra, A. Climate change impacts on Indian Sunderbans: A time series analysis (1924–2008). *Biodivers. Conserv*. **2012**, *21*, 1289–1307.
66. Jalais, A. *Forest of Tigers: People, Politics and Environment in the Sundarbans*; Routledge: London, UK, 2014; p. 268.
67. Ostrom, E. A polycentric approach for coping with climate change. *Ann. Econ. Financ.* **2014**, *15*, 71–108.
68. Mitra, A.; Banerjee, K.; Sengupta, K.; Gangopadhyay, A. Pulse of climate change in Indian Sundarbans: A myth or reality. *Natl. Acad. Sci. Lett.* **2009**, *32*, 19–25.
69. Banerjee, K. Decadal change in the surface water salinity profile of Indian Sundarbans: A potential indicator of climate change. *J. Mar. Sci. Res.* Dev. **2013**, 7.
70. Iftekhar, M.S.; Saenger, P. Vegetation dynamics in the Bangladesh Sundarbans mangroves: A review of forest inventories. *Wetl. Ecol. Manag.* **2008**, *16*, 291–312.
71. Mitra, A.; Gangopadhyay, A.; Dube, A.; Schmidt, A.C.; Banerjee, K. Observed changes in water mass properties in the Indian Sundarbans (northwestern Bay of Bengal) during 1980–2007. *Curr. Sci. India* **2009**, *97*, 1445–1452.
72. Gupta, A.; Basu, J.; Bhatta, A. "@110/hr", *Down to Earth*; Society for Environmental Communications: New Delhi, India, 2009; Volume 18.

73. Singh, O.P. International variability and predictability of sea level along the Indian coast. *Theor. Appl. Climatol.* **2002**, *72*, 11–28.
74. Unnikrishnan, A.S.; Kumar, M.R.R.; Sindhu, B. Tropical cyclones in the Bay of Bengal and extreme sea-level projections along the east coast of India in a future climate scenario. *Curr. Sci. India* **2011**, *101*, 327–331.
75. Parth Sarthi, P.; Agrawal, A.; Rana, A. Possible future changes in cyclonic storms in the Bay of Bengal, India under warmer climate. *Int. J. Climatol.* **2014**, *35*, 11.
76. Harun-or-Rashid, S.; Biswas, S.R.; Böcker, R.; Kruse, M. Mangrove community recovery potential after catastrophic disturbances in Bangladesh. *For. Ecol. Manag*. **2009**, *257*, 923–930.
77. Gopinath, G.; Seralathan, P. Rapid erosion of the coast of Sagar island, West Bengal, India. *Environ. Geol.* **2005**, *48*, 1058–1067.
78. Dinesh Kumar, P.K.; Gopinath, G.; Laluraj, C.M.; Seralathan, P.; Mitra, D. Change detection studies of Sagar island, India, using Indian remote sensing satellite 1C linear imaging self-scan sensor III data. *J. Coast. Res.* **2007**, *23*, 1498–1502.
79. Das, M. Deformation of the Jambudwip island of Sundarban region, Eastern India. Int. *J. Geomat. Geosci.* **2014**, *5*, 9–18.
80. Hazra, S.; Ghosh, T.; DasGupta, R.; Sen, G. Sea level and associated changes in the Sundarbans. *Sci. C.* **2002**, *68*, 309–321.
81. Nandy, S.; Bandopadhyay, S. Trend of sea level change in the Hugli estuary, India. *Indian J. Geo-Mar. Sci.* **2011**, *40*, 802–812.
82. DasGupta, S.; Huq, M.; Khan, Z.H.; Ahmed, M.M.Z.; Mukherjee, N.; Khan, M.F.; Pandey, K. Cyclones in a changing climate: The case of Bangladesh. *Clim. Dev.* **2014**, *6*, 96–110.
83. Cornforth, W.A.; Fatoyinbo, T.E.; Freemantle, T.P.; Pettorelli, N. Advanced land observing satellite phased array type L-Band SAR (ALOS PALSAR) to inform the conservation of mangroves: Sundarbans as a case study. *Remote Sens.* **2013**, *5*, 224–237.
84. Ganguly, D.; Mukhopadhyay, A.; Pandey, R.K.; Mitra, D. Geomorphological study of Sundarban deltaic estuary. *J. Indian Soc. Remote Sens.* **2006**, *34*, 431–435.
85. Hazra, S.; Samanta, K.; Mukhopadhyay, A.; Akhand, A. *Temporal Change Detection (2001–2008) of the Sundarban*; Unpublished Report; WWF-India: New Delhi, India, 2010.
86. Ghosh, T.; Hajra, R.; Mukhopadhyay, A. Island erosion and afflicted population: Crisis and policies to handle climate change. In *International Perspectives on Climate Change*; Filho, W.L., Alves, F., Caeiro, S., Azeiteiro, U.M., Eds.; Springer: Berlin, Germany, 2014; pp. 217–225.
87. Mitra, A.; Banerjee, K. Trace elements in edible shellfish species from the lower Gangetic delta. *Ecotoxicol. Environ. Saf.* **2011**, *74*, 1512–1517.
88. Rahman, M.A. A comprehensive report on sundry (*Heritiera fomes*) trees with particular reference to top dying in the Sundarbans. In *Seminar on Top Dying of Sundri (Heritiera fomes) Trees*; Rahman, M.A., Khandakar, M.A., Ahmed, F.U., Ali, M.O., Eds.; Bangladesh Agricultural Research Council: Dhaka, Bangladesh, 1990; p. 256.
89. Zaman, S.; Bhattacharyya, S.B.; Pramanick, P.; Raha, A.K.; Chakraborty, S.; Mitra, A. Rising water salinity: A threat to mangroves of Indian Sundarbans. In *Water Insecurity: A Social Dilemma*; Abedin, M.A., Habiba, U., Shaw, R., Eds.; Emerald Group Publishing Limited: Bingley, UK, 2013; pp. 167–183.

90. Selvam, V. Environmental classification of mangrove wetlands of India. *Curr. Sci. India* **2003**, *84*, 757–765.
91. Loucks, C.; Barber-Meyer, S.; Hossain, M.A.A.; Barlow, A.; Chowdhury, R.M. Sea level rise and tigers: Predicted impacts to Bangladesh's Sundarbans mangroves. *Clim. Change* **2010**, *9*, 291–298.
92. Siddiqi, N.A. *Mangrove Forestry in Bangladesh*; University of Chittagong: Chittagong, Bangladesh, 2001.
93. Bhattacharya, S. Sundarban—Dying a slow death. In *The Hindu Survey of Environment* 1998; pp. 89–94.
94. Rudra, K. Changing river courses in the western part of the Ganga–Brahmaputra delta. *Geomorphology* **2014**, *227*, 87–100.
95. Bandyopadhyay, S.; Bandyopadhyay, M.K. Retrogradation of the western Ganga-Brahmaputra delta: Possible reasons. *Natl. Geogr.* **1996**, *31*, 105–128.
96. Inman, M. Working with water. *Nat. Rep. Clim. Change* **2010**, doi:10.1038/climate.
97. Kazmierczak, A.; Carter, J. *Adaptation to Climate Change Using Green and Blue Infrastructure. A Database of Case Studies*; GraBS Project; University of Manchester: Manchester, UK, **2010**.
98. Dinda, A. Evaluation of eco-tourism activity: A case study of Sundarban tiger reserve. In *Man in Biosphere: A Case Study of Sundarban Biosphere Reserve*; Gyan: New Delhi, India, 2007.