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Distribution and dynamics of mangrove forests of South Asia☆

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ABSTRACT

Mangrove forests in South Asia occur along the tidal sea edge of Bangladesh, India, Pakistan, and Sri Lanka. These forests provide important ecosystem goods and services to the region's dense coastal populations and support important functions of the biosphere. Mangroves are under threat from both natural and anthropogenic stressors; however the current status and dynamics of the region's mangroves are poorly understood. We mapped the current extent of mangrove forests in South Asia and identified mangrove forest cover change (gain and loss) from 2000 to 2012 using Landsat satellite data. We also conducted three case studies in Indus Delta (Pakistan), Goa (India), and Sundarbans (Bangladesh and India) to identify rates, patterns, and causes of change in greater spatial and thematic details compared to regional assessment of mangrove forests.

Our findings revealed that the areal extent of mangrove forests in South Asia is approximately 1,187,476 ha representing ~7% of the global total. Our results showed that from 2000 to 2012, 92,135 ha of mangroves were deforested and 80,461 ha were reforested with a net loss of 11,673 ha. In all three case studies, mangrove areas have remained the same or increased slightly, however, the turnover was greater than the net change. Both, natural and anthropogenic factors are responsible for the change and turnover. The major causes of forest cover change are similar throughout the region; however, specific factors may be dominant in specific areas. Major causes of deforestation in South Asia include (i) conversion to other land use (e.g. conversion to agriculture, shrimp farms, development, and human settlement), (ii) over-harvesting (e.g. grazing, browsing and lopping, and fishing), (iii) pollution, (iv) decline in freshwater availability, (v) floodings, (vi) reduction of silt deposition, (vii) coastal erosion, and (viii) disturbances from tropical cyclones and tsunamis. Our analysis in the region's diverse socio-economic and environmental conditions highlights complex patterns of mangrove distribution and change. Results from this study provide important insight to the conservation and management of the important and threatened South Asian mangrove ecosystem.

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1. Introduction

Mangrove forests in South Asia occur on the tidal sea edge of Bangladesh, India, Pakistan, and Sri Lanka and represent approximately 7% of the global total (Giri et al., 2011b). The largest contiguous mangrove forest in the world, Sundarbans, is located in the border of Bangladesh and India. Mangrove species diversity in the region ranges from 8 to 10 species in Pakistan, 12–13 in Bangladesh, 18–20 Sri in Lanka, and 30–35 in India (Polidoro et al., 2010). The mangrove forests of South Asia provide important

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ecosystem goods and services to the environment and densely populated coastal population including shoreline stabilization, storm protection, water quality maintenance, micro-climate stabilization, groundwater recharge and discharge, flood and flow control, sediment and nutrient retention, habitat protection and biodiversity, biomass, productivity and resilience, recreation, tourism and culture, hunting and fishing, forestry products, and water transport (Blasco and Aizpuru, 2002; Dahdouh-Guebas et al., 2005; Duke et al., 2007).

Following the Indian Ocean tsunami of 2004, the protective role of mangroves from natural disasters have become more widely realized (Giri et al., 2007b). Research shows that ecologically healthy mangrove forest helped save lives and property during the tsunami (Bahuguna et al., 2008; Danielsen et al., 2005; Oyana et al., 2009), although counter arguments were also presented (Kerr et al., 2006). Recent findings also suggest that Asian mangroves are among the most carbon-rich forests in the tropics (Donato et al., 2012). The carbon content in the mangrove forests of Asia and the Pacific is estimated to be 1.023 Mg carbon per hectare, more than 50% of which is stored in organic-rich soils (Donato et al., 2012).

Despite their ecological and socio-economic values and importance, mangrove forests in South Asia are being lost or degraded from both natural (e.g. coastal erosion, disturbances from tropical cyclones and tsunamis) and anthropogenic factors (conversion to other land use, over-harvesting, pollution, decline in freshwater availability, flooding, and reduction of silt deposition) (Cornforth et al., 2013; Giri et al., 2007a; Porwal et al., 2012; Satyanarayana et al., 2011). However, accurate and timely information on the extent, condition, and spatio-temporal dynamics of this change is not available. Local studies conducted at different region of these countries are available (Cornforth et al., 2013; Kumar et al., 2013; Nandy and Kushwaha, 2011; Porwal et al., 2012; Rahman et al., 2013; Srinivasa Kumar et al., 2012), however, a holistic view of the whole South Asian region using consistent data sources and methodology was not available. The regional overview of mangrove ecosystem is needed for various applications including: (i) development of regional action plan, (ii) identification of how South Asian mangroves respond to climate change impacts, and (iii) enumeration of the roles, impacts, and response of mangroves relative to natural disasters. This information is critically important because the region is experiencing increasing threat from coastal development, climate change, and natural disasters (Pachauri, 2008).

Thus, the objective of this study was to enumerate the extent and location of mangrove forests of South Asia for the year 2012, and quantify and characterize change dynamics from 2000 to 2012 using state-of-the-science remote sensing and cloud computing technologies. The secondary objective was to enumerate rates, patterns, causes, and consequences of mangrove forest cover change in three case study sites located in the Sundarbans (Bangladesh and India), Goa (India), and Indus Delta (Pakistan) at higher spatial and thematic resolutions compared with regional assessments. The geo-spatio-temporal mangrove database generated from this research will be freely distributed through the web that could be used for regular monitoring and improving conservation and management of mangrove resources of South Asia.

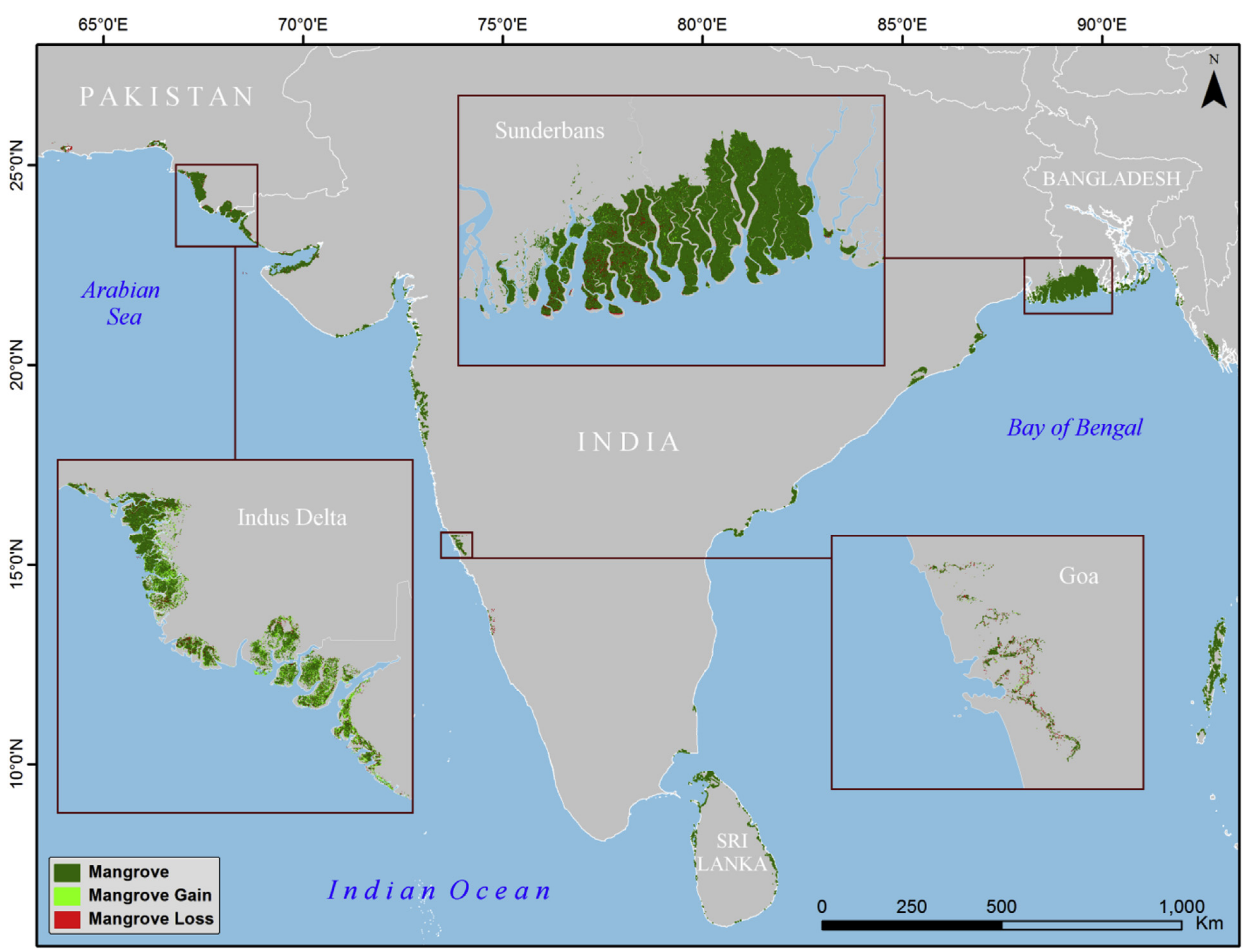

Fig. 1. Persistent mangroves of South Asia with forest gain and loss from 2000 to 2012.

2. Materials and methods

2.1. Study area

The study area included the coastal mangrove areas in Bangladesh, India, Pakistan, and Sri Lanka (Fig. 1). Three case study sites are located in Indus Delta (Pakistan), Goa (India), and the Sundarbans (Bangladesh and India) (Fig. 1).

Within each country, mangroves are located in coastal pockets. Mangroves in Sri Lanka are restricted to estuaries along the coasts, the extent of which ranges from 6000–7000 ha. The largest mangrove patches are found in the Puttalam Lagoon-Dutch Bay-Portugal Bay complex, Batticaloa, and Trincomalee. Dominant mangrove species are *Rhizophora, Avicennia, Bruguiera* and *Acanthus* species.

In Pakistan, approximately 95% (~935,00 ha.) of mangroves are concentrated in the Indus Deltaic swamps of the Sindh Province along the Arabian seas coastline. Other major areas are.

Sandspit, Sonmiani(Miani Hor), Kalmat Khor, and *Jiwani (Gwader). Avicennia marina* is the dominant species together with *Ceriops roxburghiana* (*Rhizophora* family), *Aegicerias corniculata* (*Myrinaceal* family), *Rhizophore mucronata* and *Ceriops tagal*

India has 4500 square kilometers of mangrove, the majority (60%) is found on the east coast compared to only 14% along the west coast due to the availability of nutrient rich deltas and suitable terrain in the east coast. The remaining 26% are found in the Andaman and Nicobar Islands. West Bengal has the largest area of mangroves followed by Gujarat and Andaman and Nicobar. The east coast including West Bangal and Andaman and Nicobar has higher species diversity compared to the west coast. Three species, *Sonneratia caseolaris, Sueda fruticosa*, and *Urochondra setulosa* are indigenous to the west coast.

Mangroves in Bangladesh are well protected in “reserved forests” located in the Sundarbans, the Chittagong region in the southeast and the Modhupur tracts in the north-central region. These mangrove forests are also found in Cox’s Bazar and the Noakhali coastal belt. The total mangrove area is an estimated 6300 square kilometers. Out of 12–13 mangrove species found in Bangladesh, species such as sundri (*Heritiera minor*) and gewa (*Excoecaria agallocha*) are most predominant.

The forests are changing due to distinctive reason in some location including sea salt extraction in the Indus Delta in Pakistan, over-harvesting of fruits in Sundarbans, and garbage disposal in Mumbai, India. Conversely, mangrove areas are increasing because of aggradation, plantation efforts, and natural regrowth. Regrowth is happening as a result of protection of existing mangrove areas.

Three case study sites were selected because they are representative samples of South Asian mangroves. Each site also exhibits their own uniqueness, which is of genuine interest to researchers. In addition, our research team had access to local scale data and information for these three sites. These case studies allow in-depth analysis of mangrove forest distribution and dynamics at a local scale which may be useful for management intervention. Brief descriptions of each site are provided below.

2.1.1. Indus Delta, Pakistan

Within the intertidal zone of Pakistan, the Indus Delta harbors the second largest mangrove ecosystem in the subtropics. The coastal climate of Pakistan is a typical arid subtropical climate with a mean annual rainfall of 100–200 mm. The Indus Delta which occupies approximately 600,000 ha extending from Korangi Creek in the north to Sir Creek in the South. The area has 17 major creeks, numerous minor creeks and extensive mudflats (Amjad and Jusoff, 2007). The Indus delta constitutes 95% of total mangrove forest found in Pakistan and is an important stopover for migratory birds from Siberia. The survival of mangrove forests is largely associated with perennial fresh water and sediment supplies from the River Indus that flows through the delta before reaching the Arabian Sea. The Indus Delta mangroves provide important ecosystem services including; habitat and breeding ground for economically important marine life and migratory birds; protect coastline and sea ports from erosion and siltation; meet fuel wood and fodder requirements of local communities, act as natural physical barrier to cyclones and typhoons and provide livelihood to a coastal population of more than 100,000 people.

2.1.2. Goa, India

The Mandovi – Zuari estuarine complex selected for the study is located in the state of Goa along the central western coast of India. The Mandovi River originates in the Western Ghats, entering Goa from the north via the Sattarisub-district, eventually pouring into the Arabian Sea. The Zuari River, the largest river of Goa, originates in Hemad-Barshem also in the Western Ghats. The Cumbarjua canal (15 km) links the two river channels of Mandovi and Zuari, forming an estuarine complex which supports a substantial mangrove extent. In order to study the mangrove distribution, it was imperative to include the associated physical aspects, especially in the case of our study region as both rivers intrude deep into the Western Ghats. Hence, an overlay analysis was done by taking into consideration all the appropriate physical factors to demarcate the boundary of the study region.

2.1.3. Sundarbans, Bangladesh and India

The Sundarbans mangrove spans the border between Bangladesh and India, extending from the Hooghly River in India to the Baleswar River in Bangladesh (Fig. 1). The forest lies on the delta of the Ganges, Brahmaputra, and Meghna Rivers on the Bay of Bengal. The area is intersected by a complex network of tidal waterways or channels, mudflats, and dense man-grove forests. The Sundarbans offers coastal bio-protection to millions of people in Bangladesh and India. The forests are located in a zone of cyclonic storms and tidal bores that originate in the Bay of Bengal and periodically strike the coastal areas. At the beginning of the colonial era (1757) in India, the Sundarbans mangrove forest occupied approximately twice its current extent (Islam et al., 1997). Currently, the Sundarbans covers approximately 1000,000 ha, 40% of which is in India and the rest is in Bangladesh (WCMC, 2005).

2.2. Data and methods

Various types of remotely sensed satellite data have been used for mapping and monitoring of mangroves at local, regional, and global scales. For large-scale studies, freely available Landsat scale (30 m) satellite data was found to be suitable (Giri and Muhlhausen, 2008). Coarse resolution satellite data such as MODIS and AVHRR is not suitable for mangrove studies because mangroves are typically found in small patches and in narrow strips along rivers. Currently, very high resolution satellite data such as QuickBird, IKONOS are cost prohibitive and full coverage covering the entire region is not currently available (Giri et al., 2011a). For this assessment, we used Landsat ETM + satellite data acquired from January to December of 2012 and 2000.

Level-one-terrain corrected product (L1T) Landsat 7 data were obtained from USGS EROS (http://eros.usgs.gov/). The use of multitemporal satellite data at a regional scale poses a number of challenges: geometric correction error, noise arising from atmospheric effects and changing illumination geometry, and instrument errors (Homer et al., 2004). Such errors are likely to introduce biases or noise into mangrove forest classification and change

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analyses. Therefore, preprocessing is necessary to remove or minimize such errors.

Pre-processing steps for this study included Top Of Atmosphere (TOA) reflectance conversion, BRDF/View angle normalization, and cloud masking. Each image was normalized for solar irradiance by converting digital number values to the TOA reflectance. This conversion algorithm is "physically based, automated, and does not introduce significant errors to the data" (Huang and Townshend 2003). Bi-directional reflectance distribution function (BRDF) effects correction was performed to the TOA image employing a per scene BRDF adjustment. Hansen et al. (2008) showed that per scene BRDF adjustments improves radiometric response and land cover characterizations. The next step was to prepare a mosaic consisting of year 2000 and 2012 by selecting best growing season pixels for each year.

We used the Classification and Regression Tree (CART) algorithm for image classification. CART is one of the commonly used classification algorithms for land cover characterization and mapping. The algorithm recursively splits training data pixels into increasingly homogeneous subsets until reaching terminal nodes with maximum homogeneity. Homogeneity is measured relative to classes defined by training data. Training data in this case being selections of pixels corresponding to areas of known land cover based on expert analysis and ancillary data We used Landsat bands (1–5 & 7), SRTM digital elevation model, and mangrove database as explanatory variable and mangrove/non-mangrove classes as response variables. We mapped "true mangroves," defined as trees, shrubs, and palms that grow exclusively in the tidal and intertidal zones of the tropical and subtropical regions. The minimum mapping unit used in this study was 0.08 ha.

The regional analysis of South Asia was performed using Google Earth Engine (http://earthengine.google.org/#intro) and Classification and Regression Tree (CART) algorithm. The Google Earth Engine provides an online platform with data, software, and computing infrastructure for data analysis. Using Earth Engine saved substantial costs in resources and time by eliminating the need for data search and download, pre-processing, software licensing, disk-space, and computing. The platform provides pre-processed Landsat data from 1999 to present, disk-space, a number of classification algorithms including CART, and Random Forests, and super-computing resources. Similar platforms are also available from the NASA Earth Exchange (https://c3.nasa.gov/nex/) and ESRI ArcGIS online (http://www.arcgis.com/about/).

Validation of land cover products based on rigorous sampling methods and high quality contemporaneous reference data is clearly desirable, however, as is very often the case, limited resources made fully rigorous quantitative validation and unreachable ideal. Nonetheless, we evaluated our database with other existing regional and local datasets. We also performed qualitative validation with the help of local experts and high resolution satellite data such as QuickBird and IKONOS. We divided the entire area into 500 m × 500 m grids and checked each grid visually to identify and correct gross errors in the classified maps. This measure helped characterize the map qualitatively and improve the overall classification.

Case studies were performed using diverse data sources, and methodologies. A brief description of data sources and methodology for three case study sites are presented in Table 1.

Landsat and Global Land Survey (GLS) satellite data used in the studies were acquired through US Geological Survey (USGS), Center for Earth Resources Observation and Science (EROS) (http://eros.usgs.gov), and the Global Land Cover Facility (GLCF) (http://glcf.umd.edu). Detailed description of Geo-Cover data can be found at: http://zulu.ssc.nasa.gov/mrsid. The Indian Remote Sensing (IRS) Linear Imaging Self Scanning Sensor-3 (LISS-III) data were acquired from National Remote Sensing Agency (NRSA), Hyderabad – India. Collection and use of ancillary data plays a crucial role to improve classification accuracy. In addition to satellite images, all three case studies used GIS layers such as administrative boundaries, populated places, creeks, roads, forest maps, and land use/land cover maps.

Satellite data were geo-referenced to UTM WGS 84 with a Root Mean Square (RMS) of less than half pixel (<15 m). Mangrove classes were identified and labeled which were then merged into a single mangrove category. Three land cover classes consisting of mangrove, water and others (barren land, agriculture, habitation) were mapped. Post-classification editing 'recoding' was performed to remove obvious errors. Finally, post-classification change analysis was performed Giri et al. (2007b).

3. Results and discussion

South Asia had 852,606 ha (7% of global total) mangroves in 2012. Spatial distribution shows that major mangrove areas are concentrated in Sundarbans in India and Bangladesh, Gujarat, Andaman & Nicobar, and Pichavaram in India, Indus Delta, Kalmat Khor Jiwani, and Miani Hor in Pakistan, and Puttalam Lagoon-Dutch Bay-Portugal Bay comples, Batticalo, and Trincomalee in Sri Lanka (Fig. 1).

Globally, mangrove extent decreases with the increase in latitude, except between 20° N and 25° N in latitude in South Asia. In this region, majority of mangroves are confined in sub-tropical regions compared to tropical regions. The higher percentage of mangroves in sub-tropical region is because of the largest remaining contiguous tract of mangroves in the Sundarbans and relatively high percentage in mangrove forests in Indus Delta (Pakistan) and Orissa (India). The areal extent of mangrove forests in each country together with forest gain and loss is presented in Table 2.

We performed post-classification change analysis using 2000 and 2012 mangrove databases. Both, natural and anthropogenic changes were enumerated. Our results revealed that from 2000 to 2012, 92,135 ha of mangroves were deforested and 80,461 ha were reforested with a net gain of 11,673 ha.

Major causes of forest loss include conversion to agriculture, urban development, shrimp ponds, and over harvesting. However, other factors such as urban pollution, mining, siltation, top dying, and natural disturbances are dominant factors in localized areas. Major causes of forest growth include plantation, and forest protection and conservation.

Table 1
Summary of data used, date of acquisition, software uses, classification methods and validation approaches.

Site	Data source (scale in m)	Date of acquisition	Software used	Classification methods	Quality check/Validation
Indus, Delta, Pakistan	Landsat MSS (60), TM (30)	1973, 2010	ERDAS, Definiens	Supervised, object oriented	Google Earth
Goa, India	Landsat, IRS-LISS-III (23.5)	1975, 1997, 2001, 2006, 2011	ERDAS	Unsupervised, ISODATA	Available Maps
Sundarbans, Bangladesh & India	GLS (30)	1975, 1990, 2000	ERDAS	Unsupervised, ISODATA	Google Earth, QuickBird, Aerial Photographs

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3.1. Case studies results

3.1.1. Indus Delta, Pakistan

The Indus Delta is considered one of the world's most threatened large deltas due to upstream freshwater extraction which irrigates 180,000 square kilometer of agriculture area (Spalding et al., 2010). A severe reduction in fresh water flow from 93 to 48 million acre feet (maf) was observed during a 80 years period spanning from 1922 to 2002 http://cms.waterinfo.net.pk/pdf/indusbasin.PDF. The impact of the reduction in fresh water flow to mangroves in the Indus Delta is not fully understood because of conflicting figures from various stakeholders including the Sindh Forest Department, Sindh Coastal Development Authority, the International Union for Conservation of nature (IUCN) and World Wide Fund for Nature – Pakistan (WWF – Pakistan). Previous estimates of mangrove cover change in Indus Delta were based on comparison between the results of different one-time-assessments done by numerous institutions over a period of time.

We assessed the mangrove cover change during the last four decades using multi-temporal Landsat MSS and TM satellite images acquired during 1973–2010 (Fig. 2). The results show current mangrove cover on the Indus Delta is 98,014 ha including 26,555 ha of dense mangrove forest (>50% canopy cover) and 71,459 ha of sparse mangrove (<50% canopy cover) forest (Table 3).

Our multi-temporal change analysis from 1973 to 2010 revealed that the delta is highly dynamic and there is simultaneous process of erosion and accretion occurring in the area. In terms of mangrove cover a total net increase of 1530 ha (1.5%) has been observed. Considering the highly dynamic ecosystem and image interpretation inaccuracies, this total change is insignificant. However, cumulative forest gain and loss was 45,126 ha and 43,596 respectively.

We found extensive degradation of mangrove forest in the upper tidal zone of the western end and intertidal zone of eastern part along the country boundary line with India. The degradation in the upper tidal zone can be seen in context of decreasing fresh water discharges from the Indus River. Over the past sixty years the quantity water flow reaching the delta has been reduced significantly, which has created two environmental problems. First, the salinity of water within the mangroves has increased to 50 parts per thousand (ppt) Aziz and Khan (2001), which is detrimental to mangrove growth. Second, the flow of alluvium–the fine gained nutrient-rich soil brought by the rivers during their course through the fertile plains has declined from 400 million to 100 million tons per year. This decline has prevented transport and uniform dispersal of suspended sediments over mangrove areas. As a result of these two factors, the surviving Indus Delta mangroves are sparse and stunted.

On the eastern side of the Indus Delta, the Left Bank Outfall Drain (LBOD) was constructed during late 1980's to dispose the saltwater of Indus Plans in the Arabian Sea to reduce the water logging and salinity from the productive agriculture lands. As a consequence, higher quantities of saline water and salt load added to the delta degraded the mangrove cover as well as impacted other marine habitat.

The other major causes of mangrove deforestation and degradation in Indus Delta include over harvesting for fuel wood, camel grazing and fodder use, meandering and erosion of creeks, and sea water intrusion.

Most of the regeneration has been observed in the intertidal zone. The gain in mangroves forest cover has been attributed to conservation efforts in the area including intensive mangrove plantation and raising awareness of the importance of mangroves in the local communities. IUCN began its efforts to restore degraded mangroves forests in Pakistan in the early nineties and over 30,000 ha have been restored and restocked, mainly in the Indus Delta. During this time fast growing and salt tolerant mangrove species, *Rhizophora mucronata* (Kumri), and *Avicennia marina* (Teemer) were planted in the inter-tidal zones of the Indus Delta. The other possible causes of mangrove cover increase may include changes in local morphology driven by changes in stream flows and an increase in atmospheric CO_2 concentrations suggested by several studies (Archer et al., 1995; Eamus and Palmer, 2008; McKEE and ROOTH, 2008), which require further investigations in context of Indus Delta.

Table 2
Areal extent of mangrove forests and forest gain and loss in each country.

Country	Mangrove area (in ha)	Loss	Gain
Bangladesh	411,487	16179	6575
India	343,065	58020	29654
Pakistan	76,616	17691	44230
Sri Lanka	21,437	243	1

3.1.2. Goa, India

Three land cover classes (mangrove, water, and others) were classified for the entire study area for the year 1975, 1997, 2001, 2006 and 2011(Fig. 3). The Kappa coefficient and the overall accuracy are reported in Table 3.

Mangroves of Mandovi-Zuari Estuarine Complex in Goa are among the best mangrove forests on the west coast of India. Jagtap (1985) reported that 90% of the mangroves in Goa are distributed along the Mandovi and Zuari estuaries. Our time series analysis revealed that the mangroves in Goa particularly along the Mandovi and Zuari (including Cumbarjua Canal) increased gradually from 1973 to 2011. Change detection study was carried out around the Mandovi estuary regions from 1990 to 2003 (ManiMurali et al., 2006).

Mangrove area has increased continuously from 1973 to 2011, with the largest gain occurring from 2006 to 2011 (Table 4). A visual interpretation of the classified images identified that the areas along the rivers is where mangroves area has increased the most. There are mostly fringing patches of mangroves along these rivers with small strands distributed sporadically. Chorao Island has a thick mangrove cover along the Mandovi estuary. This mangrove forest has been declared by the Government of Goa for the purpose of conservation as Dr. Salem Ali Bird Sanctuary in 1988. Afforestation work to restore degraded mangrove areas started in Goa in 1985–1986; by the end of 1996–1997 the program had restored 876 ha (Forest Department of Goa statistics). Zuari has scattered and degraded patches of mangroves along its length. Considerable mangrove cover can also be seen along the Cumbarjua Canal which significantly contributes to the values estimated for Zuari River.

The species mainly found in these estuaries are *Rhizophora mucronata, R. apiculata, Avicennia* officinalis, A. marina, A. alba, Kandelia candel, Sonneratia alba, S. caseolaris, Bruguiera gymnorrhiza, B. cylindrica, Aegiceras corniculatum, Excoecaria agallocha, Acanthus illicifolius.

Although mangrove areas have been increasing, the forest is under threat from increasing urbanization which has led to increased encroachment to the nearby mangrove areas. There has been a considerable increase in urbanization of about 2612.8 ha in the past 38 years. The conversion of mangroves on public lands for aquaculture, agriculture, mining (e.g. near the Mapusa estuary in Goa), human habitation and industrial purposes has also led to degradation. The other reasons for the decrease in mangrove vegetation could be the movement of barges (for iron -ore transfer) that causes damage to the young mangrove seedlings.

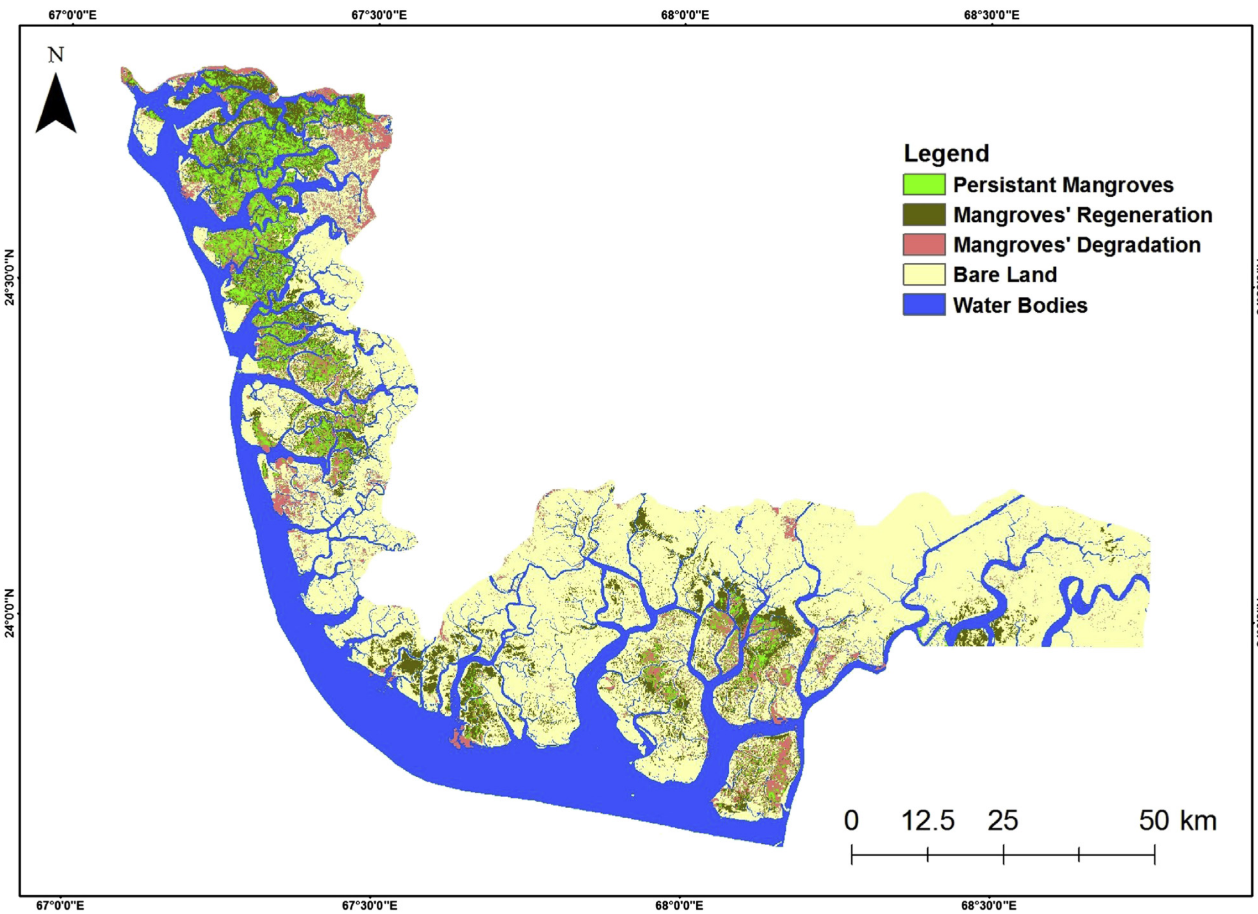

Fig. 2. Persistent mangroves with forest loss and gain of Indus Delta from 1973 to 2010.

3.1.3. Sundarbans (Bangladesh and India)

From the 1970s–2000s, mangrove forest in the Sundarbans decreased by 1.2%. The rate of change, however, was not uniform from the 1970s–1990s and from 1990s to 2000s. From the 1970s–1990s, mangrove forest area increased by 1.4%, and from 1990s to 2000s, the area decreased by 2.5%. These changes are non-significant in the context of errors associated with classification and the dynamic nature of mangrove ecosystems. In other words, these changes are well within the margin of error. For example, because of the fluctuation of tide, certain areas in flooded areas, barren lands, and water bodies could be misclassified from one class to another. Small changes less than 3x3 pixels were not detected from this study as this was the minimum mapping unit used. This is expected to minimize the errors arising from miss-registration of satellite imagery.

While the measured net loss of mangrove forest was not considerable, the change matrix (Table 5) shows that turnover was much greater than net change. For example, 7% of the 1970s-era mangrove forest had changed to non-mangrove, flooded, water bodies, or barren lands by 2000. The largest category of mangrove forest change was loss to flooded (4.6%). The change matrix also revealed that during the same period approximately 37% of flooded areas, 21% of barren lands, 8.3% of non-mangrove, and 2.2% of water bodies were converted to mangroves. Similar patterns of change were observed from the 1970s–1990s and from 1990s to 2000s (Table 5).

In all three classifications, 93–95% of mangrove forests, 93–96% of water bodies, and 69–79% of non-mangrove areas did not change. During the same period, the turnover for flooded areas and barren lands was, however, quite high, only 30–35% of flooded and 15–50% of barren lands remain unchanged. The large change between flooded and barren lands may possibly be due to variation in tidal inundation at the time of satellite data acquisition. Major change areas were concentrated either in the outer periphery or near the shoreline (Fig. 4), caused by anthropogenic and natural forces, respectively.

Table 3
Land cover change matrix from 1973 to 2010.

	Dense mangroves	Sparse mangroves	Mudflats	Water	Total in 1973	Total mangroves in 1973
Dense Mangroves	7627	6021	3006	1583	18,237	96,483
Sparse Mangroves	12,058	27,182	31,710	7297	78,246	
Mudflats	5644	35,208	335,410	46,235	422,497	
Water	1227	3048	31,568	170,226	206,069	
Total in 2010	26,555	71,459	401,694	225,341	725,048	
Total Mangroves in 2010	98,014					

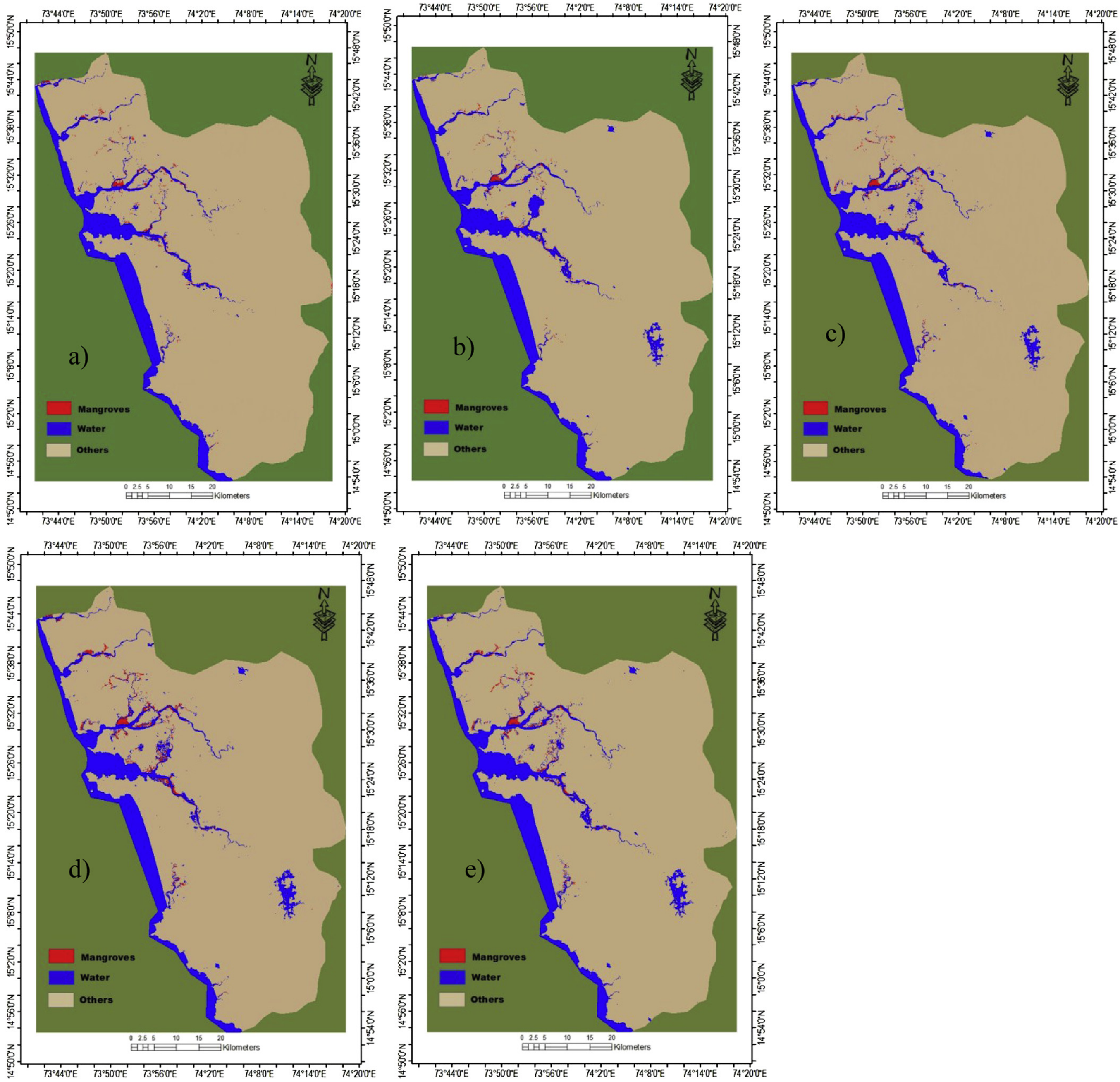

Fig. 3. Distribution of mangroves in Goa in 1975(a), 1997(b), 2001(c), 2006(d) and 2011(e).

The high turnover between mangrove and non-mangrove is due primarily to encroachment, erosion, aggradation, and mangrove rehabilitation programs. The rate of erosion is highest at the southern edges of Mayadwip, Bulcherry Island, and Bhangaduni Island. For example, Bhangaduni Island lost one-fourth of its land area (25.1%) and just less than one-fourth of its mangrove area to erosion between the 1970s and 2000s. The majority of this loss in this island occurred between 1989 and 2000s, which is evident from the following illustrations (Fig. 5).

Due to aggradation, land continues to be made afresh in the Sundarbans, offsetting a large part of the loss to erosion. This process has increased the land and mangrove forest areas. Once the new land is formed, such lands are typically colonized by a sequence of plant communities, culminating in the establishment of mangrove forests. Examples of aggradation can be seen in Fig. 5.

Between 1970s and 1990s, mangrove forest gained from aggradation (2925 ha) nearly equals mangrove forest lost to erosion (3157 ha). From the 1990s–2000s, however, the rate of erosion claimed seven times as much mangrove forest (4151 ha) as aggradation created (592 ha). Erosion was concentrated along the banks of major river channels and at the land–water interface with the Bay of Bengal. Approximately half of the mangrove forested land lost was at the extreme southern edge of the Sundarbans where almost no compensating aggradation took place.

On the India side of the Sundarbans, the most dramatic area of change is located approximately 14 km east of Kisoripur. In the 1970s image, 1085 ha of mangrove forest, interspersed with open flooded areas, extended approximately 4 km inland from the Matla/Bidya River. By 1990s, the classification shows that 13.27% of the mangrove forest had been lost, and the boundary between

Table 4
Mangroves area extent, overall accuracy and kappa statistics for classification in Goa, India.

Year	Change area (km^2)	Overall accuracy (%)	Kappa statistics
1975	6.2	91.00	0.86
1997	8.5	93.33	0.90
2001	12.2	92.67	0.88
2006	13.6	92.33	0.88
2011	19.4	91.67	0.87

development and mangroves had receded approximately 1 km to the east. By 2000s (ETM+),

Only a ring of mangrove at the shoreline remained. The evidence of development is apparent with the building of diked areas and canals as the forest was removed. This area falls outside of the managed forest reserves and contrasts sharply with the mangrove forested areas to the south and east, which remained generally unchanged during the same period.

Again, the net mangrove loss over the whole of the Sundarbans is about 1% as the numerous areas of loss are counter-balanced by areas of gain. Most of this gain is found in areas where new land formed through deposition has become vegetated. One of the exceptions is an area of afforestation located in the Jilla forest block on the northern forest boundary of the India side. This area of approximately 400 ha was completely degraded in 1975, but had been re-vegetated by 1989 and was generally indistinguishable from surrounding forested areas in a remote-sensing image by 2000s.

Overall accuracy of 86%, 85%, and 79% were achieved for 2000s, 1990s, and 1970s classification with the Tau coefficient of 0.85, 0.83, and 0.76, respectively. The tau coefficient for the year 2000, for example, indicates that our classification systems produce a map on which 85% more pixels were classified correctly than would be expected by random assignment. This means that for this classification, we were correct 85% of the time. Confusion arose in discriminating flooded and water bodies, and non-mangrove and barren lands classes. Mangrove class was relatively well classified.

The canopy closure layers derived from NDVI measurements for the three mosaics show changing patterns of forest condition in the Sundarbans. The pattern of healthy upper-story vegetation is different in the different era classification results. Therefore, the least healthy areas in 2000s are different from the least healthy areas of 1990s. Furthermore, the pattern of relatively unhealthy vegetation in 2000s corresponds to areas of reported top dying. As explained above, the lack of multiple images for each era, the different seasons of acquisition for images of different eras, and variation in the degree of tidal inundation in the various images prevents comparison of absolute values derived from each of the canopy closure layers. While the absolute values for canopy closure that the model is designed to generate are not reliable, patterns of relative canopy closure are confirmed as generally valid. Visual confirmation of the validity of the canopy closure layer comes from two sources: the 1985 (1983 data) Chaffey et al. inventory maps and QuickBird high-resolution remote-sensing images from 2002. The Chaffey et al. (1985) maps from 1983 aerial photography, while compiled approximately 6 years later, support the validity of the 1970s-era canopy closure layer. The 1983 maps show roughly two-thirds of this area as having canopy closure above 70% and little or none of this area to be below 30% canopy coverage. These areas correspond well to the high and low canopy closure areas in the 1970s-era canopy closure layer. The largest change in the pattern of canopy closure is between the TM and ETM$^+$ eras, when a large corridor of reduced canopy closure appears between the Bal and Sibsa Rivers. This corresponds to forest compartments that have high rates of top dying (Canonizado and Hossain, 1998; Iftekhar and Islam, 2004).

Table 5
Percent land cover changes from the 1970s–2000s, from the 1970s–1990s, and from 1990s to 2000s.

	Mangrove	Non-mangrove	Flooded	Water bodies	Barren lands
1970–2000					
Mangrove	92.9	0.1	4.6	2	0.4
Non-mangrove	8.3	69.2	22	0.5	0
Flooded	37.5	2.3	35.4	22.3	2.5
Water bodies	2.2	0	3.7	93.5	0.5
Barren lands	21.4	0	29.1	22.6	26.8
1970-1990					
Mangrove	95.4	0.1	3.1	0.9	0.6
Non-mangrove	4.1	78.6	17.1	0.1	0
Flooded	41.5	3	30.4	18	7.1
Water bodies	1.5	0	4.6	93.2	0.6
Barren lands	15.2	0	22.5	10.2	52.1
1990-2000					
Mangrove	93.1	0.1	5.1	1.3	0.4
Non-mangrove	7.3	66.6	25	1.1	0
Flooded	35.8	2.9	35.5	23.4	2.4
Water bodies	0.9	0	3.3	95.5	0.3
Barren lands	25.8	0	40.5	18.8	15

4. Conclusion

Mangrove forests in South Asia represent approximately 6% of the global total and can be found on the tidal sea edge of Bangladesh, India, Pakistan, and Sri Lanka. The forests provide important ecosystem goods and services to the functioning of the biosphere and densely populated coastal population. The forests are under threat from both natural and anthropogenic stressors. The net deforestation has slowed down during the period from 2000 to 2012, partly because of increased awareness and planation and forest protection initiatives. Our results revealed that from 2000 to 2012, 92,135 ha of mangroves were deforested and 80,461 ha were reforested with a net loss of 11,673 ha.

We also identified major deforestation fronts located in eastern part of Indus Delta, Goa, Mumbai, and Indian part of Sundarbans. Major mangrove regrowth were observed in western Indus Delta, Goa, Orissa, and eastern Bangladesh. Major causes of forest loss include conversion to agriculture, urban development, shrimp ponds, and over harvesting. However, other factors such as urban pollution, mining, siltation, top dying, and natural disturbances are dominant factors in localized areas. Major causes of forest growth include plantation, and forest conservation.

Three case studies conducted in Indus Delta (Pakistan), Goa (India), Sundarbans (Bangladesh and India), identified rates, patterns, and causes of mangrove change at better spatial and thematic detail than previously available.

Our Landsat multi-temporal change analysis from 1973 to 2010 in Indus Delta revealed that the delta is highly dynamic and there are simultaneous processes of erosion and accretion occurring in the area. In terms of mangrove cover a total net increase of 1530 ha (1.5%) was observed with cumulative forest gain and loss of 45,126 ha and 43,596 ha respectively. Forest loss is mainly attributed to the reduction in freshwater flow and reduction in flow of alluvium. A decrease in freshwater flow consequently resulted in an increase in salinity levels which is detrimental to mangrove survival and growth. The other major factors of mangrove deforestation and degradation in Indus Delta include over harvesting for fuel wood, camel grazing and fodder use, meandering and erosion of creeks, and sea water intrusion. Most of the regeneration has been observed in the intertidal zone. The increase in mangrove forest cover was attributed to conservation efforts in the area including

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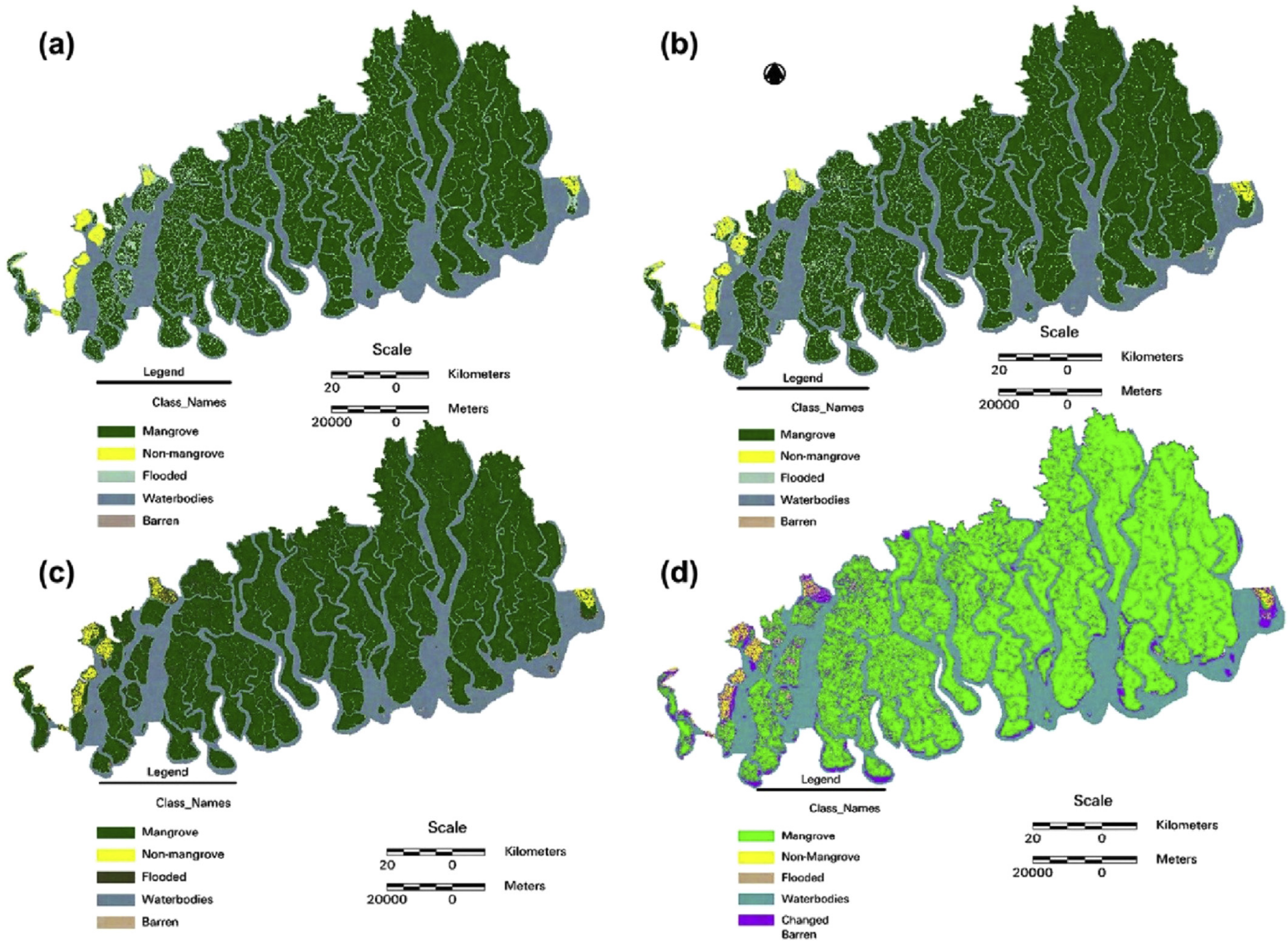

Fig. 4. Classification maps of (a) MSS, (b) TM, and (c) ETM$^+$ data, and (d) change maps from the 1970s–2000s.

intensive mangrove plantation and raising awareness of the importance of mangroves in the local governments and communities.

Approximately 90% of the mangroves in Goa are found in Mandovi-Zuari Estuarine Complex which is considered one of the best mangrove forests on the west coast of India. Our time series analysis revealed that the mangroves in Goa particularly along Mandovi and Zuari (Including Cumbarjua Canal) increased gradually from 1973 to 2011; the largest gain occurred during the period from 2006 to 2011. The increase was observed along the rivers with small stands distributed sporadically. Conservation efforts such as declaration of mangrove sanctuary and plantation initiatives contributed to the increase of mangrove forest cover. Although an overall mangrove area has been increasing, the forest is under threat from increasing urbanization.

From the 1970s–2000s, mangrove forest in the Sundarbans decreased by 1.2%. As expected, the rate of change was variable during the period from the 1970s–1990s and from 1990s to 2000s. During 1970s–1990s, mangrove forest area increased by 1.4%, and from 1990s to 2000s, the area decreased by 2.5%. These changes are non-significant and are within the margin of error. Even though the net change was not that high, turnover was much greater than the net change. This is primarily because of encroachment, erosion, aggradation, and mangrove rehabilitation programs. Land continues to be made afresh in the Sundarbans because of aggradation, offsetting a large part of the loss to erosion. Erosion was concentrated along the banks of major river channels and at the land–water interface with the Bay of Bengal. In addition, the canopy closure layers derived from NDVI measurements for the three mosaics show changing patterns of forest condition in the Sundarbans, with areas of declining condition corresponding to forest compartments that have high rates of top dying.

Overall, the area of mangrove forests of South Asia have not changed or have slightly decreased from 2000 to 2012. In all three case studies, mangrove areas have remained the same or increased slightly, however, the turnover was greater than net change. Both, natural and anthropogenic factors are responsible for the change and turnover. The major causes of forest cover change are similar throughout the region; however, specific factor may be dominant in specific areas. Major causes of deforestation in South Asia include (i) conversion to other land use (e.g. conversion of agriculture, shrimp farms, development, and human settlement), (ii) overharvesting (e.g. grazing, browsing and lopping, fishing), (iii) pollution, (iv) decline in freshwater availability, (v) floods, (vi) reduction of silt deposition, (vii) coastal erosion, and (viii) disturbances due to cyclones and hurricanes. Other causes in specific areas include sea salt extraction in Indus Delta in Pakistan, overharvesting of fruits in Sundarbans, and garbage disposal in Mumbai, India. Conversely, mangrove areas are increasing because of aggradation, plantation, and regrowth. Regrowth is occuring as a result of protecting existing mangrove areas. Our remote sensing based approach could be used for regular (e.g. annual) monitoring of mangroves that can be used for sustainable management of this important coastal ecosystem.

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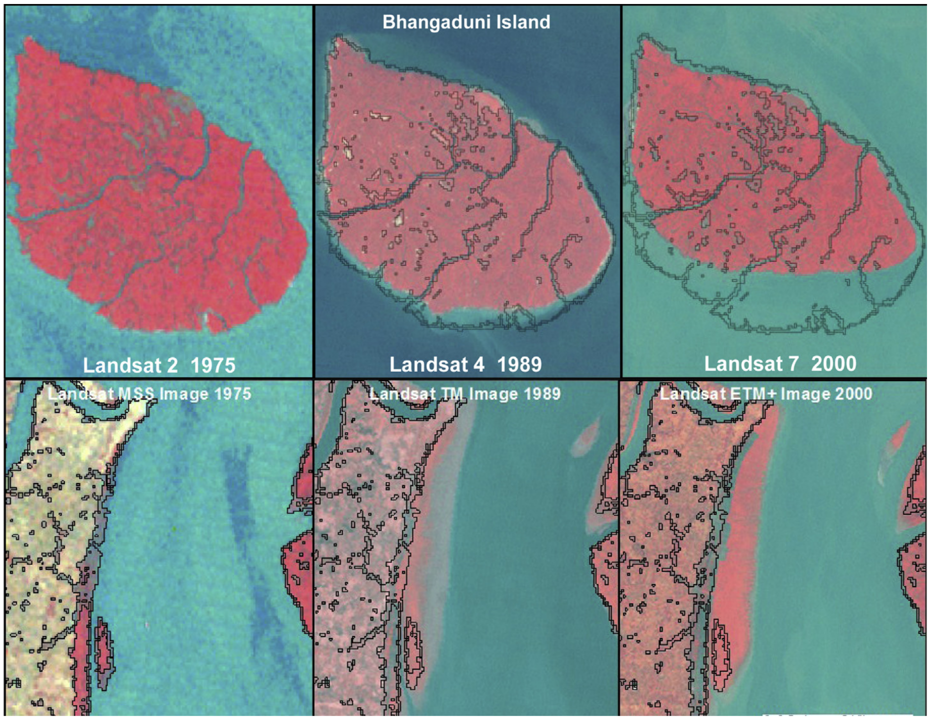

Fig. 5. Example of erosion and aggradation in the Sundarbans (red color represents mangroves). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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