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Monitoring mangrove forest dynamics of the Sundarbans in Bangladesh and India using multi-temporal satellite data from 1973 to 2000☆

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Abstract

Mangrove forests in many parts of the world are declining at an alarming rate—possibly even more rapidly than inland tropical forests. The rate and causes of such changes are not known. The forests themselves are dynamic in nature and are undergoing constant changes due to both natural and anthropogenic forces. Our research objective was to monitor deforestation and degradation arising from both natural and anthropogenic forces. We analyzed multi-temporal satellite data from 1970s, 1990s, and 2000s using supervised classification approach. Our spatio-temporal analysis shows that despite having the highest population density in the world in its periphery, areal extent of the mangrove forest of the Sundarbans has not changed significantly (approximately 1.2%) in the last ∼25 years. The forest is however constantly changing due to erosion, aggradation, deforestation and mangrove rehabilitation programs. The net forest area increased by 1.4% from the 1970s to 1990 and decreased by 2.5% from 1990 to 2000. The change is insignificant in the context of classification errors and the dynamic nature of mangrove forests. This is an excellent example of the co-existence of humans with terrestrial and aquatic plant and animal life. The strong commitment of governments under various protection measures such as forest reserves, wildlife sanctuaries, national parks, and international designations, is believed to be responsible for keeping this forest relatively intact (at least in terms of area). While the measured net loss of mangrove forest is not that high, the change matrix shows that turnover due to erosion, aggradation, reforestation and deforestation was much greater than net change. The forest is under threat from natural and anthropogenic forces leading to forest degradation, primarily due to top-dying disease and over-exploitation of forest resources.

Keywords: mangroves; mapping; monitoring; remote sensing; Sundarbans; South Asia

1. Introduction

Mangrove forests, found in the inter-tidal zone in the tropics and subtropics, play an important role in stabilizing shorelines and in helping reduce the devastating impact of natural disasters such as tsunamis, and hurricanes. They also provide important ecological and societal goods and services including breeding and nursing grounds for marine and pelagic species, food, medicine, fuel, and building materials for local communities. These forests, however, are declining at an alarming rate, perhaps even more rapidly than inland tropical forests, and much of what remains is in degraded condition (Wilkie and Fortune, 2003). The rate and causes of such changes are not fully known. And, the remaining mangrove

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forests are under immense pressure from clear cutting, encroachment, hydrological alterations, chemical spills, and climate change (Blasco et al., 2001; McKee, 2005).

The Sundarbans offers coastal protection to millions of people in Bangladesh and India. The forests lie in a zone of cyclonic storms and tidal bores that originate in the Bay of Bengal and periodically devastate coastal areas. At the beginning of the colonial era (1757–1947) in India, the Sundarbans mangrove forest occupied approximately twice its current extent (Islam et al., 1997). Currently, the Sundarbans covers approximately 10,000 km^2, 40% of which is in India and the rest is in Bangladesh (WCMC, 2005).

Periodic forest inventories have been taken, recording the volume and condition of the timber resources of the Sundarbans at intervals of approximately 15 to 20 years. Through the 1900s inventories and management plans became more sophisticated and accurate, but remained focused on maximizing timber yield (Chaudhuri and Choudhury, 1994). However, in Bangladesh, for example, it has been 20 years since the Department for International Development of United Kingdom (formerly, Overseas Development Administration) conducted the last detailed inventory (Chaffey et al., 1985). Availability to up-to-date information on the status and conditions of this important ecosystem is critical for managing mangrove resources in a sustainable manner.

Remote sensing could play an important and effective role in the assessment and monitoring of mangrove forest cover dynamics. While remote-sensing data analysis does not replace field inventory, it provides supplementary information quickly and efficiently. The use of remotely sensed data offers many advantages including synoptic coverage, availability of low-cost or free satellite data, availability of historical satellite data, and repeated coverage. In addition, recent advances in the hardware and software used for processing a large volume of satellite data has helped increase the usefulness of remotely sensed data. Moreover, it is extremely difficult to get into vast swamps of mangrove forests, and conducting field inventory is time consuming and costly. A number of studies conducted in the Sundarbans have begun to develop and apply remote-sensing techniques mainly for mapping purposes (Islam et al., 1997; Dwivedi et al., 1999; Blasco et al., 2001; Nayak et al., 2001). These studies were conducted either in Bangladeshi or Indian parts of the Sundarbans at different times; thus, they lacked a holistic view of the whole Sundarbans mangrove forests. Monitoring of this important ecosystem in terms of both deforestation and forest degradation was urgently needed.

In this paper, we examine deforestation and degradation of the Sundarbans using multi-temporal Landsat data. More importantly, we investigate the dynamic nature of mangrove forests considering both net change and “turnover”. We measure the extent and condition of the Sundarbans at three intervals between the 1970s and 2000s, using data from the newly compiled GeoCover data set. GeoCover is a collection of Landsat imagery from three decadal intervals: the 1970s, 1990s, and 2000s. Our specific objectives are to assess the current extent of the remaining forest, to measure change in the extent of the forest from the 1970s to 1990s, from 1990s to 2000s, and from the 1970s to 2000s, to identify localized areas of intensive change, and to identify changes in patterns of canopy density.

2. Study area

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 mangrove forests.

The Sundarbans support an exceptional biodiversity with a wide range of flora and fauna including more than 27 mangrove species, 40 species of mammals, 35 species of reptiles, and 260 bird species. Wildlife species found in the area include the man-eating Royal Bengal tiger, the Indian python, sharks, crocodiles, spotted deer, macaque monkey and wild boar. The forests are characterized two main tree species Sundri, and Gewa. Other species that make up the forest assemblage include *Avicenia, Xylocarpus, Sonneratia, Bruguiera, Rhizophora* and Nypa palm. The area experiences exceptional ecological processes such as monsoonal rains, flooding, delta formation, tidal influence and mangrove colonization. Rainfall in the area is as high as 2800 mm, mostly during the monsoon season lasting from June to October. Storms, cyclones and tidal surges are quite common throughout Sundarbans.

The forest is also a center for economic activities, such as the extraction of timber and fuel wood, fishing and collection honey and other forest products. Within the Sundarbans, there are three wildlife sanctuaries and one national park covering 27% of the area; all of these are listed as a World Heritage Site by the United Nations Educational, Scientific, and Cultural Organization (UNESCO). Over 2.5 million people live in villages surrounding the Sundarbans and depend for much of their subsistence on products from mangrove forests. The forest provides a livelihood for some 300,000 people, working seasonally as wood-cutters, palm collectors, fisherman, and honey hunters. Population density in the vicinity of Sundarbans is among the highest in the world.

3. Data and methodology

We used the recently compiled GeoCover data set, available freely through the Global Land Cover Facility (GLCF) (http://glcf.umd.edu) and the U.S. Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS) (http://eros.usgs.gov). GeoCover is a collection of Landsat data that provides near global coverage with generally cloud-free images, collected for three eras: (1) the 1975 edition, with imagery collected from 1973 to 1983, (2) the 1990s edition, with imagery collected from 1989 to 1993, and (3) the 2000s edition, with imagery collected between 1997 and 2000s (referred to hereafter as the 1970s, 1990s, and 2000s data, respectively). Detailed description of GeoCover data can be found at: http://zulu.ssc.nasa.gov/mrsid/. A complete list of the Multi-spectral Scanner (MSS),

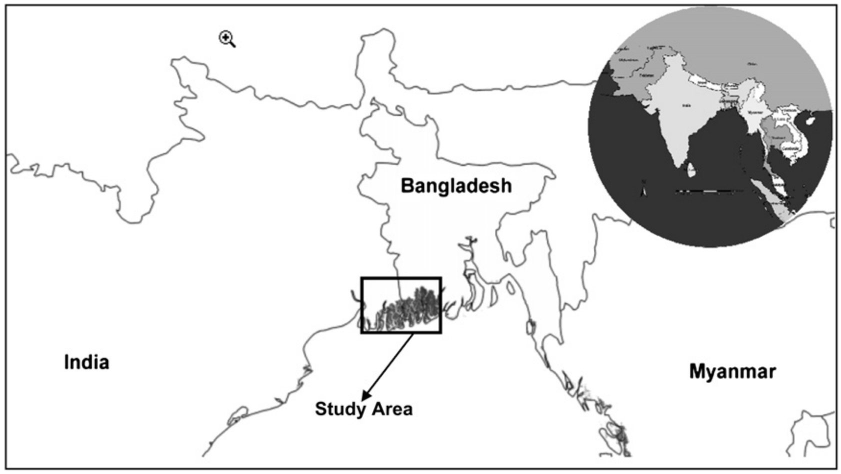

Fig. 1. Location map of the study area.

Thematic Mapper (TM), and Enhanced Thematic Mapper Plus (ETM^+) data used in this study is listed in Table 1. Despite our effort to acquire MSS data of the same month, we were not able to acquire it. Instead, data acquired within the period of three months were used. Because two Landsat MSS and ETM^+ scenes do not cover the entire area of Sundarbans, third scene was used to fill a small gap. The images are orthorectified and projected with an RMS error of less than 50 m (m) for the TM (1990s era) and ETM (2000s era) and to less than 100 m for the MSS (1970s era) (Tucker et al., 2004).

The use of multi-temporal satellite data at a large scale using MSS, TM and ETM^+ possesses a number of challenges including geometric correction error, noise arising from atmospheric effect, errors arising from changing illumination geometry, and instrument errors (Homer et al., 2004). Such errors can introduce biases in mangrove forest classification and change analyses.

Because the Sundarbans fall across two Universal Transverse Mercator (UTM) zones, each scene was reprojected to polyconic projection using 46 ground control points (GCP) distributed evenly throughout the study area. Re-projection was performed using cubic convolution re-sampling technique which provides superior spatial accuracy compared to nearest neighbor re-sampling technique (Park and Schowengerdt, 1982). GCPs were collected from 1:50,000 topographic maps. With additional GCPs, it was possible to decrease the root mean square (RMS) error to ±1/2 pixel. Additionally, the resolution of Landsat MSS data was re-sampled to 30 m to make it consistent with Landsat TM and ETM^+ data. This re-sampling, however, did not improve the spatial details of MSS data. Thermal band (band 6) was not used for both TM and ETM^+.

Table 1
Landsat scenes used to create mosaics

Mosaic	Satellite	Date	Path and Row
MSS	Landsat 2	Jan. 3, 1977	p147r45
	Landsat 2	Feb. 9, 1977	p148r44
	Landsat 2	Dec. 5, 1977	p148r45
TM	Landsat 4	Jan. 12, 1989	p137r45
	Landsat 5	Jan. 3, 1989	p138r45
ETM^+	Landsat 7	Nov. 26, 2000	p137r45
	Landsat 7	Nov. 17, 2000	p138r44
	Landsat 7	Nov. 17, 2000	p138r45

To reduce the noise due to influence of the atmospheric and illumination geometry, we used the techniques developed for the National Land Cover Database of the United States (Homer et al., 2004). Each image was normalized for variation in solar angle and Earth-sun distance by converting the digital number values to the top of the atmosphere reflectance (Chander and Markham, 2003). Considering the relative uncertainty of algorithms currently available, atmospheric correction was not performed. Only first-order normalization conversion to at-satellite reflectance was performed. This conversion algorithm is ‘‘physically based, automated, and does not introduce significant errors to the data’’ (Huang et al., 2002). Finally, mosaics were created for each decade with no further radiometric normalization. An example of the mosaic that was prepared is presented in Fig. 2.

Training samples were collected from these mosaics. Selecting training samples from these cloud-free mosaics was straightforward due to the very distinctive signature of mangrove forest. High contrast with open water in the south and croplands in the north helped in selecting the training data successfully. Same training samples with slight modifications in each mosaic (addition and removal of few training samples) were used for the classification of all three date images. Four major classes were delineated: Mangrove, Non-mangrove, Flooded, Barren lands, and Water bodies (Table 2). A supervised Maximum Likelihood Classification (MLC) method was used for the classification.

For change detection, we used post-classification techniques. This approach may have three sources of uncertainty: (1) semantic differences in class definitions between maps, (2) positional errors, and (3) classification errors. To minimize the semantic differences in class definitions, we used the same number of classes for all three dates. To minimize positional errors, additional GCPs were selected and RMS was reduced

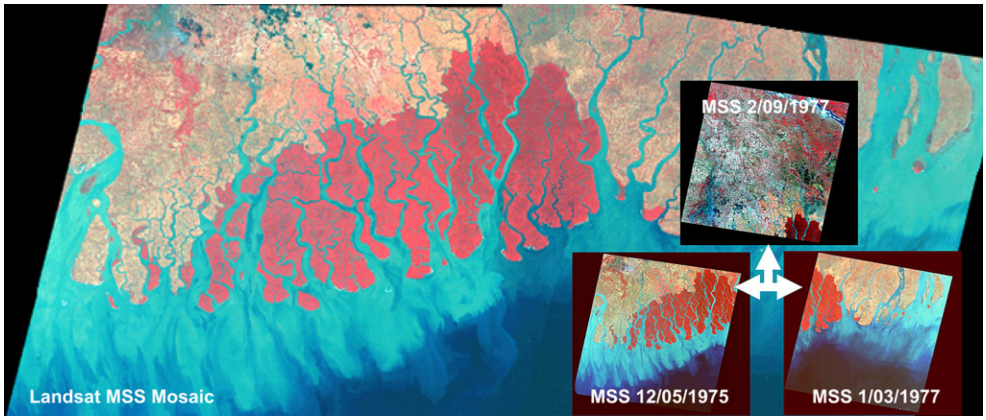

Fig. 2. Three sets of Landsat images from 1975–1977, 1989, and 2000 were used to create mosaics corresponding to the three decadal intervals of the study.

to ±1/2 pixel. Post classification editing using secondary data was used to minimize classification errors. However, there might still be errors associated with positional errors and classification errors. Civco et al. (2002) compared the results of for four land use and land cover change detection techniques: traditional post-classification cross-tabulation, cross-correlation analysis, neural networks, knowledge based expert system, and image segmentation and object-oriented classification. They concluded that each method assessed in the study has advantages and disadvantages and none of the method was able to solve the change detection problem. For example, change detection accuracy of all the methods was quire low.

A post-classification change matrix function was applied between 1970s–2000s, 1970s–1990s, and 1990s–2000s classification results. These change layers contained numerous areas of false alarms along and parallel to the many small streams of the Sundarbans. Much of this was caused by minor georeferencing errors in the data. Manual editing using secondary data was performed to remove those false alarms. Once the change areas were identified, further analysis was performed to examine net gain and loss due to deforestation, erosion, and aggradation. Changes observed in these analyses were compared to previous inventories (Chaffey, 1985) and other change detection studies (Islam et al., 1997) and were shared with local forestry experts for interpretation as to the validity and cause of these changes.

A second process was applied to the mosaic images to create a surface related to canopy closure. The normalized difference vegetation index (NDVI) has been shown to correlate very well with mangrove canopy closure: $r = 0.91$ (Jensen et al., 1991) using SPOT XS data. For our study, NDVI was calculated for each mosaic. A simple model explained by Gutman and Ignatov (1998) was used to scale NDVI to the green vegetation fraction per pixel. They used NDVIo (bare soil) and NDVI (dense vegetation) to estimate the green vegetation fraction from National Oceanic and Atmospheric Administration/Advanced Very High Resolution Radiometer (NOAA/AVHRR) data for use in numerical weather prediction models. We estimated $NDVI_{min}$ (0.2) and $NDVI_{max}$ (0.7) for open and closed mangrove forest. This estimation is based on our own analysis and findings from earlier studies. The NDVI range was then used to compute percent canopy closure from 0% to100%, where 0% corresponds to $NDVI_{min}$ and 100% corresponds to $NDVI_{max}$. Because of variation in season of collection, atmospheric conditions, tidal inundation, and the availability of only one pair of images for each era, calculation of absolute values for canopy closure were not expected to be reliable. However, within individual scenes, relative patterns of canopy closure were assumed valid.

Finally, confusion matrix was prepared using the training points collected from QuickBird images (8 scenes acquired in 2005 and available freely from http://glcf.umiacs.umd.edu/data/quickbird/sundarbans.shtml), aerial photographs (collected from national mapping agencies acquired in various dates), and mangrove forest classification maps (collected from forest departments of India and Bangladesh). Altogether 322 random sample points were used to compute overall accuracy and tau coefficient. Calculation of tau coefficient is necessary because the overall accuracy fails to take into account the correct allocation of pixels by chance.

Table 2
Class definitions

Classes	Supervised classification class definitions
Mangrove	Areas covered by both closed and open mangrove forests
Non-mangrove	Areas covered by croplands and other land uses
Flooded	Barren lands inundated at the time of image acquisition
Barren lands	Areas devoid of vegetation; e.g., sand dunes, sediments, or exposed soil
Water bodies	Areas of open water with no emergent vegetation; e.g., channels and waterways

4. Results

4.1. Forest cover change

From the 1970s to 2000s, mangrove forest in the Sundarbans decreased by 1.2%. The rate of change, however, was not uniform from the 1970s to 1990s and from 1990s to 2000s. From the 1970s to 1990s, mangrove forest area actually 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 error margin. For example, because of the fluctuation of tide, selected areas in flooded areas, barren lands, and water bodies could easily be misclassified from one class to another. Areal extents of major land cover types for three time periods area presented in Table 3. Small changes less than 3×3 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 imageries.

While the measured net loss of mangrove forest is not that high, the change matrix (Table 4) 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 forests. Similar patterns of change were observed from the 1970s to 1990s and from 1990s to 2000s (Table 4).

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.

Non-mangrove areas are found in the outer periphery of the western and eastern parts of the Sundarbans (Fig. 3a–c). Major change areas were concentrated either in the outer periphery or near the shoreline (Fig. 3d), caused by anthropogenic and natural forces, respectively.

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. 4).

Table 3
Areal estimates of major land cover types

Class/Area (ha)	1970s	1990s	2000s
Mangrove	588,696.5	596,842.8	581,642.2
Non-mangrove	10,376.8	10,785.4	9,359.5
Flooded	73,190.9	55,622.4	66,564.5
Barren lands	2,921.0	11,651.7	6,366.9
Water bodies	270,664.8	270,947.7	281,916.9
Total	945,850.0	945,850.0	945,850.0

Table 4
Percent land cover changes from the 1970s to 2000s, from the 1970s to 1990s, and from 1990s to 2000s

	Mangrove	Non-Mangrove	Flooded	Water bodies	Barren
1970–2000					
Mangrove	92.9	0.1	4.6	2.0	0.4
Non-mangrove	8.3	69.2	22.0	0.5	0.0
Flooded	37.5	2.3	35.4	22.3	2.5
Water bodies	2.2	0.0	3.7	93.5	0.5
Barren lands	21.4	0.0	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	0.0
Flooded	41.5	3.0	30.4	18.0	7.1
Water bodies	1.5	0.0	4.6	93.2	0.6
Barren lands	15.2	0.0	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	25.0	1.1	0.0
Flooded	35.8	2.9	35.5	23.4	2.4
Water bodies	0.9	0.0	3.3	95.5	0.3
Barren lands	25.8	0.0	40.5	18.8	15.0

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 to 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.

While the most dramatic and indisputable areas of change were found along the major waterways and at the southern boundary with the Bay of Bengal, some inland areas showed evidence of change as well. For example, in Bangladesh forest compartment 30, the change matrix (Table 4) shows an area of mangrove forest lost partly to the flooded class and partly to barren lands. This finding is consistent with comparison of maps from Chaffey et al. (1985) and high-resolution QuickBird remote-sensing images from 2002.

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

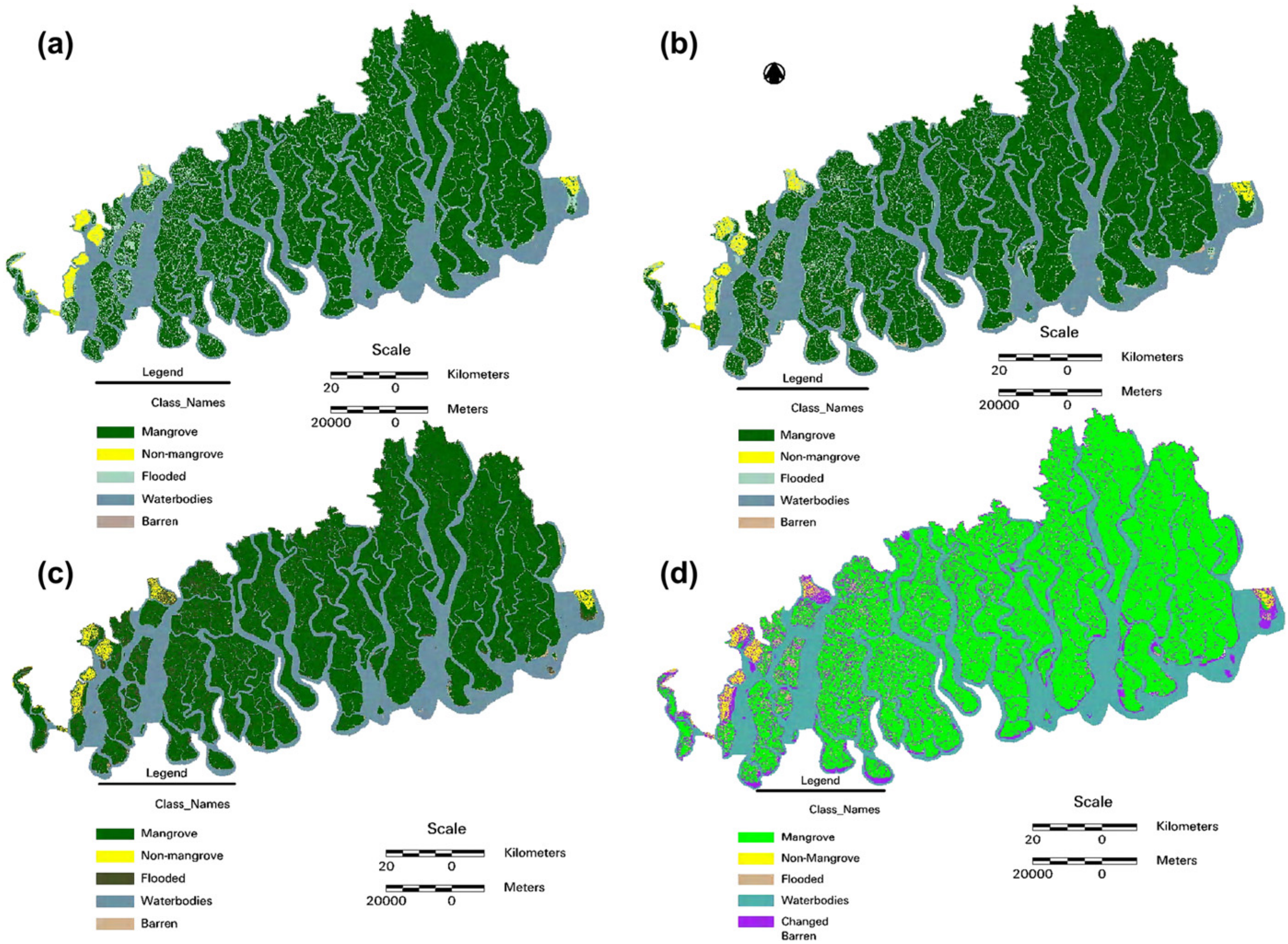

Fig. 3. Classification maps of (a) MSS, (b) TM, and (c) ETM^{+} data, and (d) change maps from the 1970s to 2000s.

only 7.57% of the original 1085 ha of tree cover remained in a ring of mangrove at the shoreline. 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 counterbalanced 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.

4.2. Accuracy assessment

Three confusion matrices were created to compute overall accuracy, users' accuracy, producers' accuracy, and tau coefficient. We assumed that the ground or reference data used in the study accurately represent the ground reality. The ground data may however represent another classification by the interpreter which may contain error, and moreover, such ground data did not correspond with the date of satellite data classified.

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.

4.3. Comparison of percent canopy closure

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 upperstory vegetation is different in the different era classification results. Therefore, the least healthy areas in 2000s are different

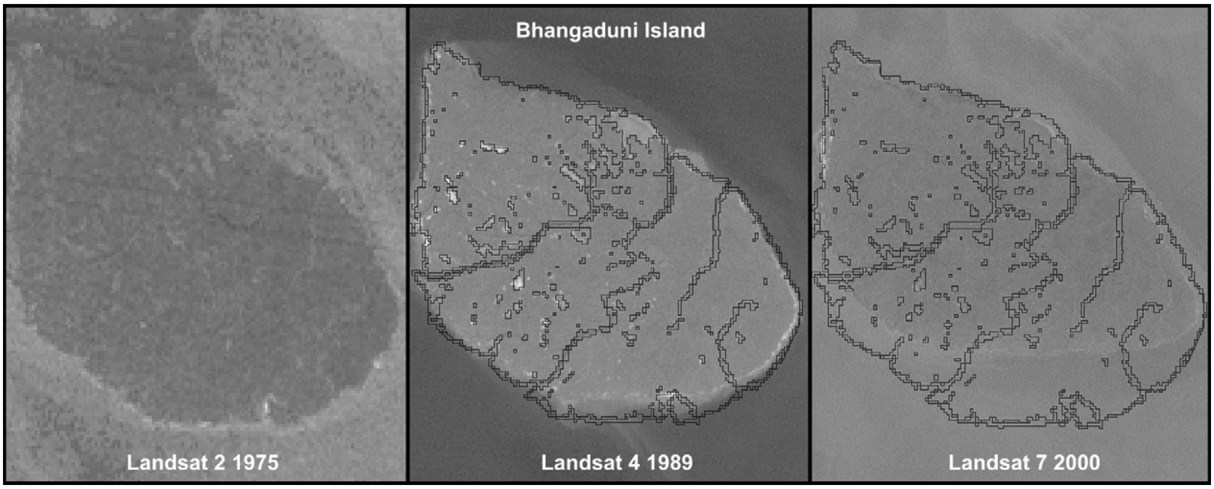

Fig. 4. Erosion claimed 25% of the land area and 24% of the mangrove forest of Bhangaduni Island between 1970s and 2000s.

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 (Fig. 6). This corresponds to forest compartments that have high rates of top dying (Canonizado and Hossain, 1998, in Iftekhar and Islam, 2004).

5. Discussion

Despite having one of the highest population densities in the world in its immediate vicinity, mangrove forest areas of the Sundarbans have not changed significantly from the 1970s to 2000s. Our multi-temporal analysis of Landsat data revealed that the decrease in forest area from the 1970s to 2000s was 1.2% of the total mangrove area. The decrease in area was higher (2.5%) from 1990s to 2000s, and forest area increased by 1.4% from the 1970s to 1990s. Measurement of change on the order of 1–2% has to be taken in the context of variability in the area measurements of this study and the studies reported in the literature. Mangrove forest areas estimated in Bangladesh and India vary considerably depending on the source data, methods, definition of mangrove forest,

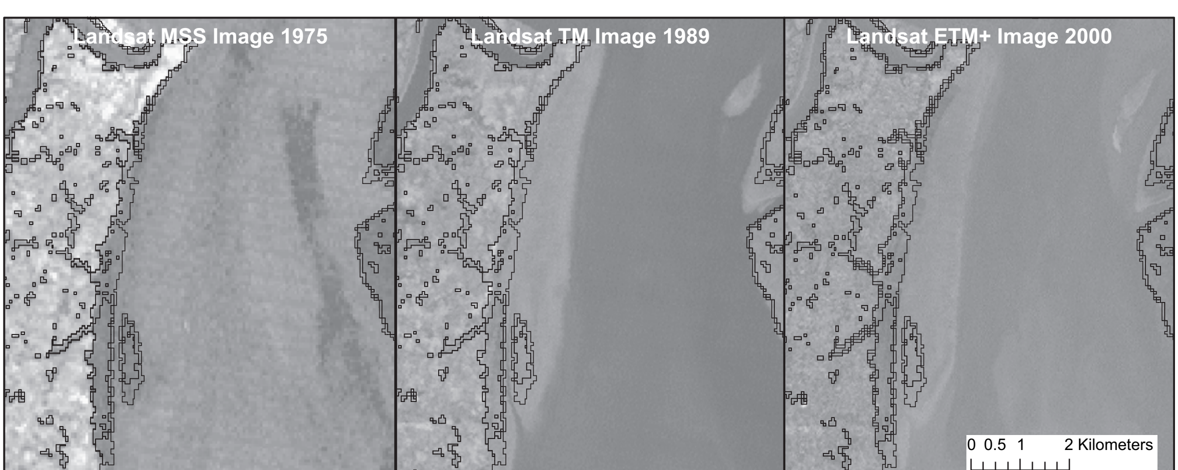

Fig. 5. Example of aggradation in which the extent of mangrove forest areas represented by red has increased from 1970s to 2000s.

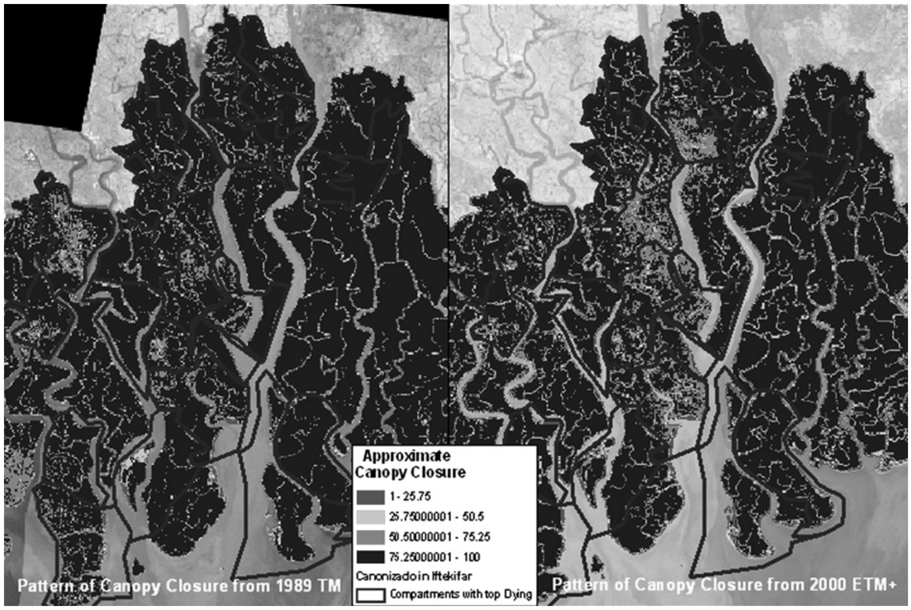

Fig. 6. Change in the pattern of canopy closure from 1989 to 2000 corresponds to areas of the greatest occurrence of Sundri top dying.

and the boundaries used. An estimate of the entire Sundarbans was not available. Our study estimated a total of 653,000 ± 9795 ha. This estimate includes mangrove, flooded, and barren classes. Including water bodies, the total area of the Sundarbans is 945,850 ha (Table 3).

Our estimates of mangrove on the Bangladesh side are within 4% of the published estimates. In addition, our rate of change for the Bangladesh side is consistent with the difference in change between the Chaffey et al. (1985) inventory (1983 data) and the estimates of Revilla et al. in 1998 (1996 data) (reported in Iftekhar and Islam, 2004), equaling 1.4% loss in area from 1983 to 1996 for Bangladesh.

On the India side, however, both of our estimates of forested area are roughly 20% lower than those of either Banerjee (1964) (from Blasco, 1975) or Naskar et al. (2004). These figures were found in secondary sources with no explanation of the methods or definitions. A calculation of the entire land area, forested or not, within our delineated Sundarbans study area matches quite well with these figures. Based on this fact, it is assumed that these estimates (Banerjee, 1964; Naskar et al., 2004) were for all land area within a boundary delineating the Indian Sundarbans. Therefore, these two estimates do not provide a good basis for comparison on the India side.

The apparent acceleration of erosion relative to accretion of new land during the second decade of the study seems to suggest that upstream hydrological changes, most notably the building of the Farakka barrage in India, have disrupted the balance of land creation and land loss that existed prior to human alteration of the local hydrology. While this may be the case, the geomorphology of this area is extremely dynamic. Large areas of erosion have been recorded for more than a century (Mitra, 1914), and large new islands are currently forming at the mouth of the Baleshwar River and elsewhere (Hoque, pers. commun.). Ongoing study over a more extended period of time would likely be needed to separate any anthropogenic influence from the background of dynamic change that is natural in this environment.

This study suggests that some of the mangrove forest is being lost within the Sundarbans boundaries. While this is not sustainable over the long term, it is a relatively modest rate of loss considering the intense population density in the area surrounding the Sundarbans (Fig. 2). Under various protections from forest reserves, wildlife sanctuaries, national parks, and international designations, the area of the Sundarbans mangrove forest seems to be holding relatively stable. Unfortunately, this only tells part of the story.

The consensus in the literature regarding the Sundarbans is that increasing salinity, over-harvesting of timber, and other human influences are degrading the condition of the Sundarbans mangroves (Iftekhar and Islam, 2004). The detailed inventories of forest in 1959 and as reported by Chaffey et al. (1985) show a dramatic decline in the density of desirable lumber species between their respective inventories (Islam et al., 1997). The Sundri tree (*Heritiera fomes*) is generally believed to be the namesake of the Sundarbans (Iftekhar and Islam, 2004) and is also the most commercially valuable species in the Sundarbans, contributing more than 60% of the forest's merchantable timber (Rahman et al., 1990). Average stand density of Sundri has declined by 95% since Curtis's inventory, which was taken between 1926 and 1928 (Iftekhar and Islam, 2004), presumably due to over-harvesting, both legal and illegal. In addition, since around the 1970s, the Sundri trees have been increasingly affected by a phenomenon commonly called "top dying disease" (Rahman, 1990). Our study found a pattern of reduced canopy closure coinciding with the Bangladesh forest compartments that had the greatest occurrence of top dying (Canonizado and Hossain in Iftekhar and Islam, 2004). Further validation is needed to confirm this relationship. If relative canopy closure were demonstrated to provide a good indication of Sundri top dying, this would provide an extremely valuable tool for understanding and managing this devastating phenomenon.

6. Conclusions

Our measure of extent for the Sundarbans mangrove forest shows little change in net area (approximately 1% loss) in the last 25 years. This finding is consistent with other recent remote-sensing studies at the local level (Islam et al., 1997; Dwivedi et al., 1999; Blasco et al., 2001; Nayak et al., 2001). This small change was generally expected based on the management and protection status of the Sundarbans, including the ban on clear cutting and forest encroachment. The relative stability of the forest's extent hides an equally significant change in the condition of the forest. The forest is undergoing constant change due to erosion, aggradation, deforestation, reforestation/afforestation, and forest degradation. Selective timber harvest, both legal and illegal, and more diffuse environmental pressures such as decreased freshwater flow, decreased sediment supply, water contamination, and disease have degraded the forest's condition. These pressures have led to decreased canopy closure in several areas of the forest. The patterns of changing canopy closure have been captured in remote-sensing data from the past 25 years. Correlation of NDVI data with canopy closure (Jensen et al., 1991) is generally borne out by our study. However, we conclude that this measure is not robust enough to transcend variation in the three data formats, slight variations in seasonal phenology, and limited samples from each epoch to provide reliable measure of absolute canopy closure. Nevertheless, the relative canopy closure within the mosaicked image for each decade was found to relate quite well to areas of degraded forest. With adequate validation and calibration, canopy closure layers, even ones derived from single date images as were the ones in this study, may provide valuable information about patterns of change in the forest's density and condition.

Early recognition of the value of the Sundarbans mangrove forest led to adoption of management practices designed for maximum sustainable yield of a limited number of timber species. This has been a crucial factor in preserving what remains of the Sundarbans. Recent emphasis on managing the entire ecosystem (Iftekhar and Islam, 2004) may be able to sustain this valuable resource well into the future. To do this, reliable and frequent measures of several dimensions of the forest's health will be required. Continued development and use of remote-sensing technology for this application could provide valuable and spatially explicit information about deforestation and degradation as well as a means of linking smaller-scale studies to a holistic appraisal of the state of the mangrove forests of the Sundarbans.

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