Analysis of coastal land use/land cover changes in the Indian Sunderbans using remotely sensed data

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The world’s largest mangrove ecosystem, the Sunderbans is experiencing multidimensional threats of degradation. The present study was aimed to understand these problems and search for proper remedies by applying suitable remote sensing technologies. South-western parts of Indian Sunderbans Biosphere Reserve had been chosen for assessment of land use/land cover changes in between 1975 and 2006 by using multitemporal Landsat data. Results indicated considerable reduction of open mangrove stands and associated biodiversity mainly in the forest-habitation interference zones of Sunderbans. On the contrary, increase in the coverage of dense mangroves in the reserved forests had been observed indicating the existence of proper centralized management regimes. Overall, a cumulative loss of approximately 0.42% of its original mangrove cover in between 1975 and 2006 had been estimated for this part of the Sunderbans which was at parity with the findings of other studies in the Sunderbans or similar mangrove ecosystems of the tropics. Expansion of non agricultural lands in the last two decades was found to be related with the growth of new settlements, tourism infrastructure, and facilities. This transformation was attributed to the shifting of local peoples’ interest from traditional forestry and subsistence farming towards alternative occupations like shrimp culture, coastal tourism, and commercial fishing although environmentally hazardous livelihood activities like collection of prawn seeds along the riverbanks were still persistent.

Keywords: sustainable mangrove management; landsat data; land use/land cover changes

1. Introduction

Mangroves are among the biologically most productive ecosystems on Earth and occupy intertidal zones in the tropical and subtropical coastlines depending primarily on local temperature conditions. Approximately 75% of the world’s tropical coastlines are covered by mangroves supporting more than 80 species of flora and 1300 species of fauna. However, in recent years mangroves are declining globally in both biodiversity and extent at an alarming rate. According to a Food and Agriculture Organization (FAO) estimate, a sharp decline in worldwide mangrove coastlines from 198,000 km in 1980 to 146,530 km in 2000 has been observed (1).

The world’s largest mangrove forest, stretching from India to Bangladesh, i.e. the Sunderbans, is not an exception in this regard (2). Although the aerial extent of the mangroves in the Sunderbans has not changed greatly in the last three decades, the internal vegetation structure has been highly altered, especially from open mangrove to agricultural lands and shrimp ponds (3). The magnitude of change is higher in the buffer and transition zones of the forest, where forest dynamics are frequently disturbed by the local village communities due to their unsustainable livelihood practices (2). Consequently, Sunderbans has been affected immensely for decades by quasi-natural hazards like cyclones, floods, sea surge, riverbank erosion etc. (4, 5). In order to achieve the sustainable productivity of natural resources through proper management regimes, comprehensive sources of information on the condition of these mangrove dominated ecosystems are needed (6). Due to the relative physical inaccessibility of the Sunderbans regarding traditional field surveys, remotely sensed data can be a synoptic and steady source of information in this region (7, 8).

In recent years, several studies have been conducted on the Sunderbans mangroves based on remotely sensed data, especially in the Bangladesh parts of the forest, to detect the patterns of landscape changes (9, 10). Most of the studies in Indian parts of the Sunderbans are, however, regional level studies covering the whole of Indian Sunderbans (11, 12). Site-specific or microlevel studies are very rare for the Indian Sunderbans, especially in the south-western parts, and among these few studies, the majority deal with coastal geomorphic and shoreline changes (13). Aspects of landscape transformation and the consequent changes in vegetation dynamics are somehow neglected in these micro/mesolevel studies. Hence in the present study, an attempt had been made to
assess the changes in land use/land cover (LULC) patterns with special emphasis on the extent and condition of the Sunderbans mangroves by applying multitemporal Landsat images. The objective was to examine the dynamics of landscape change and thereby suggest some achievable guidelines towards better management of these vulnerable coastal ecosystems.

2. Materials and methods

2.1. Study area and its importance as a coastal Biosphere Reserve

The mangrove forest of Sunderbans is world’s largest halophytic formation situated on the estuary created by the Ganges and the Brahmaputra. It was declared a “World Heritage Site” by International Union for Conservation of Nature in 1987 and “Biosphere Reserve” by UNESCO in 1989. The Indian Sunderbans has an aerial coverage of 9630 km² (14). The region consists of 106 deltaic islands of which 54 have human habitation and characterized by a maze of innumerable rivers, rivulets, and creeks. Abundant biodiversity had been reported in the Sunderbans comprising 87 plant species of which 37 are true mangroves, 127 species of euryhaline fishes, 1287 species of animals including 186 bird species, and innumerable micro-organisms (15).

In the last 150 years, intense human interventions and natural calamities have been posing an increasing threat to the existence of the Sunderbans as evident from the continual loss of significant amount of biodiversity. Species like Javan rhinoceros have become extinct and several others like the Royal Bengal Tiger (Panthera tigris tigris) and Gangetic Dolphin (Platypus gangeticus) are highly endangered (15). The probabilities of flood and bank erosion have also been enhanced by increased rate of silation in riverbeds. In addition, changes in global climatic patterns and the consequent rise of sea levels are now an immense threat to the very existence of this fragile ecosystem since these changes are accentuating the frequency and magnitude of several natural calamities (2). Moreover, the acute dearth of food in the mangroves and alterations in the intra-mangrove structure force animals to trespass in the forest-fringe villages, thereby increasing the frequency of man–animal conflicts (15).

The present study area is located from 21°52′32″ N to 21°32′00″ N and 88°08′29″ E to 88°35′31″ E. The area consists of the entire Namkhana Community Development Block (CDB) and parts of Patharpratima and Kakdwip CDBs. Along with the small Lothian Island Wildlife Sanctuary, the area also possesses several deltaic islands covered with mangroves. More than half a million people live in this area; most of them are primarily marginal farmers and fishermen (15). Despite the presence of such a large population, this area still has considerable mangrove cover. This is chiefly due to the protection and surveillance by the state-run Forest Department (FD) and community-based Forest Protection Committees (FPCs) under the Indian Joint Forest Management (JFM) program in the late 1980s. Traditionally, the felling and thinning of mangroves were annual practices before the creation of Biosphere Reserve and initiation of JFM (15). As mangrove resources became depleted, people gradually shifted towards brackish water aquaculture and paddy monoculture. Several beach resorts like Bakkhali and Fraserganj emerged as potential sources of income for the local communities in the last 15 years. However, many of the villagers living in the study area are still dependent for their subsistence on products derived from mangroves making sustainable management of the remaining mangroves and associated landscapes supremely imperative.

2.2. Data sources

Three multitemporal cloud-free satellite images (Landsat) covering whole or parts of Sunderbans Biosphere Reserve were downloaded from the freely available United States Geological Service (USGS) Glovis (http://glovis.usgs.gov) and the Global Land Cover Facility (GLCF) (http://glcf.umiacs.umd.edu/) web sites on 24 December 2009 for the present study. These orthorectified images (with Universal Transverse Mercator projection and World Geodetic System 84 datum) consist of Landsat Multispectral Scanner (MSS) data (Path 148, Row 45; dated 5 December 1975), Landsat Thematic Mapper (TM) data (Path 138, Row 45; dated 14 November 1990) and Landsat Enhanced Thematic Mapper Plus (ETM+) data (Path 138, Row 45; dated 18 November 2006). Being mostly of same season, these images are less likely to have had misclassification errors during spectral analysis of different LULC types. A topographic map (79 C/4) from Survey of India (SOI) at a scale of 1:50,000 were used for georeferencing purposes. Field investigations were conducted between June and December 2009 through 300 ground control points (GCPs) and 120 plots of different LULC classes and then applied for accuracy assessment of prepared LULC maps (Figure 1).

2.3. Image processing

The whole image processing procedure was conducted using ERDAS IMAGINE 9.1 software. Individual band data stacking to produce false colour composites (FCCs) was done for all four bands of MSS, bands 1–5 and 7 for TM and bands 2–6 and 8 for ETM+ image.

Image rectification and registration was done in comparison to the SOI topographic map and ground truth verification with the selected GCPs (Readings using a handheld GARMIN 12 channel GPS). The root mean-squared error (RMSE) of less than 50 m for the TM and ETM+ data and less than 100 m for the MSS data were estimated for these datasets. The nearest neighbor algorithm was applied to these data-sets for resampling so that the original brightness values of pixels could be kept unchanged with RMSE of less than 1 pixel at the first order (16). Area of interest was selected after hedge reduction.
2.4. Image classification and accuracy assessment

For supervised classification of each of the images, a parametric decision rule, i.e. maximum likelihood classification method was chosen as classification technique because of its ready availability and the fact that it did not require an extended training process (17). Altogether six LULC classes were adopted for image classification based on the authors’ a priori knowledge and field experiences of the study area. These LULC classes are dense mangrove, open mangrove, agricultural land, bare earth/sand beach, non agricultural land, and water body. Analysis of signature separability was carried out on the preselected training signatures before conducting supervised classification with the aim of producing superior classification outputs. Thereafter, majority spatial filters of 3 × 3 dimension were applied on each of the produced LULC images to remove the isolated pixels. Following the classification, accuracy assessment had been performed by error matrices for all the images which had different measures of accuracy. In the post classification stage, change-detection had been carried out to produce change area matrices of subsequent pairs of the classified single date LULC images.

2.5. Mapping of vegetation attributes

A wide range of spectral vegetation indices are generally used in the assessment of vegetation density and canopy closure. Normalized difference vegetation index (NDVI) is the most extensively used one among all these indices (18). The basic principal of NDVI is that the rates of reflection differ for the band 4 near infrared (NIR) and band 3 (Red) of an image and thereby these differences can produce an image which characterizes the status of green plants and is least influenced by topography. The NDVI calculation is done by the following equation:

\[ NDVI = \frac{NIR - RED}{NIR + RED} \] (1)

NDVI maps were developed from these NDVI ratios for the three Landsat images used in the present study by calculating the reflectance value of a pixel in the NIR region (700–1100 nm) and that of the same pixel in the red region (600–700 nm). Theoretically, the biomass of the mangrove leaves (chlorophyll portion) reflects more prominently in the middle infrared region (18). In general, NDVI values range from −1 to +1 but in reality extreme negative values correspond to water content. Values near zero denote bare earth while values beyond 0.5 represent lush green vegetation. Specifically, NDVI values for “dense mangrove” usually range from 0.7 to 0.9 (3).

2.6. Change detection using NDVI

For change detection analyses, overlaying geographic information system (GIS) techniques integrated within ERDAS IMAGINE had been used to explore the transformation in vegetal cover that occurred between the given time periods of multiple image acquisitions. NDVI differencing technique was used to assess mangrove biomass change by comparing computed NDVI values between images of two particular dates. For the preparation of these differential NDVI maps, each pair of images (1975–1990 and 1990–2006) was stacked first,
following effective masking of water segments of all the images. This had minimized the chances of further confusion in this analysis created by water content. Furthermore, an unsupervised classification of all the three masked NDVI images (1975, 1990, and 2006) was performed cumulatively using the ISODATA clustering algorithm by firstly stacking these NDVI images together and then conducting the classification process (19). This classification generated 45 user-defined classes at a convergence level of 99%, which were later merged to form 10 broad classes of landscape changing phases.

3. Results

3.1. Assessment of land use/land cover patterns through classified images

Estimated areas under different LULC categories for the three images of the present study area are shown in Figures 2 and 3. In 1975, areas under dense mangrove and open mangrove classes were approximately 12,650.80 ha (7.01%) and 33,248.70 ha (18.43%), respectively. In general, dense mangroves were found to be occurring primarily in the remote islands devoid of any human habitation and partly along the river banks and mouths. Open mangroves were in a spatially heterogeneous and discrete order throughout the study area. Agricultural land was 20.15% of total land area. In contrast, the bare earth (3.11%) and non agricultural land (1.85%) classes occupied comparatively lesser area than the former chiefly due to the presence of greater vegetal cover and moderately dispersed settlements as well as physical inaccessibility of this area at that time.

In 1990, the area of dense mangrove (10.39%) increased by more than 48% from its 1975 value while open mangrove occupied approximately 16.09% of the total area. As better management regimes were being developed under the “Biosphere Reserve” and “Project Tiger” initiatives, the remaining mangrove covered islands started to be protected and guarded from any outside interference by the FD. Consequently, the amount of dense mangrove classed land started to increase in the islands with Reserved Forest designation. Conversely, the amount of open mangrove classed land reduced while that of bare earth/sand beach (7.16%) increased greatly, probably due to forest clearing and consequent land reclamation trends during that period. Figure 2(B) reveals this pattern, especially in the northern and western parts of the study area that were largely inhabited by subsistence farmers and forest dependents. Creation of protected and reserved forests might have resulted in accentuated seclusion and alienation of these people from their primary livelihood generating areas and thereby, in desperation, they engaged in resource extraction and land reclamation from open mangrove stands. A few medium and large-scale shrimp firms were established in the Namkhana and Kakdwip area in the 1980s as alternative sources of income but these did not provide sufficient employment opportunities for the local populace since skilled labor was imported from outside.

However, the land under open mangrove decreased drastically to about 12.63% of the total area in 2006. Most of these reduction occurred in the eastern part of Patharpratima where maximum amount of land was transformed for agricultural uses and shrimp farms.

![Figure 2](image_url)
Dense mangrove and agricultural lands occupied 12.71 and 20.93%, respectively. Major improvements in both the extent and condition of dense mangroves were observed in the protected forest areas managed jointly by the FPCs and FD. The remaining area was occupied by non agricultural land, bare earth/sand beach, and water bodies. A notable concentration of non agricultural lands was found along the southernmost coastline of Namkhana, especially in the Bakkhali and Fraserganj locality due to the emergence of built-up areas and infrastructural facilities for development of coastal tourism since the late 1990s. Large nucleated settlements were also observed in the Kakdwip and Ramganga areas with semi-urban land use characteristics. During field studies, several locations with abandoned shrimp ponds were found corresponding to the bare earth category.

3.2. Analyses of changes in land use/land cover

Analysis of LULC data from 1975 to 2006 indicated an obvious decrease of open mangroves with time, which is just the opposite of the trend for dense mangroves (Table 1). These decreases were probably due to the massive increase of population, i.e. more than 20% per decade and subsequently with the establishment of new settlements as well as expansion of old ones in the entire Sunderbans region in spite of the vicinity to dense forest, saline top soil, and persistent natural calamities. Similarly, the expansion of agricultural activities and shrimp farming in previously unsettled and forested lands also contributed sufficiently in this process (14). In contrast, continual increase of dense mangrove areas might be the result of decade long stringent surveillance and protection activities by the FPCs and the FD within the purview of JFM and Wildlife Sanctuary (15). Between 1975 and 1990, little conversion from dense mangrove to agricultural land (only 4.93%) occurred (Table 2). An overall reduction of approximately 0.42% had been estimated for the cumulative mangrove cover comprising both dense and open mangroves of this area from 1975 to 2006. Remarkably, areas under agricultural land use decreased in the 1975–1990 phase but increased in the 1990–2006 phase (Table 3). This apparent anomaly might be due to the fact that the local practice of rainfed paddy monoculture during the 1970–1980s usually resulted in temporary fallow and barren lands in the winter season which ultimately led to a probable erroneous classification of agricultural lands as bare earth LULC types. Large scale construction of shrimp ponds

Table 1. Area under different land use/land cover categories for 1975, 1990, and 2006.

| Land cover classes | Year 1975 | Year 1990 | Change (1975–1990) | Year 2006 | Change (1990–2006) |
|--------------------|-----------|-----------|---------------------|-----------|---------------------|
|                    | Area (ha) | %         | Area (ha)           | (ha) %    | Area (ha)           | (ha) %    |
| Dense mangrove     | 12,650.80 | 7.01      | 18,743.90           | 10.39     | 22,928.28           | 12.71     |
|                    |           |           | +6093.10            | +48.16    | +4184.38            | +22.32    |
| Open mangrove      | 33,248.70 | 18.43     | 29,015.44           | 16.09     | 22,778.24           | 12.63     |
|                    |           |           | -4233.26            | -12.73    | -6237.19            | -21.50    |
| Agricultural land  | 36,340.60 | 20.15     | 30,487.70           | 16.90     | 37,756.72           | 20.93     |
|                    |           |           | -5852.90            | -16.11    | +7269.02            | +23.84    |
| Bare earth/ Sand   | 5,611.72  | 3.11      | 12,913.45           | 7.16      | 10,158.31           | 5.63      |
| beach              |           |           | +7301.73            | +130.12   | -2755.14            | -21.34    |
| Non agricultural land | 3,345.15 | 1.85      | 4,646.86            | 2.58      | 6,305.93            | 3.50      |
|                    |           |           | +1301.71            | +38.91    | +1659.07            | +35.70    |
| Water body         | 89,168.10 | 49.44     | 84,557.73           | 46.88     | 80,437.57           | 44.60     |
|                    |           |           | -4610.37            | -5.17     | -4120.16            | -4.87     |
| Total              | 180,365.07| 100.00    | 180,365.07          | 100.00    | 180,365.07          | 100.00    |

Figure 3. Amount of land under different land use/land cover classes in 1975, 1990, and 2006.
in place of riverside farmlands also contributed to this decrease. However, the trend reversal happened in the 1990–2006 phase with widespread introduction of high yielding varieties of crops as well as groundwater-dependent “boro” rice cultivation in winter leading to a sharp increase (23.84%) in the proportion of agricultural lands. In addition, huge amount of area (26.80% of original open mangrove cover) was converted from open mangrove to agricultural land uses. Notably, non-agricultural land uses like settlements, roads, and other semi-urban built-up areas increased considerably between 1990 and 2006 by almost 35.70%. The reason for this increase was the gradual shift of local people’s interest towards non-agricultural livelihood practices, e.g. coastal tourism, shrimp culture and processing, deep sea fishing, handicraft, and house-hold based food processing industries. While amount of land in the bare earth category decreased between 1990 and 2006 with comparison to 1975–1990 period, most of these lands were either being transformed into agricultural lands or occupied by newly forming rural settlements, fish drying units, sea salt production units, and built-up areas around commercial shrimp farms falling in non-agricultural land use classes during 1990–2006. The salient characteristics of these settlements were that these were forming in a dispersed manner all over the region and mostly of a temporary nature. Many settlements shifted their location between 1990 and 2006 chiefly under the impacts of extreme quasi-natural hazards periodically devastating the Sunderbans.

### 3.3. Accuracy assessment and field verification

Assessments of accuracy were carried out on the LULC maps through a comparison with ground reference data collected during field surveys executed from 2007 to 2009. For identification of past LULC patterns at these sites, information and feedback from knowledgeable persons in local communities was taken into consideration. Error matrices were generated for each of the classified images. Overall Kappa coefficients had been represented in Tables 4–6 for images of 1975, 1990, and 2006 which were 0.8696, 0.8925, and 0.8357, respectively. Conversely, overall accuracy was 91.33, 92.33, and 88.00% for those three images, respectively indicating sufficient accuracy for post-classification comparison. Regarding classified Landsat MSS image, higher levels of accuracy were achieved despite its coarser pixel dimension (2400 × 3240) than the images of TM and ETM+ as it contained more spectrally separable features. Among the various LULC types, agricultural land, water bodies, and dense mangrove had highest producer accuracies in the 1975, 1990, and 2006 images, respectively. In the case of user accuracy, the highest values were achieved in the non-agricultural land use class for the first two images and in the water body class for the last image. The values for producer accuracy were found to be always

### Table 2. Land use/land cover transformation matrix of the study area from 1975 to 1990 (in ha).

| Land use (1975) | Dense mangrove | Open mangrove | Agricultural land | Bare earth/Sand beach | Non agricultural land | Water body |
|----------------|----------------|---------------|-------------------|-----------------------|-----------------------|-----------|
| Dense mangrove | 10,129.65      | 1057.34       | 623.86            | 548.66                | 223.45                | 67.84     |
| Open mangrove  | 5675.92        | 24,480.11     | 1939.72           | 574.76                | 529.91                | 48.28     |
| Agricultural land | 567.56        | 1254.96       | 27,465.05         | 3795.42               | 1813.62               | 1443.99   |
| Bare earth/Sand beach | 1711.61       | 952.81       | 42.18             | 2463.00               | 121.67                | 320.45    |
| Non agricultural land | 129.54       | 343.77       | 89.87             | 428.22                | 1929.45               | 424.30    |
| Water body      | 529.62         | 926.45        | 327.02            | 5103.39               | 28.76                 | 82,252.87 |

### Table 3. Land use/land cover transformation matrix of the study area from 1990 to 2006 (in ha).

| Land use (1990) | Dense mangrove | Open mangrove | Agricultural land | Bare earth/Sand beach | Non agricultural land | Water body |
|----------------|----------------|---------------|-------------------|-----------------------|-----------------------|-----------|
| Dense mangrove | 16,845.23      | 708.32        | 456.97            | 611.28                | 33.23                 | 88.87     |
| Open mangrove  | 2860.53        | 17,090.18     | 7776.89           | 469.28                | 742.73                | 69.83     |
| Agricultural land | 502.34        | 1363.26       | 27,357.78         | 681.14                | 542.08                | 41.10     |
| Bare earth/Sand beach | 1967.01       | 1588.81       | 859.39            | 6459.68               | 1289.41               | 749.15    |
| Non agricultural land | 59.28        | 220.48        | 229.62            | 687.29                | 3213.28               | 236.91    |
| Water body      | 687.89         | 1807.19       | 1076.07           | 1249.64               | 485.20                | 79,251.71 |

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higher than user accuracy for dense and open mangrove as well as for agricultural land use. For bare earth and non agricultural land, opposite trends were observed. Major areas of confusion and misinterpretation were found to roughly coincide with the transitional areas between agricultural land and open mangrove or bare earth classes.

### 3.4 Change detection in vegetation dynamics

NDVI was used as an effective LULC change detection parameter in this study to delineate mangrove change areas. Two NDVI differencing maps viz. 1975–1990 and 1990–2006 were created by subtracting NDVI values of one date from those of the previous date (Figure 4). The outcomes of this analysis clearly indicated an overall positive change i.e. more than 2% growth in NDVI values of this area during 1975–1990. However, this kind of increase does not always necessarily correspond to the growth and expansion of mangrove cover as all types of vegetation including cultivated crops and vegetables, scrubs, orchards, and even eutrophic wetlands also contribute to the increment. For example, few extremely eutrophic wetlands identified during the field verifications were later found to be misclassified as either agricultural land or open mangroves and thereby not effectively covered by the water masking process. Posi-

### Table 4. Accuracy assessment for supervised classification of Landsat MSS classified image (1975).

| Class name                 | Reference total | Classified total | Number correct | Producer’s accuracy | User’s accuracy | Kappa (k) |
|----------------------------|-----------------|------------------|----------------|--------------------|----------------|-----------|
| Dense mangrove             | 23              | 24               | 19             | 82.61              | 79.17          | 0.7744    |
| Open mangrove              | 48              | 51               | 42             | 87.50              | 82.35          | 0.7899    |
| Agricultural land          | 37              | 44               | 37             | 100.00             | 84.09          | 0.8185    |
| Bare earth/Sand beach      | 22              | 15               | 12             | 54.55              | 80.00          | 0.7842    |
| Non agricultural land      | 12              | 7                | 7              | 58.33              | 100.00         | 1.0000    |
| Water body                 | 158             | 159              | 157            | Overall classification accuracy = 91.33% | 98.74          | 0.9734    |
| Column total               | 300             | 300              | 274            | Overall classification accuracy = 91.33% | Overall Kappa = 0.8696 |

### Table 5. Accuracy assessment for supervised classification of Landsat TM classified image (1990).

| Class name                 | Reference total | Classified total | Number correct | Producer’s accuracy | User’s accuracy | Kappa (k) |
|----------------------------|-----------------|------------------|----------------|--------------------|----------------|-----------|
| Dense mangrove             | 26              | 29               | 25             | 96.15              | 86.21          | 0.8490    |
| Open mangrove              | 37              | 42               | 34             | 91.89              | 80.95          | 0.7827    |
| Agricultural land          | 54              | 55               | 48             | 88.89              | 87.27          | 0.8448    |
| Bare earth/Sand beach      | 33              | 26               | 23             | 69.70              | 88.46          | 0.8704    |
| Non agricultural land      | 10              | 8                | 8              | 80.00              | 100.00         | 1.0000    |
| Water body                 | 140             | 140              | 139            | 99.29              | 99.29          | 0.9866    |
| Column total               | 300             | 300              | 277            | Overall classification accuracy = 92.33% | Overall Kappa = 0.8925 |

### Table 6. Accuracy assessment for supervised classification of Landsat ETM+ classified image (2006).

| Class name                 | Reference total | Classified total | Number correct | Producer’s accuracy | User’s accuracy | Kappa (k) |
|----------------------------|-----------------|------------------|----------------|--------------------|----------------|-----------|
| Dense mangrove             | 29              | 34               | 29             | 100.00             | 85.29          | 0.8372    |
| Open mangrove              | 41              | 48               | 35             | 85.37              | 72.92          | 0.6863    |
| Agricultural land          | 59              | 67               | 53             | 89.83              | 79.10          | 0.7399    |
| Bare earth/Sand beach      | 25              | 13               | 12             | 48.00              | 92.31          | 0.9161    |
| Non agricultural land      | 15              | 9                | 7              | 46.67%             | 77.78%         | 0.7661    |
| Water body                 | 131             | 129              | 128            | 97.71%             | 99.22%         | 0.9862    |
| Column total               | 300             | 300              | 264            | Overall classification accuracy = 88.00% | Overall Kappa = 0.8357 |
tive changes in areas with increasing human population, in spite of decrease of open mangroves, were primarily the result of increase in cropping intensity through multi-cropping. Specifically, only in a few areas like Chulkati, Dulibhasani, Lothian Island, and other protected forests or vegetated riverbanks, this growth was due to the increase of dense mangroves. A few instances of negative changes were observed mainly along the river and coastal margins due to high rates of bank erosion as well as conversion of agricultural lands and open mangroves to bare earth and built-up areas. Moreover, landward expansion of coastal sand dunes and consequent engulfing of farmlands and mangroves were also found to be responsible for the decrease in NDVI values.

In the NDVI change analysis of 1990–2006, vegetation dynamics were found to be somewhat different from what they were previously. Here, the positive changes were mainly concentrated in dense mangrove areas and along the riverbanks and coastlines of inhabited islands. Within the protected forest areas, more positive changes in the NDVI values observed in the 1990–2006 map from those in 1975–1990s’ were chiefly due to the continuous growth of dense and healthy mangrove stands. Along the riverbanks and coasts of settled areas, positive changes were the result of afforestation and restoration activities under the JFM and Social Forestry programs. However, considerable negative changes were also observed in a few areas of open mangroves, especially around Jambudwip, the northern portions of Moushuni and the eastern and southern parts of Ramganga. Notably, field verification confirmed that many mangrove areas were experiencing increasing dominance of *Avicennia* varieties in comparison to other plant species.

The spatio-temporal dynamics of mangrove forests and their changes in the study area in between 1975 and 2006 are depicted in Figure 5. Prime areas for mangroves reduction during 1975–1990 were observed to be the inner estuarine and tidal mudflat portions of Moushuni and Patibunia islands. The reduction areas were irregular and dispersed but at the same time were adjacent to the human settlements, thus indicating rampant removal of open mangroves without any major

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**Figure 4.** Changes in NDVI during (A) 1975–1990 and (B) 1990–2006.

**Figure 5.** Composite NDVI image during 1975–2006.
administrative interference. However, mangrove cover reduction during the 1990–2006 period was noticeably less than the previous period and concentrated within a few limited coastal areas like Jambudwip, Bulchery island, etc. These areas, however, were within the Reserved Forests and therefore the causes of reduction were probably more of quasi-natural character (e.g. permanent flooding of forest floors, natural calamities, erosion, changes in micro-topography, top dying diseases, pest invasion etc.) than to be entirely anthropogenic. There were clear indications of mangrove regeneration under the supervision of FD during 1975–1990 mainly within the Reserved Forest areas and partially in the pristine river-mouth bars and tidal ridges. However, considerable regeneration was found in the Reserved Forest areas as well as in community owned lands between 1990 and 2006. A noteworthy amount of areas, highlighted by the magenta tint in Figure 5, were found to be experiencing a reduction in mangrove cover between 1975 and 1990 but were sites of regeneration during 1990–2006. In contrast, fewer areas were identified where regeneration occurred during 1975–1990 followed by reduction during 1990–2006. In the northern portions of the study area, a substantial amount of land was found to have low NDVI values (light gray tint) throughout the entire study period (i.e. in months of November/December of image acquisition years). These lands roughly corresponded to the monocropped paddy fields during the on-field verification.

4. Discussion

The Sunderbans is widely recognized as a highly susceptible region to climate change induced rise in sea levels (3). Any effort towards sustainable natural resource management in the Sunderbans has to overcome many difficult odds like inaccessible terrain conditions, cyclones, sea surges, monsoonal high floods, and frequent incidents of animal straying in villages. Moreover, traditional livelihood options and timber harvesting-based forestry practices are not conducive to sustainability for either the local people or the environment. Unfortunately, evidence found and observations made during the present study unmistakably point out the presence of environmentally harmful human activities throughout the last few decades. For many years, open mangrove covers had been exploited by rural masses without any management initiative. Only in the last 10–15 years has community based management been initiated in this area. The impact was found to be optimistic (2). Interestingly, cumulative mangrove coverage in this area was estimated to be increasing by 0.27% in the 1975–1990 phase but was reduced at almost at the same rate (0.269%) during the 1990–2006 phase indicating relative stability of the mangroves. These findings were also in parity with other recent studies on mangrove extent of the Sunderbans (3, 8). However, these existing mangrove covers are not going to be sufficient against the severest tsunami waves and cyclones like that one of Aila (25 May 2009), which caused havoc in terms of flooding, landslide, bank erosion, tree uprooting and destruction of human property and lives. Although it is obvious that complete protection and immunity from such environmental calamities is not possible in this type of fragile areas, considerable minimization of the risk quotient can definitely be achieved if proper management methods with supreme emphasis on the creation of mangrove belts along the riverbanks and coastlines are adopted. Hence, based on the analysis of LULC change patterns and information gathered from field surveys and people’s feedbacks, few urgently needed guidelines for sustainable natural resource management in this area can be prescribed, like:

(1) Creation of healthy mangrove stands with a width of at least 100 m along the riverbanks of all islands followed by earthen embankments of 5–10 m height.

(2) Initiation of ecotourism in the FPC villages with proper infrastructural facilities.

(3) Controlled coastal tourism activities in Bakkhali, Fraserganj, and Moushuni according to the guidelines of Indian Coastal Regulation Zone Notification 1991 (20).

(4) Modification of JFM operating procedure by prioritizing the alternative sources of livelihood primarily depending on the non timber forest products of mangroves along with limited scopes of timber harvesting and brackish water aquaculture especially in the Patharpatima CDB.

(5) Provisions of fuel wood production in intra-village lands through Social Forestry and introduction of subsidized alternative fuel sources (coal, LPG, etc.) for the marginal people.

5. Conclusion

Sustainable management of mangrove dominated coastal ecosystems is a complex issue to tackle and calls for comprehensive interdisciplinary approaches with enhanced flexibility to incorporate information of both a qualitative and quantitative nature into the decision-making processes. As demonstrated by the present study, remote sensing technologies integrated with GIS can provide accurate, cost effective, and instantaneous information but unless these are applied in “real time” monitoring and assessment of mangrove dynamics from appropriate public platforms, optimum success cannot be achieved. Regarding the LULC changes in the Sunderbans, continual loss of open mangrove stands from inhabited areas is a matter of serious concern and needs to be addressed adequately. A distinct trend of transformation from a largely mangrove swamp dominated landscape to an agriculture and tourism-based coastal setting was observed in the study area during change detection analyses. Greater dominance of Avicennia varieties and lesser occurrence of few less
salinity tolerant species like *Heritiera fomes*, *Nypa fruticans*, etc. within the mangrove forest composition were identified by field observations. Future studies applying higher resolution optical as well as RADAR-based images and if possible, air-borne hyper-spectral data will be of great benefit in identifying these changes accurately in the hitherto inaccessible terrains of the Sunderbans and, in turn, will create new inroads in species level mapping and understanding of mangrove forest dynamics.

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**References**

(1) FAO. Global Forest Resource Assessment 2005: Progress Towards Sustainable Forest Management; Food and Agriculture Organization of the United Nations: Rome, 2005.

(2) Datta, D.; Guha, P.; Chattopadhyay, R.N. Application of Criteria and Indicators in Community Based Sustainable Mangrove Management in the Sunderbans, India. *Ocean Coast. Manag.* 2010, 56 (3), 468–477.

(3) Giri, C.; Pengra, B.; Zhu, Z. *et al.* Monitoring Mangrove Forest Dynamics of the Sunderbans in Bangladesh and India Using Multi-Temporal Satellite Data from 1973 to 2000. *Estuar. Coast. Shelf Sci.* 2007, 73 (1–2), 91–100.

(4) Bhattacharya, S. *Sunderbans-Dying a Slow Death;* The Hindu Survey of Environment; Chennai, 1998.

(5) Akhter, M.; Iqbal Md., Z.; Choudhury, R.M. ASTER Imagery of Forest Areas of Sundarban Damaged by Cyclone Sidr. *ISME/GLOMIS Electron. J.* 2008, 6 (1), 1–3.

(6) Giri, C.; Ochieng, E.; Tieszen, L.L.; Zhu, Z.; Singh, A.; Loveland, T.; Masek, J.; Duke, N. Status and Distribution of Mangrove Forests of the World using Earth Observation Satellite Data. *Glob. Ecol. Biogeogr.* 2011, 20 (1), 154–159.

(7) Zharkov, Y.; Skilleter, G.A.; Loneragan, N.R. *et al.* Mapping and Characterising Subtropical Estuarine Landscapes using Aerial Photography and GIS for Potential Application in Wildlife Conservation and Management. *Biol. Conserv.* 2005, 125 (1), 87–100.

(8) Nandy, S.; Kushwaha, S.P.S. Study on the Utility of IRS 1D LISS-III Data and the Classification Techniques for Mapping of Sunderban Mangroves. *J. Coast. Conserv.* 2010, 15 (1), 123–137.

(9) Diyan Md., A.A. Multi-scale Vegetation Classification using Earth Observation Data of the Sundarban Mangrove Forest, Bangladesh; University of Nova: Lisbon, 2011.

(10) Akhter, M. Remote Sensing for Developing an Operational Monitoring Scheme for the Sundarban Reserved Forest, Bangladesh; Institute of Photogrammetry and Remote Sensing, Dresden Technical University: Dresden, 2006.

(11) Bose, P.; Mohapatra, S.N.; Behera, M.D.; Pani, P. A Comparative Study of the Spectral Response Curves and the Assessment of Different Land Use and Land Cover Features in a Part of Sunderban Area, West Bengal, Using Geoinformatics. *Int. J. Inform. Technol. Knowled. Manage.* 2008, 1 (2), 219–226.

(12) Mitra, D.; Karunekar, S. Mangrove Classification in Sunderban using High Resolution Multi Spectral Remote Sensing Data and GIS. *Asian J. Environ. Disast. Manage.* 2010, 2 (2), 197–207.

(13) Jayappa, K.S.; Mitra, D.; Mishra, A.K. Coastal Geomorphological and Land-Use and Land Cover Study of Sagar Island, Bay of Bengal (India) using Remotely Sensed Data. *Int. J. Remote Sens.* 2006, 27 (17), 3671–3682.

(14) Chaudhuri, A.B.; Choudhury, A. Mangroves of the Sunderbans Volume One: India; IUCN-The World Conservation Union: Bangkok, 1994.

(15) WBFD. *Annual Report of Sunderbans Tiger Reserve 2006–2007.* West Bengal Forest Department, Govt. of West Bengal, Kolkata, India, 2007.

(16) Zhang, F.; Tiyp, T.; Hsiang-te, K. *et al.* The Change of Land Use/Cover and Characteristics of Landscape Pattern in Arid Areas Oasis: An Application in Jinghe, Xinjiang. *Geo-spati. Inform. Sci.* 2010, 13 (3), 174–185.

(17) Settle, J.J.; Briggs, S.S. Fast Maximum Likelihood Classification of Remotely Sensed Imagery. *Int. J. Remote Sens.* 1987, 8 (5), 723–734.

(18) Morawitz, D.F.; Blewett, T.M.; Cohen, A. *et al.* Using NDVI to Assess Vegetative Land Cover Change in Central Puget Sound. *Environ. Monit. Assess.* 2006, 114 (1–3), 85–106.

(19) Sadar, S.A.; Winne, J.C. RGB-NDVI Color Composites for Visualizing Forest Change Dynamics. *Int. J. Remote Sens.* 1992, 13 (16), 3055–3067.

(20) GOI. *The Coastal Regulation Zone Notification.* The Gazette of India (Extraordinary), No. 105, Part II, Section 3 (ii) dated February 20, 1991, Ministry of Environment and Forests, Govt. of India. New Delhi, 1991.