Photonirvachak

Springer

J. Indian Soc. Remote Sens. (March 2010) 38 : 67–83

RESEARCH ARTICLE

Spatial Analysis of Anthropogenic Disturbances in Mangrove Forests of Bhitarkanika Conservation Area, India

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Received: 03.08.2009 / Accepted: 07.09.2009

Keywords Mangrove Forests • Anthropogenic Disturbance • Remote Sensing • Geographic Information Systems (GIS) • Resource Use • Total Use Value

Abstract The dependence of coastal communities on mangrove forests for direct consumptive use due to the scarcity of alternate resources makes them one of the highly disturbed landscapes. This paper examines the spatial characteristics and extent of anthropogenic disturbances affecting the mangrove forests of Bhitarkanika Conservation Area situated along the east coast of India by using remotely sensed data and GIS, supplemented with socioeconomic surveys. The study reveals that resource extractions from these forests were considerable despite the protected status. Around 14% of the total fuel wood consumed annually in each of the household came from the mangrove forests of the Park. The patterns of consumption were spatially heterogeneous, controlled by the availability of alternatives, ease of accessibility, presence of markets, human density, and forest composition. The disturbance surface showed 30% of the major forest classes to be under high to very high levels of disturbance especially at easy access points. Besides, the distribution of economically useful species also determined the degree of disturbance. Resource use surfaces clearly identified the biotic pressure zones with respect to specific mangrove use and could be combined with the disturbance regime map to prioritize areas for mangrove restoration.

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Introduction

In many parts of the tropics, the economy of coastal communities is intricately linked with mangrove forests (Spaninks and van Beukering, 1997) where they play a major role in sustaining livelihoods by providing a wide variety of goods and services to people (Badola and Hussain, 2005, Hussain and Badola, 2008; Walters *et al.,* 2008). But like many resource rich areas of the world, mangrove forests are heavily exploited and face threats from population pressures, agricultural reclamations and other unsustainable economic activities (Saenger *et al*., 1983; Fransworth and Ellison, 1997; Blasco *et al*., 2001; Valiela *et al*., 2001). Many studies have shown that human intervention in land utilization has changed forest cover over time (e.g. Kammerbauer and Ardon, 1999; Millington *et al*., 2003; van Laake and Sanchez-Azofeifa, 2004; Abdullah and Nakagoshi, 2007). In India, mangroves occupy an area of 4482 km^2, which is 0.14 % of the country's geographic area (State of Forest Report, 2001). Attributed to the nutrient rich alluvial soil and a perennial supply of freshwater most of the mangrove formations are along the east coast of India (Krishnamurthy *et al.,* 1987; Karthiresan *et al*., 1995). However, most of these mangroves are largely degraded because of intensive human pressure (Williams, 1991).

Since the mangrove ecosystems support a wide range of human - environment interactions, an integrated study of socioeconomic forces and quantitative tools that relate the spatial conditions of the landscape to conservation goals is required (Opdam *et al*., 1995). Because of their vast extent and the problems involved in carrying field studies, it has been difficult to study and monitor the mangrove forests. However, in recent years, remote sensing techniques, in combination with spatial modeling and Geographic Information Systems (GIS), have improved our ability to assess rates, patterns, and directions of changes across landscapes (Turner, 1989; Ravan and Roy, 2000; Cohen *et al*., 2002). One of the most widely used methods to look into the recent past, and which will undoubtedly evolve into the single most important monitoring technology in future, is remote sensing (Dahdouh-Guebas and Koedam, 2008). Though the classification of remote sensing images for forest cartography is essential for regional biodiversity mapping, yet, because of the heterogeneity of forest settings, the distinction between forest types remains a difficult challenge (Couturier *et al*., 2009), especially among mangrove forests, which has been adequately addressed in recent years (Walter *et al.,* 2008). Spatial data when integrated with socio-economic data has the potential to reveal the complex role of social and economic factors underlying change (Menon and Bawa, 1997).

The mangrove forests of Bhitarkanika Conservation Area, located in the state of Orissa are the second largest mangrove forest of mainland India (Patnaik *et al*., 1995). The original area of these mangrove forests was 672 km^2. Over the years, the growing demands of local population and reclamation of land for agriculture (Roy, 1989) have reduced the area of these forests to 145 km^2 (Chadha and Kar, 1999). The remaining mangrove forests are exploited for fuel wood and construction materials by the local people. Developmental activities such as construction of jetties, roads, defense structures, missile testing site, inshore fisheries by mechanized vessels and the proposal of a major port threaten the existence of this unique ecosystem (Badola and Hussain, 2003, 2005).

A study of resource use pattern identifies not only the causative factors behind resource depredation but also indicates the spatial course of loss. So far, few studies have analyzed the spatial patterns of forest resource use (Hambrey, 1996) and mangroves are no exception. Most of the Indian remote sensing studies on mangroves are limited to mapping and detection of extent of change (Roy, 1989; Ramachandran *et al*., 1998; Selvam, 2003). Only in the recent years GIS has been used to address management issues in mangroves (Krause *et al.*, 2004; Zharikov *et al*., 2005). Biotic disturbance factors and their associated patterns remain largely unexamined and understudied.

Successful prioritization and planning to maintain or restore quality and resilience of landscapes depends in large part, on the ability to assess and map the composite departure from natural systems (White and Pickett, 1985; Sayre *et al*., 2000). The present study aims to assess the current status of the Bhitarkanika mangrove forests in light of increased biotic disturbances. For the purpose of this study, data from a socio-economic survey were used to generate various resource use layers, such as fuel wood, timber and fish catch. A landscape analysis was performed using vegetation type data obtained from satellite imagery. The layers so generated were combined with information on biotic pressure and anthropogenic impact zones using customized modeling software SPLAM (Roy *et al.,* 2005) in order to identify critically disturbed areas. SPLAM (Spatial Landscape Analysis Model) is a program generated for the analysis of porosity, interspersion, fragmentation, juxtaposition, terrain complexity, disturbance index and biological richness. SPLAM uses a generic binary image as the input and the output is also written in the same format.

Materials and Methods

Study Area

The mangrove forests of Bhitarkanika Conservation Area are found largely within Bhitarkanika Wildlife Sanctuary (BWS) between 86^0 45'E to 87^0 50'E longitudes and 20^0 40'N to 20^0 48'N latitudes in the lower reaches of the Dhamra-Pathsala-Maipura Rivers (Fig. 2). The climate in the area is tropical and annual rainfall averages 1670 mm with the main rainfall occurring during the months of August and September. The temperature ranges from 30^0 C in summer to 15^0C in winter (Kar and Bustard, 1986). In 1988, an area of 672 km^2 of these forests was declared as a Wildlife Sanctuary with a core area of 145 km^2 that was designated as National Park. Floral and faunal diversity of the area includes more than 300 plant species (Banerjee, 1984) of mangroves and non-mangroves, 31 species of mammals representing 25 genera and 14 families (Patnaik *et al*., 1995), 29 species of reptiles with four species of turtles and 174 species of birds (Pandav, 1997). It is a critical habitat of the endangered Saltwater Crocodile (*Crocodylus porosus*) and the nesting ground of the Olive Ridley sea turtles (*Lepidochelys olivacea*) (Chadha and Kar, 1999). Considering its ecological and social value the area has been identified as a Ramsar site (Hussain and Badola, 2008).

Vegetation and land cover mapping

We have used Indian Remote Sensing Satellite (IRS-P6), LISS-III data of November 2006, geo-registered to UTM projection and WGS 84 datum. Preparation of vegetation and land cover maps was accomplished through visual interpretation on the basis of image elements like size, shape, pattern, association, tone and textural variations. As mangrove communities exhibit a range of form and heterogeneity (Saenger, 2002), it requires an understanding and delineation of forest types that might not be distinguishable in digital classification. Functional classification approach (Ewel *et al.,* 1998) was followed by suitably merging it with the classification proposed by Champion and Seth (1968) for forest types of India. Digital data was georectified with the Survey of India toposheets (Survey of India, 1979). The interpretation accuracy was evaluated by field checking of the interpreted polygons. The total root mean square error of geo-rectification was estimated to be 2 m. The georectified image was classified into 50 classes. The unsupervised classification map, false colour composite and NDVI map were used to ground truth landuse and vegetation types.

Based on the administrative map, the Bhitarkanika Wildlife Sanctuary was stratified into distinct blocks. Stratified random sampling was used to collect the field data on mangrove species composition in 10 m x 10 m plots laid in perpendicular to the creeks. In each plot, the vegetation was classified on the basis of Girth at Breast Height (GBH); seedlings (<15 cm GBH), saplings (≥15 cm & ≤20 cm GBH) and trees (≥ 21 cm GBH) and their occurrence was recorded following Mishra (1968). The ground cover of meadows was estimated by using 1 m x 1 m rectangular plots and visually estimating the percentage area covered by grasses, litter, water and bare soil. Anthropogenic pressure in terms of cutting and lopping of trees and evidence of grazing, fishing, honey and grass collection were also recorded. In total 202 plots and 322 relevés were used for vegetation classification and accuracy estimation. The relevé is generally considered a description of a stand of vegetation in "semi-quantitative" terms that relies on ocular estimation of plant cover rather than on measurements. The relevé is particularly useful when observers are trying to quickly classify the range of diversity of plant cover over large units of land. In general, it is faster than the point intercept technique, which is used while developing a classification that could be used to map large areas of vegetation. This method may also be more useful than the line intercept method while validating the accuracy of mapping efforts.

Use value of mangrove species

In order to compare the relative importance of individual mangrove species, all the major and minor use values of the mangrove species were examined during the household (hhld) surveys conducted as part of the study. The use value of each species was given equal weightage and summed up to obtain a Total Use Value (Annexure I) following Prance *et al*. (1987). Subsequently, the Total Use Value (TUV) indices were computed separately for each vegetation class based on the dominant species and their relative densities.

Surface analysis of resource use

Data on resource use was collected by means of household surveys. The sampling frame comprised 336 inhabited villages located within the BWS. Data comprising 28 socio-economic parameters was subjected to factor analysis resulting in seven unique village clusters. Based on cluster size, 35 villages were selected from these clusters and 10% of households were randomly interviewed through structured questionnaires. A point was made to evenly distribute the households over the total area of the villages in order to get a full representation of all communities and economic groups. Using structured questionnaires, information on demography, land use, income and occupational pattern as well as local dependence on mangrove resources was collected from a total of 324 intensively surveyed households. The extraction and consumption patterns of biomass resources such as fuel wood, timber, thatch, fish and other NWFPs were estimated by direct observations in these households. Whenever required, participant observer method was used to supplement the information. The data were analyzed using MS Excel and SPSS software packages (Norussis, 1994).

The household consumption values of forest resources were averaged for each village and used as point geographic location to create continuous prediction surface of resource use over the entire Sanctuary through surface interpolation functions (Lam, 1983; Miller *et al.,* 1997; Burrough and McDonnell, 1998). Surface interpolation functions make predictions from sample measurements for all locations in a raster dataset whether a measurement has been taken at the location or not. The Neighborhood model with a cell size of 24 m was employed to generate the resource use surface (Moloney and Levin, 1996). The Neighborhood model is a type of deterministic interpolation technique that creates surfaces from measured points, based on the extent of similarity and specified mathematical formulas. The results obtained from this method conformed to the ground observations and hence it was chosen over other geostatistical models. The study area being small, a local interpolator was used in order to produce surfaces that accounted for local variation.

Disturbance regime analysis

Vegetation map derived from the satellite data was used as the prime input for landscape analysis. We have used the Spatial Landscape Modeling (SPLAM) software for generating fragmentation, porosity and patchiness layers and for final integration of all layers to create the disturbance regime map showing four classes of disturbance that ranged from low to very high (Roy and Tomar, 2000; Roy and Behera, 2002). A user grid cell of 250 m x 250 m was convolved with the spatial data layer to get the fragmentation per unit area. Similarly, patchiness and porosity of major forest classes were calculated following Romme and Knight (1982). Anthropogenic Impact Buffer, Biotic disturbance and forest type-wise TUV grids were combined with the above layers to include the site specific effects of biotic factors. The Anthropogenic Impact Buffer (AI) within the mangrove forest was generated based on field observations of human activities inside the Park and findings of the household surveys. Roads, settlements and aquaculture ponds were digitized on-screen with the help of Survey of India 1:50000 scale toposheets and satellite imagery. These were used as a source for generating a biotic disturbance grid. For this, buffer of 500 m, 1000 m and 1500 m from the point of disturbance were generated and inversely weighted. The TUV calculated for each mangrove class was used to generate a forest type wise TUV grid. These indices were integrated in a systematic manner to derive maps showing disturbance gradient. The Disturbance Index was computed by adopting a linear combination of the defined parameters on the basis of probabilistic weightings following McGarigal and Marks (1995).

$$DI = \text{“} (Frag_i \times Wt_{i1} + Por_{ji} \times Wt_{i2} + AI_i \times Wt_{i3} + BD_i \times Wt_{i4} + TUV_i \times Wt_{i5})$$

where, DI = Disturbance Index, Frag = Fragmentation, Por = Porosity, AI = Anthropogenic Impact Buffer, BD = Biotic Disturbance, TUV = Total Use Value, Wt = Weightages.

ARCGIS 9.0 (ESRI) and ERDAS Imagine 8.7 (Leica Geosystems Geospatial Imaging) software were used for GIS analysis and generation of maps. A simplified flowchart of the approach followed for disturbance regime analysis is given in Fig. 1.

Results

Vegetation and land cover

The area statistics of forest and land cover types as interpreted from the satellite imagery is given in Table 1. The landscape comprised of 22.9% of forest land (mangroves) in two large compact blocks and 72.3%

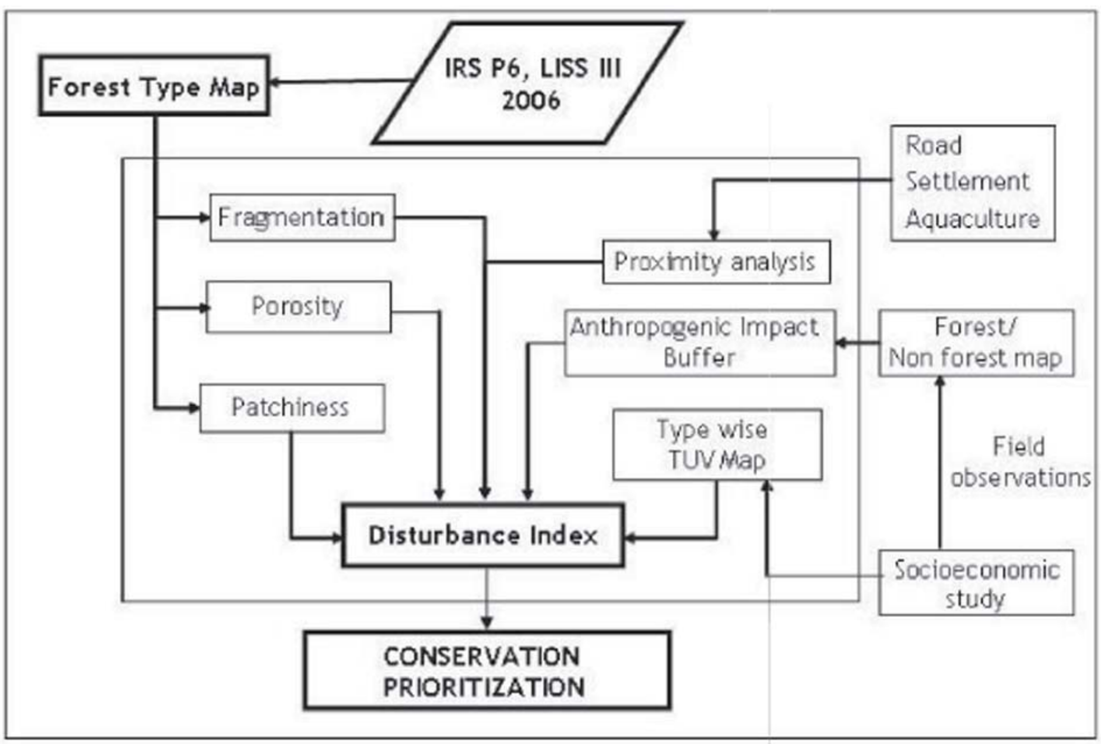

Fig. 1. Approach used for disturbance regime analysis

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matrix comprised private agricultural lands, rivers, sand/barren land, aquaculture ponds and woodland/ tree groves. Interspersed grasslands and water bodies occupied 0.2% and 13.8% area of the landscape, respectively. Thus, the landscape represented a complex of forest-grassland-wetland interspersed with agricultural lands. Five forest classes were identified, namely the 'Mangrove Forests' characterized by *Rhizophora-Avicennia-Sonneratia* formations occurring along the sea or large creeks, the 'Brackish Water Mixed Forest' dominated by *Heritiera fomes, H. littoralis, Excoecaria agallocha, Brugiera parviflora*, the 'Salt Water Mixed Forests', 'Non-Mangrove' and the 'Mangrove Scrub' (Fig. 2). Together they covered an area of 156 km^2. The Brackish Water Mixed Mangroves represented the finest development of the mangrove forests in Bhitarkanika. They formed the major forest class covering 73.8 km^2 or 10.7% of the total sanctuary area. The Salt Water Mixed Forests developed on elevated lands were subjected to lesser freshwater inflows and were dominated by low stands of *E. agallocha, Cynometra ramiflora, H. fomes, Avicennia* spp., *Sonneratia* spp. and *Phoenix paludosa.* An area of 24.4 km^2 of mangrove scrub was identified that was represented by stunted formations of *E. agallocha, Salvadora persica, Avicennia spp*., *Ceriops tagal, Cynometra ramiflora, Lumnitzera* spp.*, Acanthus ilicifolius* among others. *Suaeda* spp., members of the Cyperaceae family, *Porteresia coarctata, Myriostachya wightiana* dominated the Salt Marshes/Mudflats. A patch of 1.24 km^2 in the Bhitarkanika forest block comprised of non-mangrove species such as *Strychnos nux-vomica, Syzygium cuminii, Hibiscus tiliaceus* and *Dalbergia latifolia*. The area is also interspersed with village settlements 2.01% and aquaculture area or village ponds (1.7%).

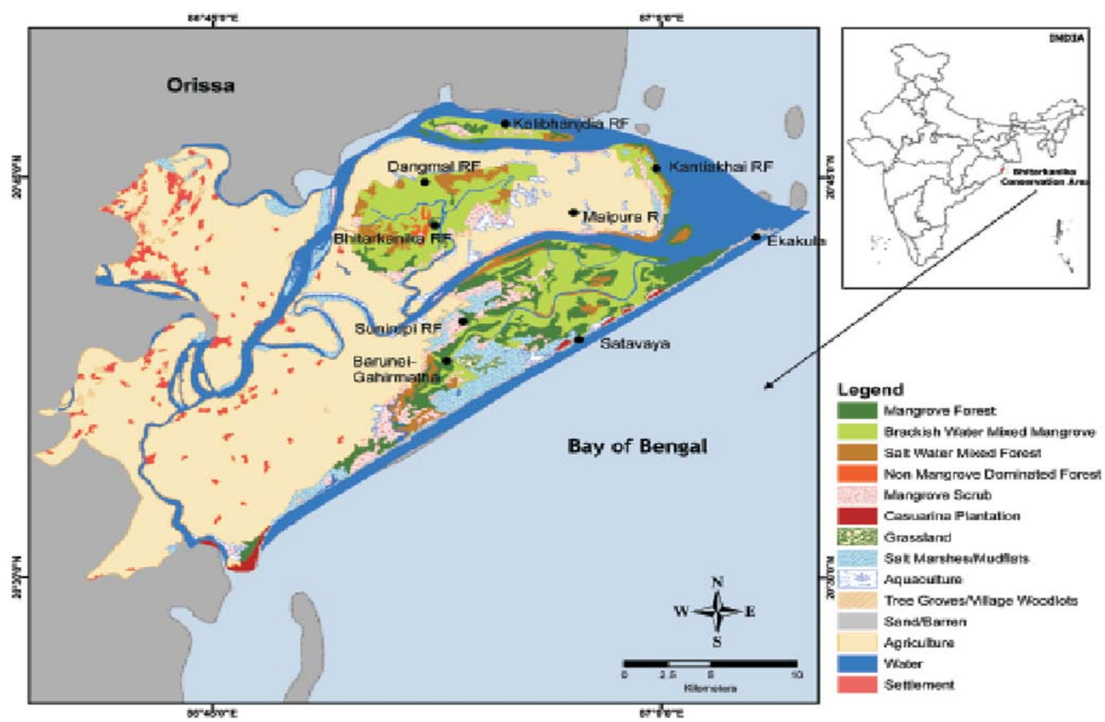

Fig. 2. Vegetation and land cover type map of Bhitarkanika Wildlife Sanctuary, India

Table 1. Vegetation and land cover statistics of Bhitarkanika Conservation Area, India

Vegetation and land cover types	Area (km^2)	% of total area
Mangrove forest	37.77	5.45
Brackish water mixed mangrove	73.83	10.66
Salt water mixed mangrove	18.79	2.71
Non-mangrove	1.24	0.18
Mangrove scrub	24.36	3.52
Casuarina plantation	2.90	0.42
Grassland	1.63	0.24
Salt Marshes/ Mudflats	30.94	4.47
Aquaculture/Ponds	11.78	1.70
Village Woodlot	3.08	0.44
Agriculture	371.95	53.70
Sand/Barren	5.01	0.72
Water	95.37	13.77
Settlement	13.94	2.01
Total	**692.60**	**100.00**

Economic characteristics and resource use

Of the 324 household surveyed, 25% of the population was engaged purely in agricultural activities and 21% also worked as unskilled labourers in this sector while doing their own agriculture. Around 5.6% people were engaged in fishing and 1.5% people were involved in Non Wood Forests Products (NWFPs) collection from the Park, although they were also carrying out some agricultural activities. Around 14% of the people were largely not engaged. The detailed occupational pattern of the sample villages has been summarized in Table 2.

Despite the protected status and a ban on resource extraction, local extractions from the Park were considerable. An average 14% of the total fuel wood consumed in each of the household *i.e.* around 312 kg came from the forests in the form of dead or felled wood collected during the dry season (Table 3). Fuel wood consumption surface showed a consumption of 1460 - 1750 kg $hhld^{-1}$ yr^{-1} in the coastal villages (Fig. 3).

Table 2. Occupational pattern of the respondents (%) of the study villages in Bhitarkanika Conservation Area, India (n = 324 households).

Occupation	Total (%)
Not engaged	13.9
Service	4.3
Business	8.6
Agriculture only	25.0
Agriculture and agriculture labour	20.9
Agriculture and others	7.7
Skilled labour	4.0
Unskilled labour	8.3
Fishing	5.6
Non Wood Forests Product extraction	1.5

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Apart from fuel wood, the other major uses of mangroves were for house construction, NWFP, fisheries, fodder and on much smaller scales for construction of jetties, forest pathways, small gap bridges, boats, fish traps, and mooring poles. The common uses of major tree species are given in the Annexure I. An average of 370 kg $hhld^{-1}$ of wood from this forest had been used in house construction. *P. paludosa* leaves were used as shingles for roofing (Table 3). The use of mangrove wood for construction showed a more uniform distribution over the Sanctuary area as compared to other uses. It was high for the southern parts of the Sanctuary where much of the present vegetation comprised degraded mangrove scrub and tidal mudflats. The coastal villages were largely dependent on mangrove wood for house construction utilizing nearly 1381 - 1652 kg $hhld^{-1}$ (Fig. 3).

The mean annual catch of fish was 98 +28.3 kg from inshore fishing (Table 3). The fishing surface (Fig. 3) showed three major areas of high fishing activity with values ranging from 420-572 kg $hhld^{-1}$ yr^{-1}. Fish catch during low tide sampling using gill nets in the Sanctuary gave results of 3.8 kg hr^{-1} giving a return of US$ 2.25 hr^{-1} (Badola & Hussain, 2003). Commercially important fish and the total fish catch decreased with increasing distance from the mangroves resulting in lesser incomes for the villages situated away from the mangroves.

Disturbance modeling

Disturbance processes are known to transform to a stress process, which reduces biodiversity. The disturbance regime map (Fig. 4) highlights the areas of high disturbance along the coasts and forest edges.

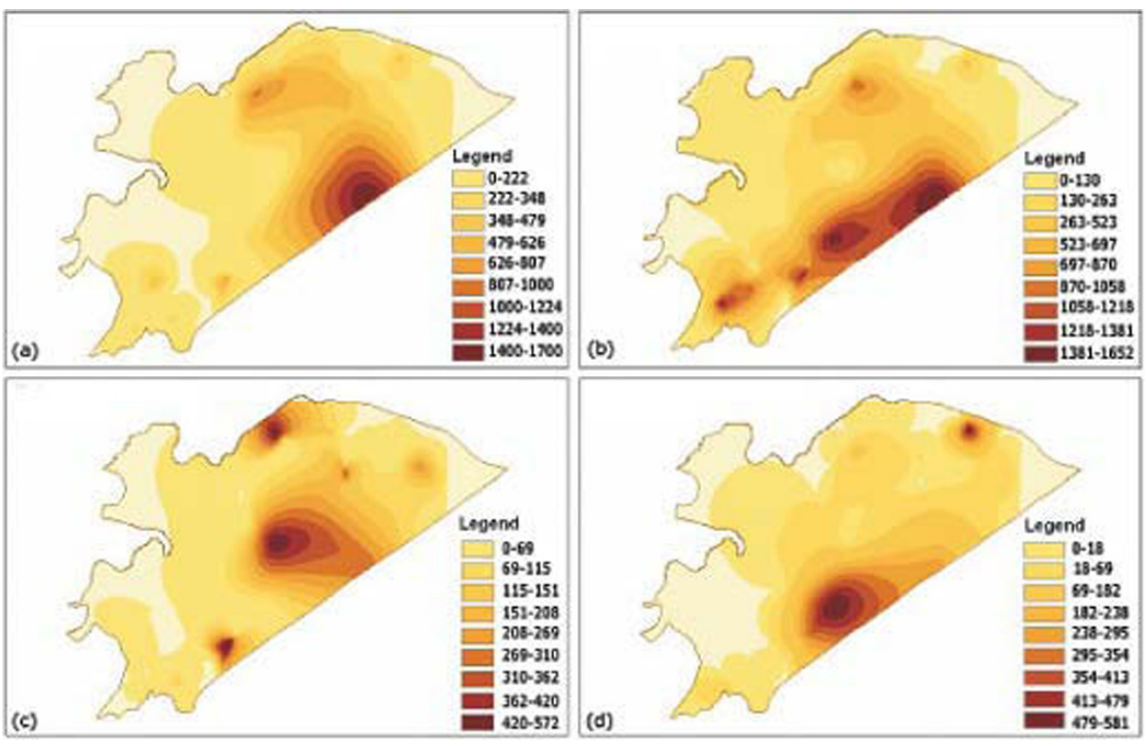

Fig. 3. Surface analysis of household consumption of mangrove resources in villages situated within Bhitarkanika Wildlife Sanctuary, India. (a) Fuel wood (b) Total wood used in house construction (c) Fish products (d) Rafters. All values are in kg.

Table 3. Resource use and dependency of local people in villages located in Bhitarkanika Conservation Area, India (n = 324 households).

Resource use		Mean Quantity (kg/hhld/annum)
Fuel wood	Total consumption of fuel	2205.0 +104.2
	Fuel wood from Park	312.0 +32.2
	Fuel wood from homesteads	21.0 +2.35
	Cow dung, farm refuse, others	1949.0 +375.0
Fish	Fish caught from the Park	98.0 +28.3
Timber	Used as rafters	343.0 +36.9
	As roof supports	27.0 +4.3
Non Wood	Honey	525.0 +239.7
Forests Product	Thatching materials (*Phoenix paludosa*)	49.0 +8.7

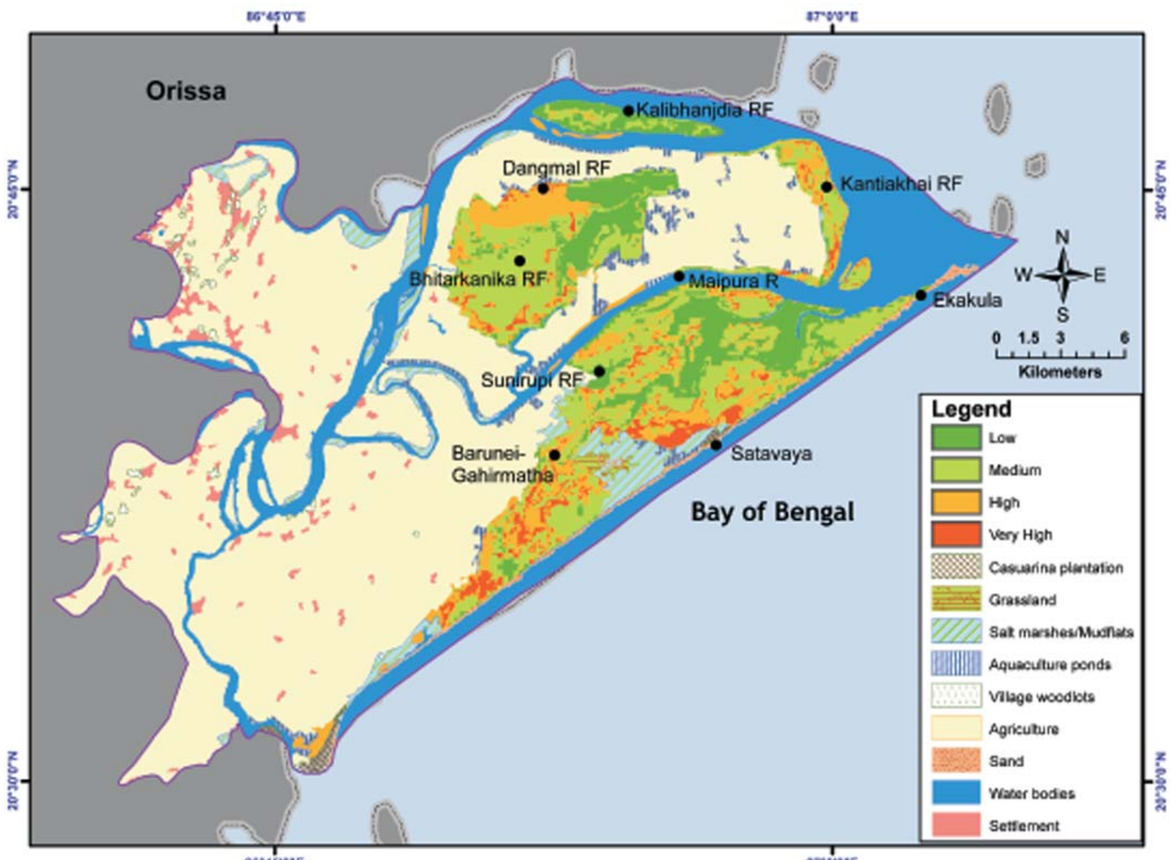

Fig. 4. Disturbance regime map of Bhitarkanika Wildlife Sanctuary, India

Fragmentation and the degree of interspersion of non-forest classes into mangroves was less and hence disturbance was limited to the peripheral areas of the National Park. The mangroves adjoining agricultural matrix generally showed high level of disturbance. Sources of disturbance such as roads, settlements and major creeks included in biotic disturbance grid also determined the disturbance distribution, which was more in the southern region of the Sanctuary. Area distribution of different forest types in various disturbance categories is given in Table 4. 63.3 % area of the vegetation class 'Mangrove Forests' were under high or very high degree of disturbance, followed by the Salt Water Mixed Mangrove Forests (23.1%). Brackish Water Mixed Forests were most extensive in the area but were comparatively less affected except for the outer edges of a few northern forest blocks where they were under very high or high degree of disturbance.

Discussion

Economy and resource dependency

In order to develop and implement effective policy regarding the socioeconomic use of mangrove forests, it is essential that stakeholders have access to accurate and cost-effective techniques for mapping and monitoring mangrove forests. Given that many of these forests are quite large and located in remote areas having experienced rapid changes, various remote sensing techniques were employed to determine their spatial distribution and health (Walters *et al*., 2008). Studies like these provide opportunities for researchers and planners to better understand and improve the management of mangrove forests.

Table 4. Distribution of major forest types in different disturbance regime within Bhitarkanika Conservation Area, India.

Forest types (km^2)	Disturbance regime*			
	Least	Moderate	High	Very High
Mangrove forest	1.5 (4.0)	12.3 (32.65)	15 (39.8)	8.9 (23.5)
Brackish water mixed mangrove	30 (40.6)	31.2 (42.21)	11.1 (15.1)	1 (1.4)
Salt water mixed mangrove	5.3(28.1)	8.9 (47.58)	3.8 (20.2)	0.5 (2.9)
Non-mangrove	0.001 (0.52)	1.2 (96.09)	0 (2.9)	0 (0.5)
Mangrove scrub	1.9 (7.75)	11.3 (46.5)	4.9 (19.9)	2.4 (9.7)
Total	38.7(26.0)	65.0(43.7)	32.3(21.7)	12.8(8.6)

*values in parenthesis give the percent area for each class

Mangrove dwellers have many different socio-economic systems focusing on subsistence activities involving agriculture, fishing and forestry. The way of life of mangrove settlers often involves adaptation to mangrove environmental conditions, and economic exploitation of several distinct ecological zones. The degree and distribution of resource extraction depends on the availability of alternatives, ease of accessibility, levels of protection, markets, roads, human density and forest composition. The mangrove economy studied was primarily agricultural, supporting a population of 379 people/km^{-2}. This was in contrast with other fishery dependent less populated mangrove economies of the tropics such as El Salvador (Gammage, 1997).

The villages situated close to the mangroves had little or no access to other sources and hence they were primarily forest dependent. Although, the Bhitarkanika mangrove forest is protected, the local people living in the Sanctuary area depend on it for forestry and fishery products and often there was indiscriminate resource extraction. Nevertheless, the restrictions enforced have ensured that the fuel wood consumption ratio was low (NSSO, 1997) with crop residues meeting majority of the energy demands (78%). The aggregated values show that 7635 tons of fuel wood was being removed annually from the Sanctuary. Direct consumption of mangrove goods (Saenger *et al*., 1983; Pinto, 1987) was less for second and third distance category villages but they too enjoyed the indirect use values such as greater fish catch. Interestingly, the villages in the second distance category were economically better off than those near to or far off from the mangroves. These villages had households with greater land holdings and income with more number of people employed in business sector. These intermediate category villages enjoyed both the subsistence and commercial benefits of mangroves as accessibility to roads enabled them to market the mangrove products.

In the present study, geospatial analysis has helped in revealing distinctive resource use patterns not quite evident from a distance wise statistical analysis. The coastal villages had poor accessibility to roads and waterways and remained cut off from other areas during the monsoon and there was a heavy dependence on mangrove resources such as fuel wood (1460-1750 kg $hhld^{-1}$ yr^{-1}). Similarly, fish catch was higher in areas near river mouths and mudflats near mangrove forests than in areas without mangroves. The northern parts of Sanctuary showed less consumption of mangrove wood for construction than other areas due to better transport facilities. In the southern parts of the BWS, a few villages which are now devoid of mangrove vegetation and are situated far from the present forest boundaries also showed evidences of wood used from mangrove forests. Since these houses were constructed within last 30 years (Badola and Hussain, 2003) it is a pointer to the presence of mangroves in these areas and the temporal changes that have occurred in the mangrove cover. Since the people are poor and heavily dependent on mangrove forest to meet basic subsistence needs they were often not in a position to be selective in terms of species and size, instead, extract what is most readily available to them (Ewel *et al*., 1998a).

Disturbance - Conservation planning at the landscape level

Native landscapes respond to the cumulative effects of many disturbance regimes. Disturbances, both human-induced and natural, shape forest systems by influencing their composition, structure, and functional processes. A composite measure of disturbance combining the effects of major landscape patterns and processes provides an important component for the design of landscape restoration plans (O'Neill *et al*., 1988; Hardy *et al*., 2001; Hemstrom *et al*., 2001). The disturbance index for BWS comprised forest quality parameters as fragmentation, patchiness, porosity, total use value grid as well parameters for assessing the biotic pressure *viz*. anthropogenic impact buffer and the biotic disturbance grid. The results show that most areas in BWS are affected by human disturbance of varying magnitude. Large areas have been cleared for settlements and now the mangrove vegetation exists in two large isolated patches. Decreasing patch size has resulted in fragmentation of the mangrove habitat and their connectivity. The northern mangrove patch lay isolated surrounded by settlements on all sides. The fringe areas were considerably disturbed particularly in the southern parts due to the presence of the surrounding agricultural land or matrix. Similarly, small patches on the seacoast were highly disturbed. The proximity of forest patches to villages and roads increased their accessibility, and vulnerability to external disturbances with threat to their survival and the supporting biodiversity (Nilsson and Grelsson, 1995). As a result of disturbance, the vegetation in these areas was reduced to low height Salt Water Mixed Mangroves or Mangrove Scrub. Mangroves within Sanctuary with high use value species were under pressure. For example, *H. fomes* is an important economic species of the Brackish Water Mixed Forest and was selectively felled by the villagers. Consequently, this forest type was under high degree of stress in certain areas in the northern and eastern parts.

Mangrove forests must be viewed as part of a complex estuarine system of interrelated habitats and

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dependent biota, which in turn are maintained by natural drainage patterns and rates of freshwater discharge from the catchments on one hand and the natural tidal and salinity regimes on the other (Saenger, 2002). Studies have shown that in most mangrove forests in India, there has been an increase in salinity due to reduction in freshwater inflow and gradual disappearance of less saline-tolerant species such as *A. marina.* Shrubby halophytes as *Suaeda maritime* and *S. monoica* which can tolerate a high and broad range of salinity are becoming dominant (Selvam, 2003). Faulty management practices that blocked several water channels in some of the forest blocks of BWS in the late 1990's led to death of many trees mainly *Heritiera* spp. which is more of a freshwater loving species requiring brackish water inflows for a few days in a month. It is now known that *H. fomes* has completely disappeared from the western parts of the Sundarbans following an eastward shift in course of Ganges due to tectonical movements (Spalding *et al*., 1997) accentuated by the construction of the Farakka barrage in 1971 (Scott, 1989). Much of the southern part of the BWS is at a lower elevation as compared to the northern part. Hence, while the Mangrove Forest dominates the former, the Brackish Water-Mixed forest comprising of species that grow on intermediate grounds has become dominant in the northern part of the BWS. Construction of dykes and settlements have obliterated many of the connections of the northern mangrove patch with the sea and major creeks, restricting tidal circulation and bringing a change in vegetation characteristics.

Conservation implications

Policies that impose protected areas on rural communities with little access to other resources more often have failed to deliver the desired results (Larson *et al.,* 1998; Badola, 2000; Brosius, 2004). As evident from this study, the resource use from the BWS by the local people is *de facto* and indiscriminate. Hence, specific management programs based on resources important to local economies and appropriate legal model comprising conservancies, "land care" groups, multiple-use zones or co-management areas need to be developed (Secretariat of the Convention on Biological Diversity, 2001). The core zone should be maintained as a *sanctum sanctorum* prohibiting all human activities whereas various economic zones can be developed and managed as state and public forest to meet the local livelihood needs. The findings of the study also highlight that the physical accessibility to mangrove forest through roads and boat landing points is a cause of forest use/degradation. Special efforts should be made to curtail such access points through social fencing.

Spatially explicit priorities for the vegetation enhancement activities can be set based on the resource scarce zones. Assisted regeneration would be required at sites with insufficient natural regeneration (Walter *et al*., 2008) particularly sites close to creeks from where mangroves have been extirpated. However, long-term success in mangrove restoration will be determined by the level of support and involvement of local communities (Primavera and Agbayani, 1997; Lewis, 2000; Walters, 2004; Barbier, 2006). In case of the BCA, the mangrove restoration activities need to be carried out particularly in the Sanctuary area, with the involvement of the local people.

There is a need to ensure the connectivity of various mangrove patches through integrated restoration activities. Remote sensing based monitoring systems need to be established for monitoring at large spatial scales combined with high value "indicator" species. Rates of mangrove gradation and degradation resulting from natural cycles of coastal accretion and erosion have been derived using multi-date SPOT satellite data (Fromard *et al*., 2004) and multi-date Landsat data (Cohen and Lara, 2003). Multitemporal satellite data have also been used to quantify the success of mangrove forest recovery (Muttitanon and Tripathi, 2005; Beland *et al*., 2006). Whilst the number of such studies is extremely limited, it has been shown that space-borne SAR can be used in conjunction with optical data or as an alternative in the mapping of mangroves. It can also be used to assess the impact of developmental activities taking in to account the ecological character of mangrove forests through coordinated land-use

Annexure 1: Use values of major plant species of Bhitarkanika Wildlife Sanctuary, India

Species	Timber				Fuelwood	Thatching	Fodder	Oil	Honey	Medicine	Furniture	Boat	Total
	Poles	Rafters & Support	Beams /Bars beams	Conne-ctors									
Heritiera fomes	1	-	-	1	1	-	-	-	-	1	-	-	4
Phoenix paludosa	-	1	-	1	-	1	-	-	-	-	-	-	3
Avicennia spp.	-	-	1	-	1	-	1	-	-	-	-	-	3
Ceriops spp.	-	-	-	1	1	-	-	-	1	-	-	-	3
Tamarix dioca	-	-	-	-	1	-	-	-	-	1	-	-	2
Hibiscus tiliaceus	-	-	-	-	1	-	-	-	-	-	-	-	1
Myriostachya wighitiana	-	-	-	-	-	-	1	-	-	-	1	-	2
Cynometra ramiflora	-	-	1	-	1	-	-	-	-	-	-	-	2
Derris indica	-	-	-	-	1	-	-	1	-	-	-	-	2
Sonneratia spp.	-	-	-	-	-	-	-	-	1	-	-	-	1
Aegiceras coniculatum	-	-	-	-	-	-	-	-	1	-	-	-	1
Amoora cucullata	-	-	-	-	-	-	-	-	1	-	-	-	1
Strychnos nux-vomica	-	-	-	-	-	-	-	-	-	1	-	-	1
Excoecaria agallocha	-	-	-	-	1	-	-	-	-	1	-	-	2
Xylocarpus granatum	-	-	-	-	-	-	-	-	-	1	-	-	1
Xylocarpus moluccensis	-	-	1	-	-	-	-	-	-	-	1	1	3
Instia bijuga	-	-	1	-	-	-	-	-	-	-	1	-	2

planning (Wilkie *et al*., 2000) and by including non-spatial attributes (Chen and Twilley, 1998) to predict the response of mangroves to perturbations.

Acknowledgements Funding for this research was provided under the Indian Environment Management Capacity Building (EMCaB) Project of IGIDR, Mumbai. We thank the Chief Wildlife Warden, Orissa and Anup Nayak, Divisional Forest Officer, Mangrove Forest Division, Rajanagar for extending necessary permission and support for carrying out the field research. We would like to thank the Director and the Dean, Wildlife Institute of India for extending their support for this project.

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