Environmental Management (2009) 44:853–864
DOI 10.1007/s00267-009-9374-9

PROFILE

Landscapes of Protection: Forest Change and Fragmentation in Northern West Bengal, India

Harini Nagendra · Somajita Paul · Sajid Pareeth · Sugato Dutt

Received: 21 August 2008 / Accepted: 29 August 2009 / Published online: 24 September 2009

Abstract In the tropics and sub-tropics, where high levels of biodiversity co-exist with some of the greatest levels of population density, achieving complete exclusion in protected area contexts has proved close to impossible. There is a clear need to recognize that parks are significantly impacted by human–environment interactions in the larger landscape within which they are embedded, and to move the frontier of research beyond the boundaries of protected areas in order to examine larger landscapes where multiple forms of ownership and access are embedded. This research evaluates forest change and fragmentation between 1990 and 2000, in a landscape surrounding the Mahananda Wildlife Sanctuary in the Indian state of West Bengal. This protected forest is bounded to the south by a less intensively protected area, the Baikunthapur Reserve Forest, and surrounded by a mosaic of unprotected, largely private land holdings. Results indicate differences in the extent and spatial pattern of forest cover change in these three zones, corresponding to different levels of government protection, access and monitoring. The two protected areas experience a trend toward forest regrowth, relating to the cessation of commercial logging by park management during this period. Yet, there is still substantial clearing toward peripheral areas that are well connected to illegal timber markets by transportation networks. The surrounding landscape, although experiencing some forest regrowth within less intensively cultivated tea plantations, is also becoming increasingly fragmented, with potentially critical impacts on the maintenance of effective wildlife corridors in this ecologically critical region.

Keywords Land cover change · Protected areas · Fragmentation · Remote sensing

H. Nagendra (✉)
Center for the Study of Institutions, Population, and Environmental Change (CIPEC), Indiana University, 408 North Indiana Avenue, Bloomington, IN 47408, USA
e-mail: nagendra@indiana.edu

H. Nagendra · S. Paul · S. Pareeth
Ashoka Trust for Research in Ecology and the Environment (ATREE), Bangalore, Karnataka, India

S. Dutt
Department of Geography, University of Hawaii, Honolulu, HI, USA

Introduction

From scattered attempts to institutionalize government control over forest lands in the 18th century, protected areas have now become a cornerstone of conservation efforts worldwide. Current estimates indicate that over 100,000 protected areas were in existence by 2003, protecting an area of 18,763,407 km^2 or 11.5% of the earth's land surface—at least on paper (Rodrigues and others 2004; Naughton-Treves and others 2005). While the majority of these protected areas attempt to limit forest clearing by access and harvest restrictions that are imposed by national governments, several of these parks have been established in areas where local communities co-exist with forests, and are dependent on resources derived from these areas. In such contexts, achieving complete protection has proved close to impossible, and has led to repeated conflicts between park authorities and local communities (Schwartzman and others 2000; Terborgh and others 2002; Chapin 2004).

Such conflicts seem to be particularly acute in the tropics and sub-tropics, where high levels of biodiversity co-exist with some of the greatest levels of population density

(Cincotta and Engelman 2000). South Asia provides a particularly illustrative example of park–people interactions and conflicts, with highly biodiverse landscapes that have been settled for centuries. There is increasing awareness of the social consequences of creating protected areas in such landscapes, when local inhabitants are prevented from accessing forest resources that form part of their cultural, social and institutional interactions with nature (Bawa and others 2004). Yet, equally valid concerns have been raised about increasing habitat fragmentation and species loss in areas where local communities coexist with protected areas (Shahabuddin and Rangarajan 2007). In India, tensions between conservation and development have been increasingly acute in recent years. Between 1975 and 1998, the number of national parks in India increased from 5 to 85, and the number of wildlife sanctuaries increased from 126 to 448. The majority of these "new" protected areas were created from former reserve forest areas by upgrading the status of their protection, resulting in a redrawing of protected area boundaries across India. Most areas set aside for protection therefore contain settlements located adjacent to, or within their boundaries, and these communities find themselves subject to strict restrictions on the extraction of forest products (Madhusudhan 2005; Shahabuddin and Rangarajan 2007).

Remote sensing, when combined with spatial analysis techniques such as Geographic Information Systems, and landscape fragmentation studies, provides a particularly effective tool for analyses of forest change in such human-dominated contexts (Fox and others 2003; Southworth and others 2006). A combination of these approaches has been increasingly found useful to analyze human incentives and actions, and explore biophysical, institutional and social impacts on landscape change and fragmentation (Liverman and others 1998; Fox and others 2003; Moran and Ostrom 2005; Ostrom and Nagendra 2006). Human pressure on land use is increasing in the unprotected landscapes that surround many protected areas across the world (Hansen and DeFries 2007). Even when land cover within protected areas remains unaffected, changes in the surrounding landscape can significantly impact ecological processes within the protected area, by changing ecosystem size, altering flows of species and energy into and outside the park, and providing increased exposure to human-impacted, high disturbance edge areas.

Thus, it is becoming increasingly clear that most parks do not, and cannot represent sacred, inviolable spaces within which conservation can achieve utopian possibilities, but rather, that parks are embedded in landscapes of change—and the patterns and processes of land cover change within parks will be a function of the larger socioeconomic, institutional, cultural and biophysical landscape within which they are embedded (DeFries and others 2005, 2007; Southworth and others 2006). There is thus a clear need to move the frontier of research beyond the boundaries of protected areas in order to examine larger landscapes where multiple forms of ownership and access are embedded (Munroe and others 2007; Robbins and others 2007). This will enable us to derive a broader understanding of when and why deforestation and regrowth occur in specific regions within these larger landscapes (Ostrom and Nagendra 2006).

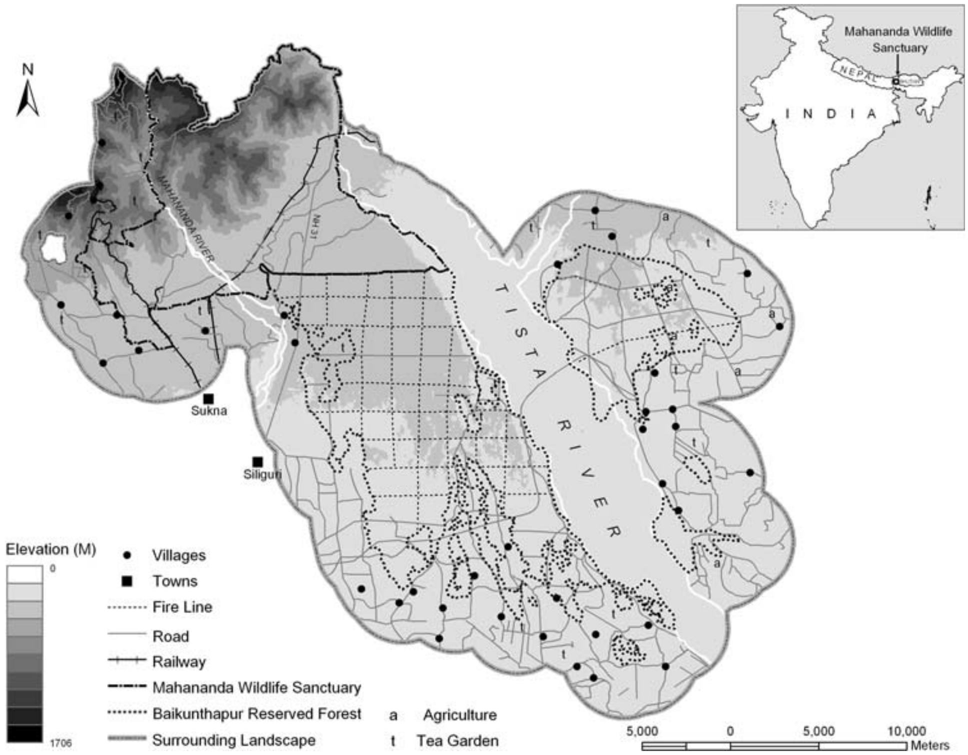
Comparisons of the rates of land cover clearing within a protected area's boundaries to rates of clearing in a comparable area located outside the protected area is a strategy that can provide useful insights (DeFries and others 2005; Nepstad and others 2005; Naughton-Treves and others 2005; Nagendra 2008). This will enable us to extend the study of land cover change within protected areas to examination of park-embedded landscapes, and to understand when and why effective forest protection, clearing and regrowth occur in different regions of a landscape (Ostrom and Nagendra 2006; Robbins and others 2007; Nagendra 2008). We adopt this strategy to evaluate forest change and fragmentation in a landscape surrounding the Mahananda Wildlife Sanctuary (MWS) in the Indian state of West Bengal. This area is bounded to the south by a less intensively protected area, the Baikunthapur Reserve Forest (BRF), and surrounded by a mosaic of unprotected, largely private land holdings. It thus provides an interesting context to evaluate the impact of different levels of protection on land cover change and forest fragmentation over time. Our objectives are to evaluate the extent and spatial pattern of forest cover change in these three different zones, which correspond to different levels of government protection, access and monitoring.

Study Area

Located at the foothills of the eastern Himalayas, the majority of the West Bengal state's network of protected areas is located in a narrow strip extending between Nepal and Bhutan. These forests harbor a rich diversity of plant and animal species, including several endemic and threatened species. Despite the critical location of these forested habitats, and their importance for biological conservation, little is known about the extent of change in land cover, levels of fragmentation, or the drivers of change in this region (Shankar 2001).

Figure 1 depicts the study area, with the Mahananda Wildlife Sanctuary (MWS) to the north, and the Baikunthapur Reserve Forest (BRF) to the south. The MWS is located in the southern part of the Darjeeling district of West Bengal. This area was declared a wildlife sanctuary in 1976, and enlarged in 1988 (Wildlife Circle 1997). The

Fig. 1 Study area



MWS extends between an elevation of 350 to 1500 m above sea level, and is located along the foothills of the Himalayas, with mixed evergreen and deciduous forest cover on the steep northern side, sloping down to gentle, almost flat stretches of the Terai dominated by *Shorea robusta* (sal) and grassy alluvial plains, to the south (Wildlife Circle 1997; Shankar 2001). The forested habitat within the sanctuary harbors a rich diversity of flora and fauna, and forms the largest compact block of forest at the western end of the elephant migration route in this region. Substantial portions of the park, especially in the riverine plains and foothills, were maintained for commercial timber extraction uptil the early 1990s, although the core area and hilly slopes were protected from timber extraction. After this period, various forest regulations including the National Forest Policy of 1988, and the subsequently passed Tree Felling Act and Supreme Court Orders of 1996 curtailed tree felling and fuelwood extraction within the sanctuary (Indian Institute of Forest Management, Bhopal 2001).

The sanctuary is surrounded by tea garden settlements and villages on all sides except the northern boundary (Das and Guha 2003). With several of the tea estates being poorly maintained in recent years, residents often supplement their income by illegal firewood and timber collection and cattle grazing in the forest (Wildlife Circle 1997; North Eastern Society for Preservation of Nature, Wildlife 2000). The non-tea garden settlements, mostly located toward the south-western and western parts of the MWS, are primarily agricultural, and also depend on the forest for fuelwood, timber and cattle grazing. The main entry point into the sanctuary is via Sukna, a small village located at the south-western end of the sanctuary. Along with the metre-gauge railway line to Assam which passes through the center of the sanctuary, the national highway 31 and the Darjeeling-Siliguri road provide access to the forests of this region. An extensive network of smaller roads in the areas outside the sanctuary provide easy access for the transport of illegally extracted timber outside the sanctuary to the furniture shops, sawmills, markets and urban centers located in Siliguri (North Eastern Society for Preservation of Nature, Wildlife 2000).

To the south is located the Baikunthapur Reserve Forest (BRF), another government protected area but assigned to a lower category of protection as compared to wildlife sanctuaries. The Baikunthapur Forest was formerly under private ownership, and the Forest Department took over its management and protection completely in 1961 (Ray 1996—in Chakrabarti and others 2002a). This area was originally extensively covered by sal dominated forests, but large plantations of teak and sal were raised in the early 1960s by the Forest Department (Chakrabarti and others 2002a, b). The BRF is located on primarily flat land, and is well connected to adjacent settlements and towns by an extensive road network. It is surrounded by agricultural, forest dependent settlements.

Population pressures have increased in this area over time. While the population of Darjeeling district had a decadal growth rate of 23.8% from 1990 to 2000, the Siliguri urban agglomeration (the urban agglomeration closest to Mahananda) has experienced much higher growth rates during the same time period, 31.2% (Government of India 1992, 2001). Siliguri and its surrounding areas have turned into a major regional trade center in the recent decades following large scale in-migration into this region from the north-eastern Indian states and from neighboring countries. Despite regular patrolling by Forest Department guards armed with guns, and a network of electric fences, illegal harvesting of timber continues, as attested by the large numbers of bicycles and trucks confiscated from these areas by forest guards (Ostrom and Nagendra 2006).

Methods

Satellite Image Classification

An assessment of land cover change between 1990 and 2000 was conducted using Landsat TM satellite imagery from November 1990, and Landsat ETM + imagery from December 2000. Both images were from the season following the rains, which enables us to ensure that the images are completely cloud free, and also allow us to differentiate forest from fallow agriculture with a greater degree of accuracy. Images were downloaded from the Global Land Cover Facility site hosted by the University of Maryland (http://glcfapp.umiacs.umd.edu). All image processing was carried out using the ERDAS Imagine™ image processing software.

The 1990 image was georeferenced to three 1:50,000 scale Survey of India topographic maps covering our area of interest, using the nearest neighbor resampling algorithm (Jensen 2000). The 2000 image was then georeferenced using the registered 1990 image as a base. Care was taken to ensure that the RMS error of image-to-image coregistration was less than 0.5 pixels (15 m). Finally, an overlay function and careful visual comparisons were used to verify that the images overlapped exactly across both image dates, and that there were no sliver areas of misregistration (Jensen 2000). This is essential to ensure that changes observed from year to year are a result of actual land cover change and not compounded by errors in co-registration.

Training information collected extensively during field visits in May–June 2004, April–May 2005, and July 2006 was used to conduct a supervised classification of images into three land-cover classes: dense forest, open forest and nonforest. Nonforest includes areas of agriculture, grassland, tea plantations, water bodies and village settlements, which were classified separately and subsequently combined into one category in order to enable us to focus on changes in the forested areas, the main objective of this research. The locations of training sites were recorded using a Global Positioning System. As positional accuracies in these mountainous areas were poor, we used large training areas of at least 3–4 hectares in size for training the classification, and collected GPS readings in the center of these large areas. Over 200 training sites were used for classification, distributed across different land cover classes in proportion to the area covered by different classes. Classification accuracy of the 2000 image was subsequently verified using an independent dataset, deriving a producer's accuracy of 88% (Table 1, Kappa = 0.81). The 1990 image was classified using information obtained in the field from interviews with people, about the distribution of land cover during that time, with a producer's accuracy of 91% (Table 2, Kappa = 0.86).

Land Cover Change Analysis

Following the creation of individual land cover classifications for 1990 and 2000, this information was combined to provide a single image that identified change trajectories, or sequences of land cover classes for both observation dates (Petit and others 2001). The output is a categorical "change image", where each pixel now includes information on land cover for both dates. Given an initial input of two images, each with three land cover categories, the output change image consists of nine possible change trajectories (i.e., combinations of land cover on two dates). For instance, nonforest–nonforest indicates a pixel of land cover that was devoid of forest cover on both image dates. In order to further simplify the interpretation of the patterns

Table 1 Accuracy assessment for 2000 classified image

Reference class	Satellite map class				
	Dense forest	Open forest	Non-forest	Row total	Producer's accuracy (%)
Dense forest	26	1	3	30	86.7
Open forest	1	16	3	20	80.0
Non-forest	0	2	31	33	93.9
Column total	27	19	37	$n = 83$	
User's accuracy (%)	96.3	84.2	83.4		

Overall producer's accuracy = 88.0%; Kappa = 0.81

Table 2 Accuracy assessment for 1990 classified image

Reference class	Satellite map class				
	Dense forest	Open forest	Non-forest	Row total	Producer's accuracy (%)
Dense forest	13	1	2	16	81.3
Open forest	0	13	2	15	86.7
Non-forest	0	0	26	26	100.0
Column total	13	14	30	$n = 57$	
User's accuracy (%)	100.0	92.9	86.7		

Overall producer's accuracy = 91.2%; Kappa = 0.86

of land cover change, we collapsed these 9 change trajectories into 4 categories. Following Peralta and Mather (2000), pixels that underwent change from nonforest to open forest, nonforest to closed forest and open forest to closed forest were combined and treated as "reforestation". Pixels that changed from closed forest to open forest, closed forest to nonforest and open forest to nonforest were combined as "deforestation". Pixels that remained open forest, or closed forest in both years, were considered "stable forest". Finally, pixels that remained nonforest in both 1990 and 2000 were considered "stable nonforest".

The accuracy of the 1990–2000 change image was assessed using field data on land cover in both 1990 and 2000 for a set of 65 points located on both images, with a producer's accuracy of 86% (Table 3, Kappa = 0.81).

Partitioning the Landscape

The primary objective of this research was to understand the impact of different levels of protection on land cover change. Toward this, we compared land cover change within the MWS with changes in the BRF, and the adjacent surrounding landscape. Information provided by the West Bengal Forest Department was used to identify and digitize spatial boundaries of these two protected areas. We then used these boundaries to segment the landscape into zones subject to different levels of protection over time, in order to associate them with measures of land cover change and landscape fragmentation.

These divisions were used to subset the raster classified images (1990, 2000) and the change trajectory image (1990–2000). These image subsets were analyzed independently in terms of land cover change and landscape pattern, in order to determine the influence of protected area management and policy within different regions of the study landscape. In addition, a buffer region was created that extended 3 km beyond the MWS and BRF polygons. This allowed for a comparison of land cover change within the two protected areas, to change in the surrounding landscape. This enables us to compare the extent and spatial pattern of land cover change within MWS and BRF to the broader context of land cover change within the region. The choice of the buffer distance (3 km) was made keeping in account the need to compare a similar extent of area in the unprotected surrounding landscape with the area covered by the two protected forests. This follows approaches frequently adopted for research in other protected areas (Nagendra 2008).

Landscape Fragmentation

In addition to information on the extent of land cover change in each study zone, evaluating the patterns of land cover distribution can provide us with critical insights on the processes impacting land cover change (Rindfuss and others 2004). Integrating information on location, extent and pattern of land cover change will enable us to evaluate the long term impacts of park management strategies on forest cover and forest fragmentation—both critical indicators of the park's success. We utilized the software Fragstats 3.3 for this purpose, as it provides a powerful and comprehensive set of descriptors of spatial pattern at the

Table 3 Accuracy assessment for 1990–2000 change image

Reference class	Satellite map class					
	Stable forest	Stable non-forest	Reforestation	Deforestation	Row total	Producer's accuracy (%)
Stable forest	17	0	1	0	18	94.4
Stable non-forest	0	17	4	0	21	81.0
Reforestation	3	0	13	0	16	81.3
Deforestation	1	0	0	9	10	90.0
Column total	21	17	18	9	$n = 65$	
User's accuracy (%)	81.0	100.0	72.2	100.0		

Overall producer's accuracy = 86.2%; Kappa = 0.81

landscape, class and patch levels (McGarigal and others 2002). Patches are spatially discontiguous units of different land cover categories—so, for instance, one patch of forest may be large and cover several hectares in area, while another patch may be smaller than a hectare. Patch descriptors contain information about all patches in a given land cover category, and provide information about intra category distribution and variability. Classes correspond to classes of land cover or trajectories of land cover. Class statistics summarize information at the level of a single land cover class or change category, such as a forest class, or a deforestation trajectory, and enable comparisons across different groups. Since several of these metrics are partially or wholly redundant (Haines-Young and Chopping 1996), we selected a sub-set of indicators at the patch and class level that helped in assessing fragmentation at this scale.

At the patch scale, we selected two indicators: patch size (area in hectares), and the nearest neighbor index (the nearest edge-edge distance in meters between a patch and its nearest neighbor of the same category)—as quantifying distinct aspects of patch structure (Forman 1995; Haines-Young and Chopping 1996; McGarigal and others 2002). We used one-tailed Mann–Whitney *U* Tests (Sokal and Rohlf 1981) to assess whether these patch attributes differed significantly ($P = 0.05$) for the same land cover change category, across zones with different levels of protection (MWS, BRF and the surrounding landscape).

At the class level, we wished to compare patterns of land cover change across zones using descriptive summary metrics of change. These metrics can be grouped into categories of area, shape, core, diversity, and contagion/interspersion (Haines-Young and Chopping 1996). To simplify interpretation, the following indices were considered, as believed to quantify different aspects of structure (Haines-Young and Chopping 1996; McGarigal and others 2002):

a) Mean size: average patch area for the class, in hectares.
b) Mean shape index: measures the average complexity for a category, of patch shape, compared to a square patch of identical area. For a single patch, the shape index is 1 when square, and increases without limit as the patch becomes more irregular.
c) Mean nearest neighbor distance: average nearest neighbor distance in meters for all patches belonging to the class.
d) Patch density: number of patches per hectare.
e) Clumpy: Measures the extent to which the habitat is aggregated, by comparing the values observed with those expected under a spatially random distribution, and takes values from -1 to 1.
f) Interspersion-juxtaposition index: measures the degree of interspersion of patches of this class, with all other categories. This index takes values from 0 to 100, decreasing as the distribution of patch adjacencies among types becomes increasingly uneven.

The indices of patch density and mean size correspond to area/density/edge metrics, and provide indications of the degree of fragmentation for different land cover change trajectories. The mean shape index is a metric of shape, the mean nearest neighbor distance an indicator of proximity or isolation, and the clumpiness and interspersion-juxtaposition index measure the contagion and interspersion of pixels in the landscape. Complete descriptions of these metrics, and equations for their calculation, are provided in McGarigal and others (2002). These indices were compared to evaluate if they differed across different landscape change categories, and across the MWS, the BRF and the surrounding landscape, with different levels of protection.

Results

Extent of Land Cover Change

The accuracies obtained for the 2000 classification (producer's accuracy 88%) and the 1990 classification (producer's accuracy 91%) indicate the reliability of these land cover maps. The accuracies achieved are well above the targets set by Thomlinson and others (1999), which indicate that overall accuracy levels should be at least 85%, with no class having a users' or producers' accuracy that is less than 70%. In addition, a separate analysis of the accuracy of the change image demonstrated its' accuracy to be greater than 86%, again with all classes having accuracies above 70%.

Table 4 describes the extent of forested and non-forested land cover in the MWS, BRF and surrounding landscape during 1990 and 2000. As a percentage, most of the area in the MWS and the BRF is covered by open or dense forest in 1990, while the surrounding landscape is dominated by nonforest. A similar pattern is observed in 2000, however, with an increase in dense forest cover across all three zones. In the MWS, this increase appears particularly dramatic with dense forest cover increasing from 57.9% of the landscape in 1990, to 75.1% in 2000—while in the BRF the increase is from 49.2% of the landscape in 1990, to 52.2% in 2000. Interestingly, while dense forest cover decreases in the surrounding landscape during the same time period, there is a large increase in the area under open forest cover in this zone, from 4.8 to 12.3%.

This data describes forest cover in each year, and may create a somewhat more static impression than is the

Table 4 Percentage of area occupied by land cover classes in 1990 and 2000; and by land cover change trajectories between 1990 and 2000, for different zones of protection within the landscape

Date	Land cover type	Mahananda Wildlife Sanctuary (%)	Baikunthapur Forest Reserve (%)	Surrounding Landscape (%)
1990	Dense Forest	57.9	49.2	2.6
	Open Forest	15.9	22.6	4.8
	Non-forest	26.2	28.2	92.6
2000	Dense Forest	75.1	52.2	4.3
	Open Forest	8.6	19.4	12.3
	Non-forest	16.3	28.4	83.4
1990–2000 change analysis	Stable Forest	50.2	43.3	3.2
	Stable Non-forest	9.2	18.6	80.0
	Deforestation	10.7	17.0	3.7
	Reforestation	29.9	21.1	13.1

case. A constant amount of overall forest cover may mask significant ongoing deforestation, if balanced by an equal amount of reforestation in other parts of the landscape (Nagendra and others 2003). It is therefore necessary to conduct an analysis of land cover change trajectories, to examine change over time in greater detail. Table 4 also describes the area occupied by the four change categories of stable forest, reforestation, deforestation and stable non-forest, between 1990 and 2000, for the MWS, BRF and the surrounding landscape. Clearly, the overall landscape is experiencing a trend toward regrowth, with more regrowth compared to deforestation in all zones. The area within the surrounding landscape appears relatively stable, with 83% of the landscape distributed between stable forest and stable non-forest categories. In contrast, the MWS and BRF have experienced substantial change, with 41% and 38% of the landscape in these zones experiencing some form of change (deforestation or reforestation) during this time period. There is much greater reforestation taking place compared to deforestation, with most regrowth occurring within MWS, followed by BRF and finally the surrounding landscape—although the net trend is in the direction of regrowth across all zones.

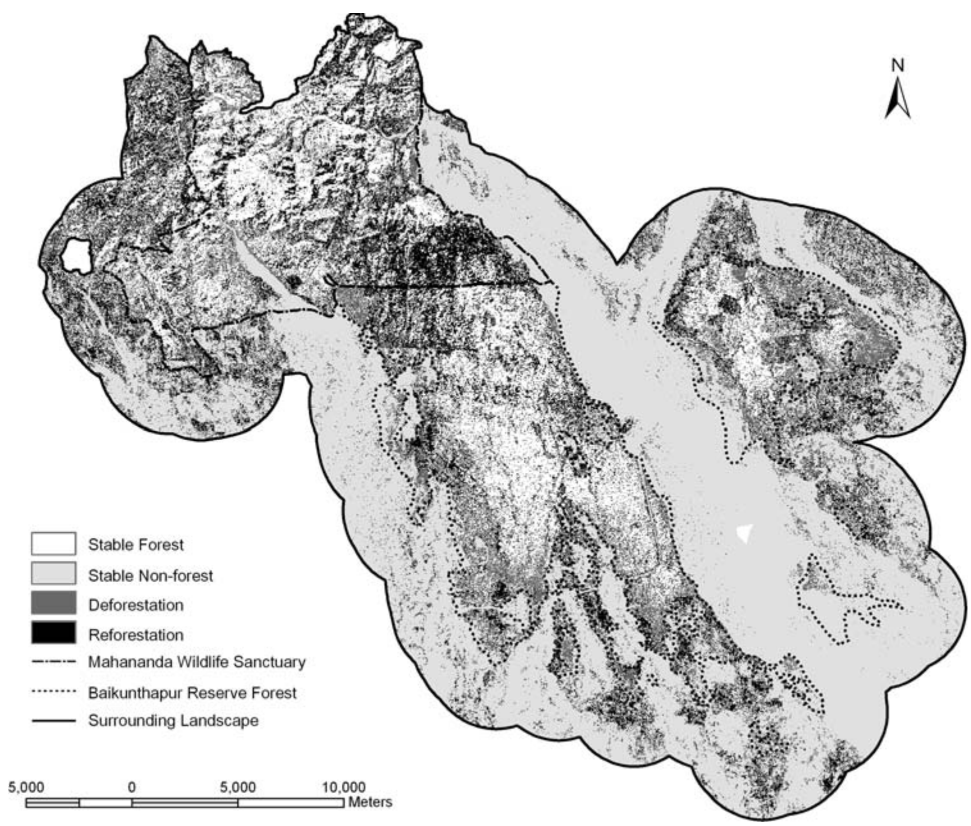


Fig. 2 Land cover change trajectories, 1990–2000

Spatial Patterns of Change

Visual observations of Fig. 2 demonstrates that most of the stable nonforest area occurs in the unprotected area in the surrounding landscape. While there is some regrowth in this landscape, much of it appears to have taken place in the areas to the north of the MWS, where there shade grown tea gardens in the hills (Fig. 1). These tea areas are no longer cultivated as extensively as they used to be in the 1990s, while these areas are protected from tree felling due to their steep topography and relative inaccessibility. Consequently, substantial regrowth of tree canopy cover can be observed here. The BRF appears to have experienced substantial deforestation. Spatially, most of this has taken place in the areas near the boundary, which are more easily accessible, as well as toward the south, where the forest is surrounded by densely populated villages and towns, and well connected road networks. There is also a great deal of reforestation within the BRF boundaries, particularly to the north, largely indicating areas of former commercial logging which have now been discontinued.

In the MWS, large patches of stable forest to the north indicate the impact of protection, as well as of the steep topography of the northern section of this protected area (see also Fig. 1), which provides some protection from large scale timber extraction. There is some deforestation observed, but this appears to be mostly in small patches along the rivers, major roads and railways, and in areas of very steep slopes where landslide scars can be clearly observed in the field. Substantial regrowth is also observed in this protected area, especially in the less hilly southern sections. This indicates areas where commercial timber extraction was formerly prevalent but discontinued during the early to mid-1990s, enabling the forest to regenerate.

Differences in forest fragmentation were observed between land cover change categories (Table 5). Stable forest cover appeared most fragmented in the surrounding landscape, with the smallest mean patch area, lowest values of the mean shape index, highest patch density, located farthest apart (highest mean nearest neighbor distance), lowest values of clumpiness and highest values of interspersion. In contrast, stable forest cover was the least fragmented in the MWS, taking intermediate values in the BRF. Stable non-forest followed an opposite trend, appearing most fragmented in the MWS, and most connected with the largest patches in the surrounding landscape. Patches of deforestation followed the pattern observed for stable non-forested patches, with the largest

Table 5 Summary table for class metrics for the change image

	Land cover change category	Mahananda Wildlife sanctuary	Baikunthapur Reserve forest	Surrounding landscape
Mean patch size (ha)	Stable forest	4.2611	2.7411	0.3703
	Stable non-forest	0.5157	1.4505	16.8044
	Deforestation	0.2542	0.4347	0.2545
	Reforestation	1.3843	0.6007	0.6793
Mean shape index	Stable forest	1.2869	1.293	1.1341
	Stable non-forest	1.151	1.2307	1.281
	Deforestation	1.1508	1.1963	1.1411
	Reforestation	1.3244	1.2462	1.2575
Mean NND	Stable forest	67.3154	69.7406	103.504
	Stable non-forest	88.7717	86.9989	66.1531
	Deforestation	76.737	73.7384	92.4271
	Reforestation	72.0619	72.1174	81.0778
Patch density (per ha)	Stable forest	0.7179	1.3849	1.8141
	Stable non-forest	1.089	1.1205	0.9926
	Deforestation	2.5665	3.4164	3.0263
	Reforestation	1.3159	3.081	4.003
Clumpy	Stable forest	0.723	0.6853	0.4492
	Stable non-forest	0.5872	0.7221	0.8809
	Deforestation	0.2757	0.4137	0.2921
	Reforestation	0.5877	0.4508	0.4433
IJI	Stable forest	63.7815	64.9169	86.2758
	Stable non-forest	75.9821	89.5685	65.5632
	Deforestation	63.3465	71.2076	77.3651
	Reforestation	67.9682	76.1153	51.6888

Table 6 Results of one tailed Mann–Whitney *U* test to determine differences in fragmentation at the patch level across different zones of protection, for different land cover change trajectories

	MWS vs. BRF	MWS vs. SL	BRF vs. SL
Stable forest			
Patch area	MWS < BRF	MWS > SL[a]	BRF > SL[a]
Nearest neighbor distance	MWS < BRF	MWS < SL[a]	BRF < SL[a]
Stable non-forest			
Patch area	MWS < BRF[a]	MWS < SL[a]	BRF < SL[a]
Nearest neighbor distance	MWS > BRF[a]	MWS > SL[a]	BRF > SL[a]
Deforestation			
Patch area	MWS < BRF[a]	MWS < SL[a]	BRF < SL[a]
Nearest neighbor distance	MWS > BRF[a]	MWS < SL[a]	BRF < SL[a]
Reforestation			
Patch area	MWS > BRF[a]	MWS > SL[a]	BRF > SL[a]
Nearest neighbor distance	MWS > BRF	MWS < SL[a]	BRF < SL[a]

[a] Significant at $P < 0.01$

and most connected patches of deforestation observed in the surrounding landscape, followed by the BRF, and finally with the smallest, patches of deforestation observed in the MWS. Again, reforestation followed an opposite trend, with patches of regrowth being largest in MWS, and smallest in the surrounding landscape.

A one-tailed Mann–Whitney *U* test was used to analyze differences in statistics of patch pattern for different zones of protection, across different land cover change trajectories (Table 6). For stable forest patches, no significant differences are observed in statistics of patch pattern (patch size and nearest neighbor distance) between the MWS and the BRF. Stable forest patches in the surrounding landscape are, however, much more fragmented compared to both protected areas, with significantly smaller patch sizes and greater inter-patch nearest neighbor distances. Stable non-forest patches are largest and closest together in the surrounding landscape, followed by the BRF, and finally the MWS where they are most fragmented. Patches of deforestation are largest in the surrounding landscape, and smallest within the MWS, while patches of reforestation follow an opposite trend, being largest in the MWS and smallest in the surrounding landscape.

Discussion

The Mahananda Wildlife Sanctuary is located in a highly fertile alluvial forest belt toward north-eastern India, and harbors a rich diversity of animal and plant species including endemic and threatened species. Given the location of this protected area in a region of dense human settlements, it is subject to a high degree of human disturbance, which has given rise to a forested protected area that is becoming increasingly isolated, and embedded in a fragmented landscape of tea plantations, agriculture, and human settlements. Our analysis addresses whether the park has experienced distinct patterns of land cover change and forest fragmentation as compared to a less intensively protected reserve forest, and a largely unprotected surrounding landscape. Such studies are integral to determining the effect of park establishment on degradation, by placing it within the context of larger changes at an ecosystem or landscape scale within which specific protected areas are embedded (Ostrom and Nagendra 2006; DeFries and others 2007; Robbins and others 2007; Nagendra 2008).

Our results indicate the landscape as a whole is experiencing a trend toward forest regrowth. There are two major reasons for the increase in tree cover. Within the MWS and the BRF this regrowth can be attributed to changes in park management policy in the early to mid-1990s, with a cessation of commercial timber logging during this period. While there is some population pressure that drives continued felling of individual trees, this is mostly at a smaller scale, with single trees being harvested at a time, compared to commercial felling. The areas with former large scale commercial logging have therefore shown considerable regeneration. The second major area of tree growth is in the tea estates to the north, where reduction in the intensity of management has led to the regeneration of trees, while the steep topography and relative low populations in these hilly areas protects these patches from clearing.

There is still substantial clearing toward the peripheral areas of the MWS and the BRF, however, especially in areas that are well connected to illegal timber markets by road and railway networks. The BRF appears to be experiencing much greater rates of deforestation compared to the MWS, in part due to the relative inaccessibility of the forests at the higher elevations of the MWS, and the greater density of settlements and increased accessibility and road connectivity around the BRF. Significant differences in landscape pattern were also observed between the three zones of protection. Stable forest patches and patches of reforestation were significantly less fragmented in the MWS compared to the BRF and the surrounding landscape.

The legal extraction of timber and firewood has decreased significantly between 1990 and 2000, when new policies were adopted by the Government of India to limit the commercial extraction of timber in protected forest areas. Yet, illegal timber and furniture markers have flourished in nearby towns, especially near Siliguri (Indian Institute of Forest Management, Bhopal 2001). The Forest Department, ill-staffed due to financial constraints, nevertheless continues frequent monitoring of the MWS and BRF, and has seized significant volumes of illegal timber from individual and large-scale poachers. Nevertheless the pressure on the park from the surrounding settlements is significant, and makes it difficult for them to completely protect the forest. The MWS represents the westernmost end of the elephant migration corridor in northern West Bengal (Bist 2002), and further fragmentation of the forest in this region can have critical impacts on the maintenance of effective wildlife corridors in this area.

The reduction of official timber harvesting and the conversion of West Bengal state's prime timber harvesting area into a network of protected areas appears to have had a major impact on forest change in this region, leading to large scale forest regrowth in formerly commercially logged areas. In the eyes of the policy maker, this represents a significant qualitative shift in perception of the production "values" in the landscape being studied—from commercial, to ecological. The very rationale for creating an elaborate forest bureaucracy was the huge revenue from the sale of timber. The decline in timber operations in the organized forestry sector thus places the department staff in a difficult situation. Ostensibly it prioritizes policing and patrolling at the expense of timber management—but in actuality, this well-intentioned shift in policy also leaves the government staff under-equipped in terms of personnel and infrastructure for this now supposedly prioritized activity. The consequences of this on staff morale need to be addressed.

Forest rangers indicate in discussions that the pressures and risks associated with forest patrolling have increased over time, while the economic rewards of engaging in professional forestry have declined substantially. The Forest Department thus finds it increasingly difficult to fill vacancies with competent staff now that the disincentives of hazardous relationships with local communities have increased and the incentives of working in these difficult situations have declined. The forestry staff find it demoralizing to compare their status in this branch of the state machinery with other organs of the bureaucracy—such as the Income Tax and Police departments, that have multiplied in their organizational strength over time. In contrast, they indicate that they face a situation where a once-wealthy and powerful timber management department has been reduced to an ineffective and inefficient policing force, that is constantly harassed for under performance while up against the hazardous task of guarding these forests against the politically connected, well armed and dangerous timber trade nexus. This does not create a situation conducive for effective forest management, by any means.

In order to ensure the survival of the forests in this region, there is a clear need to involve local inhabitants with conservation efforts. Unfortunately, efforts at creating eco-development committees, while believed to be very successful in other parts of the West Bengal State, have not been as successful in north Bengal (North Eastern Society for Preservation of Nature, Wildlife 2000; Chakrabarti and others 2002a, b). This can be attributed to factors such as the recent low population densities in this landscape, the high levels of social and ethic heterogeneity due to increased migration in recent years, and a lack of revenue benefits perceived from eco-development. In this context, development initiatives in the region, while providing a much-needed impetus for local economies, pose a significant threat to the extent and connectivity of forest cover in this landscape. The Indian Railway's plans to convert the existing meter-gauge railway line in this area into broad-gauge is likely to significantly increase rail traffic, and to adversely affect the protected forests in this region.

There has been considerable interest in understanding the impact of protected area establishment on land cover change across the world. Several recent studies indicate that while protected areas may largely be effective at limiting land cover clearing within their boundaries (Bruner and others 2001; Naughton-Treves and others 2005; Nagendra 2008); human pressure in the landscape surrounding these areas continues to increase (DeFries and others 2005, 2007; Nepstad and others 2005), with a consequent increase in isolation of the protected area habitat, and a consequent breakdown of ecological connectivity, and the capacity of parks to provide adequate protection for biodiversity, and the maintenance of ecosystem services (Hansen and DeFries 2007). This is similar to the conclusions we derive from our analysis of the landscape within which the MWS is embedded. Indeed, while there continue to be some wildlife sightings in the MWS, there is hardly any wildlife remaining in the BRF—while elephant and leopard invasions into the surrounding tea gardens, especially those at higher elevations, have become increasingly frequent, leading to a rise in human-wildlife conflicts (North Eastern Society for Preservation of Nature, Wildlife 2000).

Such research highlights the capacity of satellite remote sensing-based change analyses to provide quantitative information on rates of land cover change, as well to address issues of changes in spatial pattern and ecological connectivity. At the same time, analysis of remotely sensed data requires fieldwork to interpret human activities and incentives that relate to land cover change. As in other parts of South Asia (e.g., Ostrom and Nagendra 2006; Shahabuddin and Rangarajan 2007; Robbins and others 2007), there are many complex and interrelated processes driving recent land cover change in the MWS study area. Results emphasize the need for forest managers to interact with local communities, decreasing their economic dependence on the park by providing alternate strategies for livelihood generation, and involving them in management of the park. In addition, the hands of the forest department need to be strengthened by providing them with the capacity, manpower, funds and political support to limit the large-scale illegal extraction of timber by the powerful and well-armed timber-trade nexus.

Acknowledgments We thank the West Bengal Forest Department for permissions for field studies, and for their valuable inputs and feedback on our research. We also thank the local forest users and residents who generously assisted us with our enquiries. Financial support from the National Science Foundation to CIPEC, from a National Geographic Society Conservation Trust Grant, and from a Society in Science—Branco Weiss Fellowship—to Harini Nagendra is gratefully acknowledged.

References

Bawa KS, Raven PH, Seidler R (2004) Reconciling conservation paradigms. Conservation Biology 18:859–860

Bist SS (2002) An overview of elephant conservation in India. The Indian Forester 128:121–136

Bruner AG, Gullison RE, Rice RE, da Fonseca GAB (2001) Effectiveness of parks in protecting tropical biodiversity. Science 291:125–128

Chakrabarti M, Sarkar A, Ghosh SR, Sarkar A (2002a) Forest structure, resource use and institutions: experiences from Salugarah (Fapri), Baikunthapur Forest Division. Centre for Studies in Rural Economy, Appropriate Technology and Environment. St. Joseph's College, Darjeeling, India

Chakrabarti M, Sarkar A, Ghosh SR, Sarkar A (2002b) Forest structure, resource use and institutions: site report from Dabgram, Baikunthapur Forest Division. Centre for Studies in Rural Economy, Appropriate Technology and Environment. St. Joseph's College, Darjeeling, India

Chapin M (2004) A challenge to conservationists. World Watch Nov/Dec: 17–31

Cincotta RP, Engelman R (2000) Nature's place: human population and the future of biological diversity. Population Action International, Washington DC, USA

Das TK, Guha I (2003) Economics of man-animal conflict: a lesson for wildlife conservation. ACB Publications and DSA Centre for Regional Economic Studies, Jadavpur University, Kolkata, India

DeFries R, Hansen A, Newton AC, Hansen MC (2005) Increasing isolation of protected areas in tropical forests over the past twenty years. Ecological Applications 15:19–26

DeFries R, Hansen A, Turner BL, Reid R, Liu J (2007) Land use change around protected areas: management to balance human needs and ecological function. Ecological Applications 17:1031–1038

Forman RTT (1995) Land mosaics: the ecology of landscapes and regions. Cambridge University Press, Cambridge, UK

Fox J, Rindfuss RR, Walsh SJ, Mishra V (2003) People and the environment: approaches for linking household and community surveys to remote sensing and GIS. Kluwer Academic Publishers, Boston, MA

Government of India (1992) Final population totals. Census of India 1991, Office of the Registrar General, New Delhi

Government of India (2001) Data from the 2001 Census, including cities, villages and towns. Census Commission of India, New Delhi

Haines-Young R, Chopping M (1996) Quantifying landscape structure: a review of landscape indices and their application to forested landscapes. Progress in Physical Geography 20:418–445

Hansen AJ, DeFries R (2007) Ecological mechanisms linking protected areas to surrounding lands. Ecological Applications 17:974–988

IIFM (Indian Institute of Forest Management, Bhopal) (2001) Public forests, fuelwood collection and migration: a case study in North Bengal. Food and Agricultural Organization of the United Nations Regional Wood Energy Development Programme in Asia, Bangkok, Thailand

Jensen JR (2000) Remote sensing of the environment: an earth resource perspective. Prentice Hall, New Jersey, USA

Liverman D, Moran EF, Rindfuss RR, Stern PC (eds) (1998) People and pixels: linking remote sensing and social science. National Academy Press, Washington DC, USA

Madhusudhan MD (2005) Of rights and wrongs: wildlife conservation and the tribal bill. Economic and Political Weekly 40:4893–4896

McGarigal K, Cushman SA, Neel MC, Ene E (2002) FRAGSTATS: spatial pattern analysis program for categorical maps. Computer software program produced by the authors at the University of Massachusetts, Amherst. Available at www.umass.edu/landeco/research/fragstats/fragstats.html

Moran EF, Ostrom E (eds) (2005) Seeing the forest and the trees: human-environment interactions in forest ecosystems. MIT Press, Cambridge, Massachusetts, USA

Munroe DK, Nagendra H, Southworth J (2007) Monitoring landscape fragmentation in an inaccessible mountain area: Celaque National Park, Western Honduras. Landscape and Urban Planning 83:154–167

Nagendra H (2008) Do parks work? Impact of protected areas on land cover clearing. AMBIO: A Journal of the Human Environment 37:330–337

Nagendra H, Southworth J, Tucker CM (2003) Accessibility as a determinant of landscape transformation in Western Honduras: linking pattern and process. Landscape Ecology 18:141–158

Naughton-Treves L, Holland MB, Brandon K (2005) The role of protected areas in conserving biodiversity and sustaining local livelihoods. Annual Review of Environment and Resources 30:219–252

Nepstad D, Schwartzman S, Bamberger B, Santilli M, Ray D, Schlesinger P, Lefebvre P, Alencar A, Prinz E, Fiske G, Rolla A (2005) Inhibition of Amazon deforestation and fire by parks and indigenous lands. Conservation Biology 20:65–73

NESPON (North Eastern Society for Preservation of Nature and Wildlife) (2000) State of north Bengal's forests: Background paper. In: Discussion on combating deforestation: the question of rural development in forest areas of North Bengal, March 17, Siliguri Tathyakendra, West Bengal, India

Ostrom E, Nagendra H (2006) Insights on linking forests, trees, and people from the air, on the ground, and in the lab. Proceedings of

the National Academy of Sciences of the United States of America 103:19224–19331
Peralta P, Mather P (2000) An analysis of deforestation patterns in the extractive reserves of Acre, Amazonia from satellite imagery: a landscape ecological approach. International Journal of Remote Sensing 21:2555–2570
Petit C, Scudder T, Lambin E (2001) Quantifying processes of land-cover change by remote sensing: resettlement and rapid land-cover changes in south-eastern Zambia. International Journal of Remote Sensing 22:3435–3456
Ray TN (1996) History of forest management in North Bengal. West Bengal Forests Centenary Commemoration
Rindfuss RR, Walsh SJ, Turner BL III, Fox J, Mishra V (2004) Developing a science of land change: challenges and methodological issues. Proceedings of the National Academy of Sciences of the United States of America 101:13976–13981
Robbins PF, Chhangani AK, Rice J, Trigosa E, Mohnot SM (2007) Enforcement authority and vegetation change in Kumbhalgarh Wildlife Sanctuary, Rajasthan, India. Environmental Management 40:365–378
Rodrigues ASL, Andelman SJ, Bakarr MI, Boitani L, Brooks TM, Cowling RM, Fishpool LDC, da Fonseca GAB, Gaston KJ, Hoffmann M, Long JS, Marquet PA, Pilgrim JD, Pressey RL, Schipper J, Sechrest W, Stuart SN, Underhill LG, Waller RW, Watts MEJ, Yan X (2004) Effectiveness of the global protected area network in representing species diversity. Nature 428:640–643
Schwartzman S, Moreira A, Nepstad D (2000) Rethinking tropical forest conservation: perils in parks. Conservation Biology 14:1351–1357
Shahabuddin G, Rangarajan M (eds) (2007) Making conservation work: securing biodiversity in this new century. Permanent Black, Ranikhet, India
Shankar U (2001) A case of high tree diversity in a sal (*Shorea robusta*)-dominated lowland forest of Eastern Himalaya: floristic composition, regeneration and conservation. Current Science 81:776–786
Sokal RR, Rohlf FJ (1981) Introduction to biostatistics, 2nd edn. Island Press, Washington DC, USA
Southworth J, Nagendra H, Munroe DK (2006) Introduction to the special issue: are parks working? Exploring human-environment tradeoffs in protected area conservation. Applied Geography 26:87–95
Terborgh J, van Schaik C, Davenport L, Rao M (eds) (2002) Making parks work: strategies for preserving tropical nature. Island Press, USA
Thomlinson JR, Bolstad PV, Cohen WB (1999) Coordinating methodologies for scaling landcover classifications from site-specific to global: steps towards validating global map products. Remote Sensing of the Environment 70:16–28
Wildlife Circle (1997) Management plan of Mahananda Wildlife Sanctuary. Government of West Bengal, West Bengal