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RESEARCH ARTICLE

Assessing the Priorities for Sustainable Forest Management in the Sikkim Himalaya, India: A Remote Sensing Based Approach

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Abstract Sikkim is a small, mountainous, Indian state (7,096 km^2) located in the eastern Himalayan region. Though a global biodiversity hotspot, it has been relatively less studied. A detailed forest type, density and change dynamics study was undertaken, using SATELLITE remote sensing data and intensive field verification. The landscape was found to be dominated by alpine and nival ecosystems, with a large portion above the tree line, considerable snow cover, and a sizeable area under forest cover (72%, 5,094 km^2). A total of 18 landscape components including 14 vegetation classes were delineated, with the major ones being oak forest, alpine meadow, alpine scrub, conifer forest and alder-cardamom agro-forestry. Of the 3,154 km^2 of forests below the tree line, 40% were found to be dense (>40% tree canopy cover). A sizeable portion of the non dense forests below the tree line was contributed by the degradation of oak forests, which was confirmed by change detection analysis. However on a positive front over the past decade, ban on grazing and felling of trees in forests has been implemented. In order to expand the extent of dense forests, further efforts are needed for the restoration of oak forests such as fire protection, providing alternatives to firewood use, promotion of alder-cardamom agro-forestry in the private lands and protection of the small-sized, fragmented forest patches in the subtropical belt.

Keywords Eastern Himalaya · Spatial analysis · Change detection · Vegetation mapping · Oak forest

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Introduction

Sikkim is a small north-eastern Indian state that lies between 27° 04′ 46″ to 28° 07′ 48″ N latitudes and 88° 00′ 58″ and 88° 55′ 25″ E longitudes, covering an area of just 7,096 km^2 (Fig. 1). The elevation ranges from 300 to 8,586 m, with the dominant feature being Mt. Khangchendzonga (8,586 m), the third highest peak in the world and the highest in the country. The state is a part of the eastern Himalayan region which is one of the 34 global biodiversity hotspots of the world (Myers et al. 2000; Mittermeier et al. 2004). The sharp altitudinal gradient and complex topography

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has manifested in 12 forest types (Table 1). It harbours nearly one third of the national flowering plants diversity, an estimated 5,000 species of flowering plants (Hajra and Verma 1996).

Remote sensing technique and associated spatial analysis tools are highly useful in conservation planning (Roy et al. 1999; Singh et al. 2002; Turner et al. 2003), landscape ecology (Quattrochi and Pelletier 1990; Roy and Tomar 2000) and assessing the impacts of climate change (Kulkarni et al. 2007). Multi-spectral and multi-temporal data obtained from satellite remote sensing allows integration of several layers and change detection more quickly and effectively (Blamont and Méring 1987). These tools are particularly useful for areas located in the Himalaya, where adequate field sampling is often negated by non-negotiable rugged terrain. The present study used satellite data and is backed by extensive field verification compared to the pervious studies (ISRO 1994; IIRS 2002; Kushwaha et al. 2005). Mapping of major forest types has been attempted using a systematic approach covering the entire state.

Our goals in this paper are threefold. First, we delineate the forest types, their density and patterns of change in vegetation cover. Secondly we provide evidence which reveals that considerable portions of the temperate and subalpine forests have been converted into thickets, scrub and blanks, and thereby adversely impacted in recent times. Thirdly we compare our assessment with contemporary studies done by various agencies. We also propose management strategies that need to be prioritized for effective conservation of forested landscapes in this global biodiversity hotspot.

Data Used and Methodology

Field Data Collection

The study area was surveyed over a 6 year period from 2003 to 2008. A total of 497 well distributed ground reference points along with attribute data on location and vegetation characteristics were recorded using a hand-held Garmin Global Positioning System (GPS; 12-channel Garmin Etrex-Summit mode). Field surveys helped in creating a database of about 400 digital photographs of the landscape which helped during visual interpretation especially of areas under shadow.

Spatial Data and Image Processing

For landcover mapping, multispectral satellite images from Indian Remote Sensing satellite (IRS-1C) LISS III data with 23 m spatial resolution, of Jan and Feb, 2002 were used. Ground control points (GCPs), covering all the landuse types as well as covering the shadow areas were collected with the help of GPS (Garmin, etrex-summit, 12 channel). The spectral signatures of GCPs sites thus collected during ground checks were used for supervised classification in Erdas Imagine (version 8.5) software using standard techniques (Roy and Tomar 2000). We identified dense forests as vegetated areas with >40% of tree canopy cover, open forests as those with 10–40% tree canopy cover, very open forests as those with 5–10% tree canopy cover, scrub as areas devoid of tree cover with less than 5% cover and blank as barren areas devoid of tree and shrub cover (FSI 2005). Total forest cover refers to the combined areas of dense, open and very open forests including alpine thickets, alpine scrub and alpine meadows in forest and private lands. Image rectification, enhancement, hybrid classification and smoothening with adequate ground truthing were carried out to map the broad landcover classes. Classification and interpretation of shadow classes was done separately. For areas with deep shadows support of ground truthing, aerial photographs and digital photographs were also taken. For delineation of oak and conifer forests, band 4 (1.55–1.70 μ m wavelength range) was found to be very useful. The mixing of classes was reduced by masking the forest and non forest areas separately into 6 elevation zones (0–1,000 m, 1,000–1,500 m, 1,500–2,000 m, 2,000–2,500 m, 2,500–3,000 m and greater than 3,000 m). For the areas above 3,000 m, the Jan image was used since the Feb image showed extensive seasonal snow cover. Thereafter reclassification was carried out using a subset of the landcover categories which were known to occur in a given elevation zone was then done. This was followed by manual recoding to remove the drop lines, clouds and their shadow. Finally a mosaic of these 12 separately classified images was done to obtain a composite image, and finally area statistics were calculated after normalization. This hybrid approach, combining digital supervised classification, reclassification using elevation and visual interpretation resulted in the final 21 broad landcover classes. Quality of the classifica-

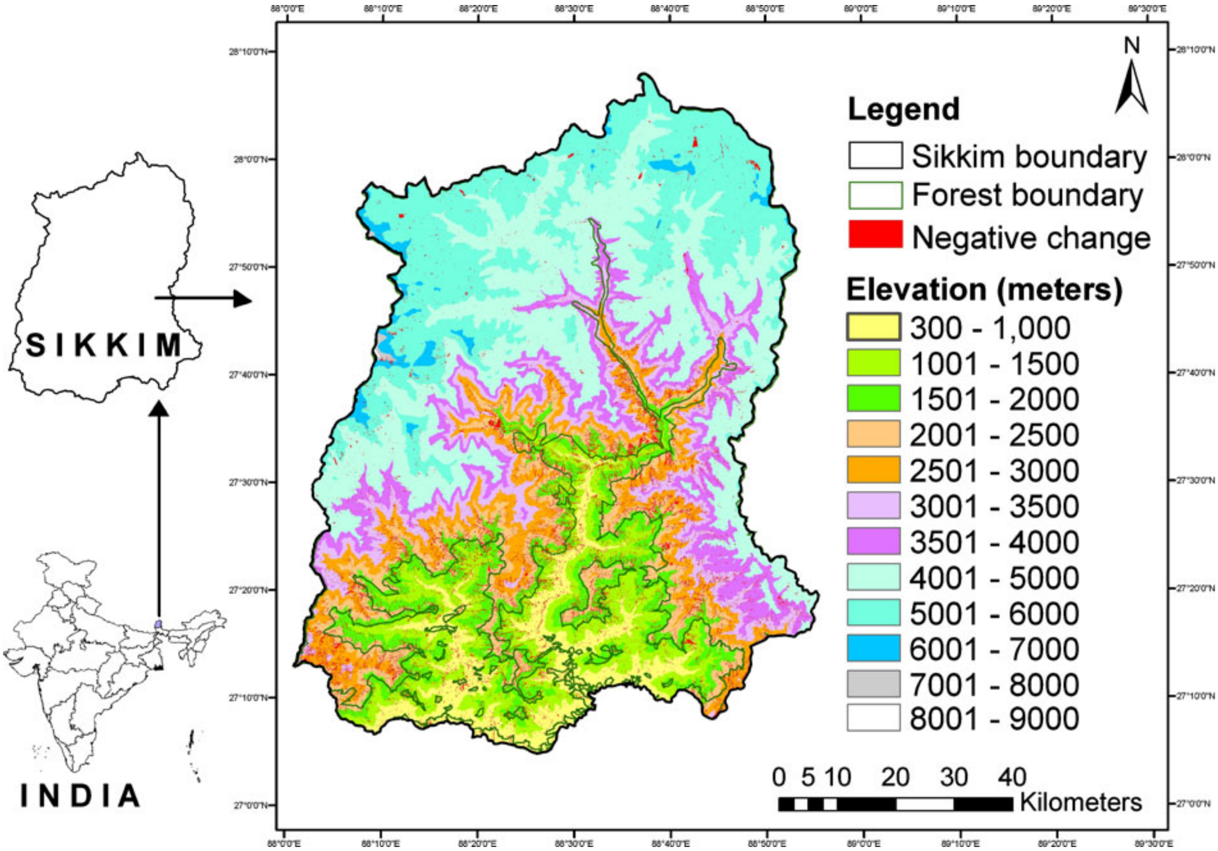

Fig. 1 Map showing the spatial distribution of areas with more than 10% decrease in NDVI (shown in red) between 1977 and 2000 along with Reserve Forest (RF) boundary and elevation zones in Sikkim, Eastern Himalaya, India

tion was found using the accuracy assessment option of the classifier module. ArcGIS (version 9) was used for integration of the various layers on a GIS platform.

Temporal Change Detection

The georeferenced Landsat time series data of 23rd January, 1977 (NASA Landsat Program 1977) and 26th December, 2000 (NASA Landsat Program 2000) were used for temporal change detection. Atmospheric correction was performed with Idrisi Kilimanjaro (v14) using the ATMOSC module. All imagery was corrected using the cos(t) model with input parameters reported in the metadata supplied by Landsat (Chavez 1996). The 30 m resolution Landsat ETM+ (2000) image was degraded to 60 m using the utilities option in the image interpreter module of Erdas to match with the Landsat MSS (1977) image. NDVI was calculated for each of the images using the spectral enhancement option, followed by change detection using the utilities option in the image interpreter module of Erdas (Lillesand and Kiefer 2000). The 2000 image had less snow cover in the alpine zone especially in the greater Himalayan portion. Because of this reduction in winter snow cover, the alpine vegetation that was concealed under snow in the older image was visible in the new image, causing the NDVI to show a positive bias in the snow covered areas. There was variation in the shadow intensity as well, with the 2000 image showing lighter shadows as compared to the 1977 image. Change detection in shadow areas was seriously hampered by variability in shadow intensity along with low spectral reflectance of vegetation. Hence all shadow areas were erroneously classified as a positive change (i.e. gain in vegetation cover) between the 1997 and 2000. To overcome these challenges inferences from change detection analysis using NDVI were drawn only from the negative changes highlighted in the map, since the positive changes could be due to reduction in shadow

Table 1 Details of forest types found in Sikkim, Eastern Himalaya, India (Adapted from Grierson and Long (1983), Champion and Seth (1968))

S. no.	Forest type adapted from Grierson and Long (1983)	Characteristic species	Altitude range	Forest type adapted from Champion and Seth (1968)	
1	Sal (*Shorea robusta*) forest	*Shorea robusta, Terminalia myriocarpa, Schima wallichii, Phyllanthus emblica, Mallotus philippensis, Bombax ceiba*	300–900	3C/Cia	East Himalayan sal forests
2	Chir pine (*Pinus roxburghi*) forest	*Pinus roxburghi, Woodfordia fruticosa, Phoenix acaulis*	500–900	$9/C_{1b}$	Himalayan chir pine forests
3	Subtropical forest	*Terminalia myriocarpa, Alstonia grandis, Duabanga grandiflora, Tetrameles nudiflora, Dillenia pentagyna, Ailanthes grandis*	300–900	$3C/C_{3b}$	East Himalayan moist deciduous forest
4	Warm broad-leaved forest	*Schima wallichii, Engelhardia spicata, Macaranga nepalensis, Castanopsis indica, Spondias axillaris, Ostodes paniculatus*	900–1,700	$8B/C_1$	East Himalayan sub-tropical wet hill forest
5	Alder forest	*Alnus nepalensis*	1,500–2,000	$12/IS_1$	Alder forest
6	Evergreen Oak forest	*Castonopsis* sp., *Quercus* sp., *Michelia* sp., *Juglans regia, Symplocos* sp., *Acer campbellii*	1,700–2,800	$11B/C_1$	East Himalayan wet temperate forests
7	Dwarf bamboo thicket	*Arundinaria maling, Thamnocalamus aristata, Thamnocalamus spathiflorus*	2,600–3,100	$12/DS_1$	Montane bamboo brakes
8	Mixed conifer forest	*Tsuga dumosa, Quercus pachyphylla, Larix griffithiana, Picea smithiana*	2,700–3,100	$12/C_{3a}$	East Himalayan moist temperate forest, East Himalayan dry temperate coniferous forest, Larch forest
9	Conifer forest	*Abies densa, Juniperus recurva, Betula utilis, Sorbus macrophylla, Prunus cornuta*	2,800–3,700	$13/C_6$, $14/C_2$	East Himalayan sub-alpine forests
10	Alpine thicket	*Rhododendron* sp., *Betula utilis, Acer* sp.	3,500–4,500	$15/C_1$	Birch/Rhododendron scrub
11	Alpine scrub	*Juniperus* sp., *Rhododendron* sp., *Caragana* sp., *Ephedra gerardiana*	4,000–5,500	$15/C_2$, $16/C_1$, $16/E_1$	Dwarf *Rhododendron* scrub, Dry alpine scrub, Dwarf Juniper scrub
12	Alpine meadow	*Kobresia* sp., *Carex* sp., *Stipa* sp., *Poa* sp.	4,000–5,500	$15/C_3$	Alpine pastures

intensity or decrease in snow cover between the two images.

Results

Landcover Types

About 79% of the geographical area of the state has been classified as reserve forests having a total extent of 5,589 km^2. However of this only 2,292 km^2 (41%) occurs below the tree line. The reserve forests occurred in 58 discrete patches comprising of one large chunk with an extent of 5,385 km^2 (Fig. 1). The next big patch was the Fambong lho with an area of 55 km^2. The mean area of the reserve forest patches is 95±707 km^2 which indicates a large variation. However without these two large polygons the extent of the remaining 56 reserve forest polygons reduced to 88 km^2 and the mean area to 1.6±2.4 km^2.

About 47% (3,323 km^2) of the geographical area of the state is above the tree line which is at 3,800± 200 m. The forest cover including alpine thickets, alpine scrub and alpine meadows stood at 72% (5,094 km^2) of the geographical area. The forest cover when calculated for the area below the tree line (3,783 km^2) increased to 76% (2,893 km^2) of which 23% occurs outside reserve forests. The final classified image of the study area had 16 classes or landscape components (Table 2, Fig. 2), with the dominant ones being oak forest (16.15%), alpine scrub (13.53%), alpine meadow (13.44%), conifer forest (11.02%), agriculture (8.33%), cardamom-alder agro-forestry (6.51%), mixed conifer (6.35%) and a high proportion (14.73%) of snow.

Forest Density

Of the forests below the tree line, 40.2% (1,268 km^2) were found to be dense (>40% canopy cover), 26% (820 km^2) open (10 to 40% canopy cover), 10.3% (326 km^2) very open (5 to 10% canopy cover), 15.2% (479 km^2) thickets, 4.2% (133 km^2) scrub (< than 5% canopy cover) and 4.1% (128 km^2) blank (Fig. 3, Table 2). *Shorea robusta* (sal) forests (91%), mixed conifer forests (90%), subtropical forests (68%) and warm broad-leaved forests (64%) were found to be the most non dense. Oak forests contributed significantly (32%, 608 km^2) to the total non dense forests below the tree line. Subtropical forests that have a total extent of 110 km^2 are the only natural forests that occur mostly (80%) outside reserve forests. Forests which are most extensive in non reserve forest lands are the cardamom-alder agro-forests with an extent of 272 km^2 and comprise 17% of the total forests in private lands.

Temporal Change Detection

Out of a total 7,096 km^2 of the state's area, 317 km^2 (4.57%) was found to be impacted by a decrease of greater than 10% in NDVI (Fig. 1, Table 3). This decrease was found to be 209 km^2 (3.8%) in reserve forest area and 108 km^2 (6.9%) in other areas. However, this change was not uniform, for instance, as much as 30 km^2 (12.7%) of the reserve forest area between 1,500 to 2,000 m, 61 km^2 (12.1%) between 2,000 to 2,500 m and 54 km^2 (9.9%) between 2,500 to 3,000 m showed a decline in forest cover, while less than 1.5% of the area in the zone above 3,000 m showed a negative change.

Table 2 Broad landcover types, their density and extent (in km^2) in Sikkim, Eastern Himalaya, India

Landcover type	Extent in km^2							
	Dense	Open	Very open	Thicket	Scrub	Blank	Total	% of Total
Alpine meadow							953.36	13.44%
Alpine scrub							959.56	13.53%
Alpine thicket							260.04	3.66%
Conifer forest	449.94	304.01	0.00	28.21	0.00	0.00	782.16	11.02%
Mixed conifer forest	46.13	90.71	0.00	256.27	0.00	57.62	450.72	6.35%
Oak forest	538.50	213.52	169.89	176.64	0.00	47.58	1146.13	16.15%
Alder forest	141.18	131.31	110.55	78.85	0.00	0.00	461.88	6.51%
Warm broad-leaved forest	51.64	29.11	16.87	39.08	3.88	2.93	143.50	2.02%
Subtropical forest	35.01	50.18	16.17	0.00	8.53	0.00	109.89	1.55%
Sal forest	5.39	1.44	12.83	10.72	10.02	19.76	60.15	0.85%
Agriculture							591.99	8.34%
Rock							101.32	1.43%
Sand							37.16	0.52%
Lake							27.98	0.39%
Snow							1045.59	14.73%
Total	1250.43	740.21	326.00	590.84	24.14	188.94	7096.00	100%

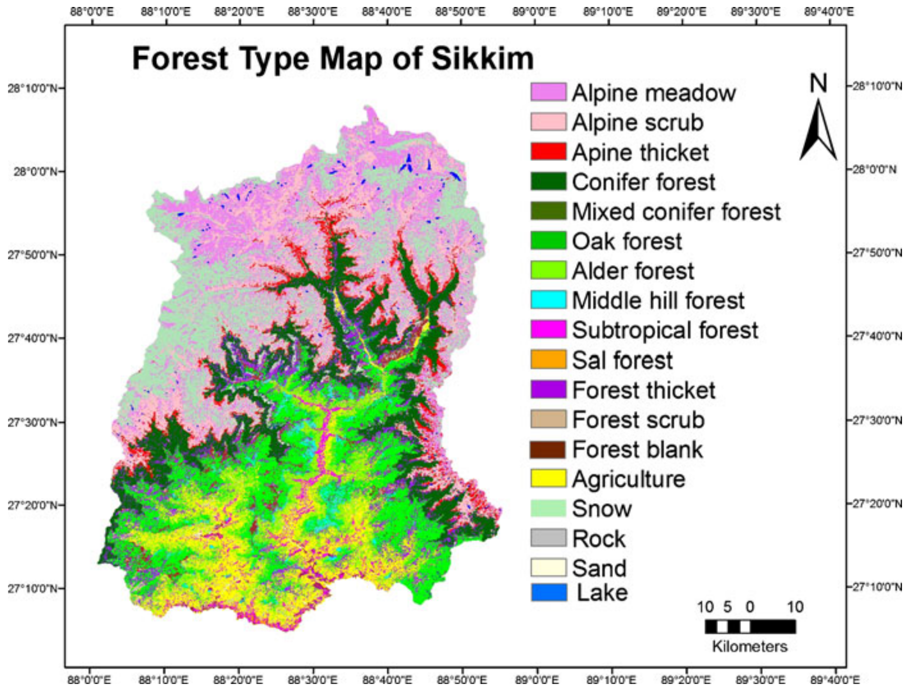

Fig. 2 Forest type map of Sikkim, Eastern Himalaya, India

Discussions

Mountain regions like Sikkim pose several challenges for the natural resource managers and ecologists in terms of understanding linkages between the landscape features and spatio-temporal changes in the composition and extent of vegetation caused by both natural and anthropogenic factors. A substantial proportion of the Eastern Himalaya remains largely inaccessible for physical verification as many areas are far from roads, not easily approached on account of un-forded rivers and steep terrain. Despite the

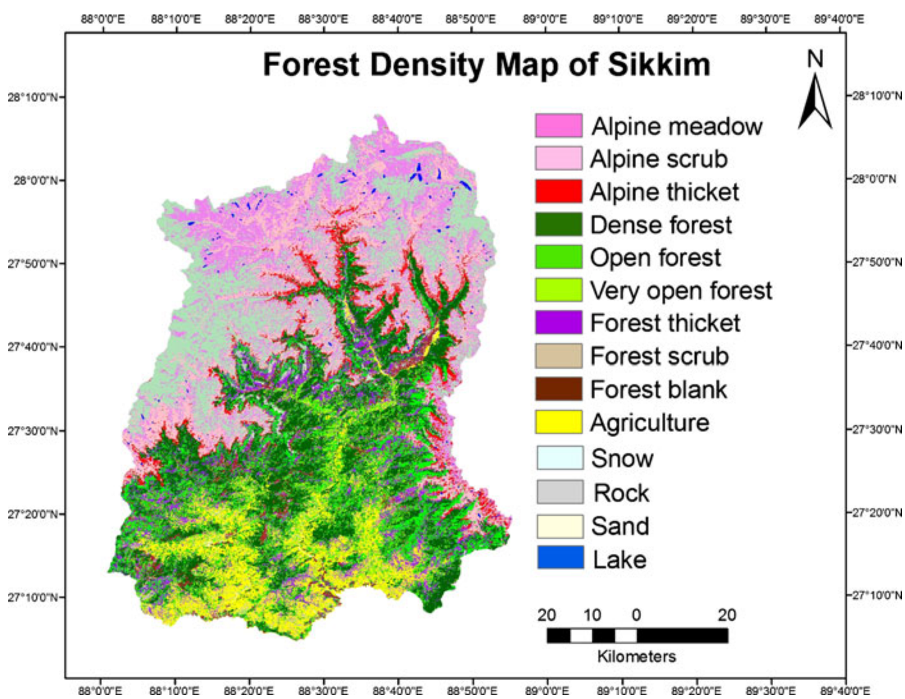

Fig. 3 Forest density map of Sikkim, Eastern Himalaya, India

Table 3 Extent of area (in km^2) with more than 10% decrease in NDVI between 1977 and 2000 presented altitude wise in Sikkim, Eastern Himalaya, India

Elevation	300–1,000 m		1,000–1,500 m		1,500–2,000 m		2,000–2,500 m		2,500–3,000 m		>3,000 m		Total	
Area in km^2	RF	Non RF	RF	Non RF	RF	Non RF	RF	Non RF	RF	Non RF	RF	Non RF	RF	Non RF
Total area	66.74	361.09	23.71	606.08	233.26	478.35	507.71	92.88	542.32	18.77	4140.37	24.72	5514.10	1581.90
Negative change	3.77	20.88	2.37	35.12	29.65	41.24	61.34	9.00	53.66	1.36	57.90	0.69	208.70	108.29
% Negative change	5.65%	5.78%	9.99%	5.80%	12.71%	8.62%	12.08%	9.69%	9.89%	7.27%	1.40%	2.77%	3.78%	6.85%

advantages of remote sensing tools, relief-induced factors limit utilization of potential of these tools (Buchrointhner 1995). Reflected signal values carry high variability and distortion caused by terrain complexity, shadow effects and cloud and snow cover. Persistent cloud cover during the summer months and snowfall in winter create only a small window of 2–3 months in early winter when the alpine zone can be adequately remotely sensed by satellites. Though these challenges result in certain uncertainty in the accuracy of vegetation classification, careful choice of the images, hybrid classification procedure and few post processing steps could overcome some of these problems. Extensive field surveys of vegetation structure and knowledge of altitudinal variation in major formations coupled with intensive ground truthing proved necessary to enhance the accuracy of classification. The classification accuracy of the various landuse types using the above approaches was found to be 86.32% (Table 4).

The reserve forest area of 5,589 km^2 was reasonably close to the recorded reserve forest area 5,451 km^2. The FSI (2005) study is based on 23.5 m resolution IRS P6 satellite data of December 2004, while our study is based on 23 m resolution IRS-1C satellite data of February 2002, hence the source and resolution of the two datasets are quite similar. The area under dense forests as per our study comes to only 1,268 km^2. FSI (2005) assessed the area under very dense (498 km^2) and moderately dense forests (1,912 km^2) in the state to be significantly higher at 2,410 km^2. Our assessment is nearer to other contemporary, satellite data based forest mapping studies like Pandit et al. (2007), who assessed extent of dense forests to be 1,040 km^2 based on the satellite image of the year 2000. Other studies by Kushwaha et al. (2005) in the south west portion of Sikkim also highlight the fragmentation of temperate forests. Earlier studies by ISRO (1994) using 72.5 m IRS-1A satellite data assess the extent of dense forests in the state to be 975 km^2.

Due to the steep elevation gradient the various vegetation classes were found to be telescoped together making the landscape heterogeneous. 56 of the 58 reserve forest polygons are considerably small (mean extent of 1.6 km^2), and comprise just 1.6% (88 km^2) of the total reserve forest area. These are distributed in the lower elevation, having S*horea robusta* (sal), subtropical forests and warm broad leaved forests as the dominant landuse and sur-

Table 4 Classification accuracy of the various landuse types as indicated by the confusion matrix

Class name	Reference totals	Classified totals	Number correct	Producers accuracy	Users accuracy
Alpine meadow	13	13	13	100.00%	100.00%
Alpine scrub	5	5	5	100.00%	100.00%
Alpine thicket	9	8	7	77.78%	87.50%
Conifer forest	33	35	28	84.85%	80.00%
Mixed conifer forest	25	19	18	72.00%	94.74%
Oak forest	250	245	230	92.00%	93.88%
Alder forest	23	22	15	65.22%	68.18%
Middle hill forest	33	34	26	78.79%	76.47%
Subtropical forest	8	12	6	75.00%	50.00%
Sal forest	52	48	45	86.54%	93.75%
Forest thicket	61	56	50	81.97%	89.29%
Forest scrub	8	14	7	87.50%	50.00%
Forest blank	8	14	6	75.00%	42.86%
Agriculture	38	35	33	86.84%	94.29%
Snow	12	10	9	75.00%	90.00%
Rock	2	5	1	50.00%	20.00%
Sand	2	2	1	50.00%	50.00%
	497	497	429	86.32%	86.32%

rounded by agricultural fields. There is an urgent need to protect and regenerate these small sized, fragmented forests, as they are susceptible to encroachment and degradation. Out of the 15 forest classes, 3 classes namely *sal* forest, subtropical forest and warm broadleaved forest were found to have a limited extent (area less than 145 km^2) and relatively higher degree of degradation. Protection of these forests is critical to prevent the loss of the characteristic biodiversity that they possess.

Cardamom farming is a perennial, low-volume, high-value, non-perishable, cash crop and it demands less nutrients and other inputs in comparison to other crops. Alder forest occurs in private lands and is grown as a shade tree for large cardamom—a valuable native horticulture plant (Sharma et al. 2000). In this zone, these forests have a sizeable extent of 272 km^2 which can be potentially increased to 462 km^2 by encouraging this landuse to bring more and more areas under forest cover and also to have an eco-friendly buffer to shield the temperate oak forests.

During the last three decades of the 20th century, 317 km^2 of degradation has taken place, with the impacts mostly concentrated (196 km^2, 62%) in the temperate oak forests, which have been converted into thickets, scrub and blank areas. This degradation was caused mainly due to open grazing, forest fires, selective felling of commercially important mature trees from forests and clear felling of temperate forests for meeting the demand for timber, firewood and charcoal. Thickets of secondary, unpalatable shrubs and bamboos have increased substantially in these degraded forests. Since 1995, several conservation initiatives have been taken up like implementation of the ban on open grazing in reserve forests and ban on green felling of trees in forests.

The main cause of degradation and fragmentation of the temperate oak and subalpine conifer forests is the heavy dependence for firewood and timber, high grazing pressure, vulnerability to forest fire, poor natural regeneration and naturally slow growing nature. While impacts of pastoralism on these forests has been substantially reduced with the removal of about 10,000 cows along with the 500 herders between 2001 and 2006 (Tambe and Rawat 2009), reducing firewood extraction by local communities and road construction labour force and preventing forest fire still needs to be prioritized. Chettri et al. (2006) documented that there is an unregulated extraction of firewood from the forests of the state, and estimated the annual dependence per rural household to be 6–8 tonnes (dry weight). Greater emphasis is needed for promoting solar water heaters, LPG and ensuring access to alternate and cheap forms of energy and fuel efficient devices will help in substantially reducing the pressure on these forests. Also there is a pressing need to take up a long term restoration program to artificially regenerate these slow growing temperate and sub-alpine conifer forests.

Unlike in other parts of the country, the long dry winter from December to March is the major fire season in the state. Offlate incidence of forest fires in temperate forests which are unaccustomed to forest fire is increasing. There is a pressing need for a greater dissemination of mountain specific fire management technology using participatory approaches.

Conclusions

To conclude, we propose the following priorities for forest management in the Sikkim Himalaya. Firstly initiate a long term restoration program for the degraded oak and conifer forests. Secondly expand the extent of dense forests by reducing the pressure from firewood extraction, grazing and fire hazard. The extent of dense forests jointly with forest cover should be used as an impact indicator. Thirdly take special steps to protect and regenerate the several small-sized, fragmented forest patches in the lower belt. Fourthly promote alder-cardamom agro-forestry in the private lands as an eco-friendly buffer and lastly protect rare forest types (sal forests, subtropical forests and warm broad leaved forest) which are being increasingly degraded and under danger of losing their characteristic biodiversity.

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