

## Assessment of Landscape Characteristics and Changes in the Khangchendzonga National Park, Sikkim Himalaya, India

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### Abstract

The Khangchendzonga National Park (KNP) in India forms a part of the eastern Himalaya global biodiversity hotspot. Being the third highest protected area in the world, much of the park is inaccessible and has remained least understood. In this study, Remote Sensing and GIS tools were used to quantify landscape composition, configuration and patterns of changes in vegetation cover. From Landsat ETM+ data, 10 land cover types could be classified with 81% accuracy, which showed relatively higher coverage of snow, rock and alpine meadows. FRAGSTATS recognized 70790 patches with mean patch size of 1.2 ha. Watershed based approach showed that parts of KNP that had higher landscape heterogeneity, reflected a greater Himalayan character, high elevation gradient, east west orientation and not dominantly sculptured by valley glaciers. Riverine areas were found to be susceptible to glacial lake outburst and flash floods. Also vegetation cover has substantially declined at lower elevations (1000 to 2500 m) in the last three decades, particularly in portions not shielded from the villages by buffer forests. The park management needs to evolve innovative co-management models, use the riverine zone carefully, strengthen buffer zone management and prioritize conservation measures in the high impact areas.

**Keywords:** Eastern Himalaya; FRAGSTATS; Conservation management; Spatial analysis; Vegetation mapping; Watershed

### Introduction

Protected areas (PAs) are viewed as cornerstones of biodiversity conservation in most of the countries and there are over 100 000 PAs in the world, covering an area of about 18 million km<sup>2</sup> [1]. It is, however, necessary for the natural resource ecologists and managers to periodically evaluate the management effectiveness of these protected systems. This requires monitoring of appropriate variables [2]. Many changes can go unnoticed in the absence of well established monitoring protocols and spatially explicit data. Remote sensing technology and associated spatial analysis tools are highly useful in conservation planning [3-5], landscape ecology [6-8] and assessing the impacts of climate change [9]. Multi-spectral and multi-temporal data obtained from remote sensing allows integration of several layers and change detection more quickly and effectively [10]. Spatial analysis tools further help to discern the spatial and functional properties of the

landscape elements which are influenced by natural and anthropogenic factors. The PA managers need to detect positive and negative changes at a landscape level in order to take appropriate management decisions. These tools are particularly useful for areas located in the Himalaya, where adequate field sampling is often negated by non-negotiable rugged terrain. Traditionally, conservation management in the Himalayan system revolved around information from natural history records documented by biologists and managers, and by intensive studies resulting into a spatial quantitative data that lacked location details and were restricted to small spatial and temporal scales. Alternately, the major paradigm shift that has been brought about positively by the application of Remote Sensing and GIS is its ability to capture information at fairly larger spatial and temporal scales, and more critically, the information is depicted in spatially explicit form. It facilitates the managers readily to understand location based details for directing appropriate conservation management decisions and efforts.

The Khangchendzonga National Park (KNP) (Figure 1), located in the eastern Himalaya, is the third highest PA in the world and represents a complex mosaic of landscape elements, the most dominating feature being the high alpine and aeolian environments. It harbours varied ecosystems which have been strongly influenced by monsoon climate and to some extent by anthropogenic pressures especially towards the outer fringes. Previous studies using remote sensing in this region were

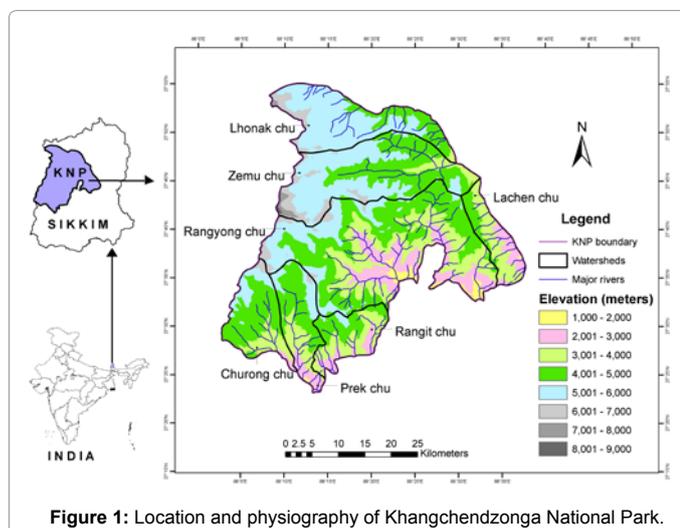


Figure 1: Location and physiography of Khangchendzonga National Park.

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largely limited to broad vegetation classification and phytodiversity characterization [11-13]. In this paper, we present details of landscape composition, configuration and patterns of changes in vegetation cover in three decades based on fine scale remote sensing data and landscape analysis using specialized software. The objectives also include demonstrating a credible model to understand management issues in a large landscape and prioritize conservation action in a biodiversity rich Himalayan state which lacks adequate financial and human resources.

## Study Area

The KNP is located on the western flank of Sikkim (India) adjacent to Nepal, between 27° 30' to 27° 55' N latitudes and 88° 02' and 88° 37' E longitudes, covering an area of 1784 km<sup>2</sup> (Figure 1). It forms a part of the eastern Himalaya that has been recognized as one of the 34 global biodiversity hotspots [14,15]. The park is named after Mt. Khangchendzonga (8586 m), the third highest peak in the world and the highest in India. The annual rainfall varies from less than 150 cm in the north to more than 300 cm in the southern parts. The park is known for its steep and rugged terrain [16]. The elevation of KNP varies from about 1220 to 8586 m within an aerial distance of less than 40 km. About 90% of the park lies above 3000 m, 70% above 4000 m which has nine peaks rising above 7000 m. There are a number of small and large glaciers, longest being 26 kms (Zemu glacier). The characteristic geomorphology and glaciated landscape has given rise to more than 73 glacial lakes within the park [17]. The park is divisible into seven major watersheds viz., Churong chu, Prek chu, Rangit chu, Lachen chu, Rangyong chu, Zemu chu, and Lhonak chu (local *chu* = river).

The sharp altitudinal gradient and complex topography have manifested in diverse vegetation types. As many as 18 distinct forest types and sub-types are discernible within KNP as per the forest classification by Champion and Seth [18]. Maity and Maiti (2007) recorded 1580 species of vascular plants from KNP and surrounding buffer forests which include 11 gymnosperms, 106 species of pteridophytes and 1463 angiosperms. The park is an important habitat for a large number of rare and threatened mammals such as the Himalayan musk deer (*Moschus chrysogaster*), red panda (*Ailurus fulgens*), snow leopard (*Uncia uncia*) and a variety of avifauna. The land use practices in the area include grazing of livestock (yaks, cow-yak crossbreeds, horses and sheep), collection of medicinal and aromatic plants and tourism.

## Methods

### Field data collection

The study area was surveyed during summer and winter seasons in 14 field visits spanning 125 days over a three-year period from 2004 to 2006. A total of 161 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 Etrex summit mode). Winter surveys helped in creating a database of about 200 digital photographs of the landscape which helped during visual interpretation especially of areas under shadow.

### Spatial data and image processing

The Shuttle Radar Topographic Mission (SRTM) produced by NASA originally, has provided high quality digital elevation data (DEMs). The SRTM 90m DEM file (srtm\_54\_07.zip) was downloaded from the CGIAR-CSI GeoPortal [19]. This file in Geotiff format was processed in Erdas Imagine software (version 8.5). The study area was subset from this image and exported to grid format. In Arcview GIS (version 3.2) the surface option of the spatial analyst extension was used to create contours and to derive aspect and slope maps.

The 30m resolution Landsat ETM+ (2000) dataset was downloaded in the Geotiff format from the Global Land Cover Facility (www.landcover.org) through the geoportal <http://glcapp.umiacs.umd.edu>. The sub-scene (path/row, 139/041, 5<sup>th</sup> December, 2000) corresponding to Sikkim was extracted. The input files were unzipped and the layer stack option in the image interpreter module of Erdas was used, and the bands 1 to 5 were selected to create the output multispectral image file. The Landsat-7 ETM+ data was classified in unsupervised (40 classes) mode, and failed to show adequate separability between vegetation classes like oak and conifer, and subalpine thickets and bamboo thickets. Using the classifier module of Erdas an unsupervised maximum likelihood classification of the 5-band (1:5) composite was carried out with 40 classes initially. Isodata clustering algorithm was used, and maximum number of iteration was found to be 10 for the convergence threshold of 0.96. The resultant 40 classes were checked individually against ground-truth data of landcover types collected in the field along with geographic coordinates. The problems encountered were misclassification of the shadow areas, non-separability of temperate oak and subalpine fir and bamboo thickets merging with *krummholz*. These uncertainties were addressed by visual interpretation process involving ground truth data, image tone and elevation information. The hybrid approach combining efforts from both unsupervised classification process and visual interpretation resulted in the final 10 broad landcover classes (Figure 2). Separability of the classes and classification accuracy were then assessed. 161 ground truth points were used for assessing the separability of the classes and classification accuracy. The population of the villages was taken from the Census of India [20].

### Landscape analysis

The landscape configuration was analyzed using the spatial pattern analysis software FRAGSTATS (version 3.3) [21]. The grain of the study was the spatial resolution of the satellite image (28.5 m), while the extent was 1784 km<sup>2</sup> (the area of the KNP). Both natural and disturbed vegetation classes were used in the study. Since bamboo thickets occur as a middle storey in oak forests, it was natural to club it with this

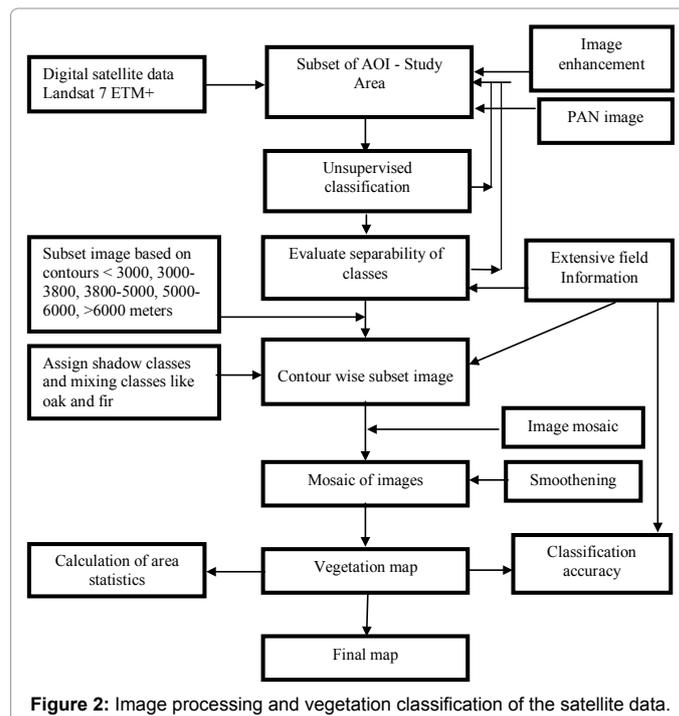


Figure 2: Image processing and vegetation classification of the satellite data.

vegetation class. The results were aggregated thematically at vegetation class level. The landscape characteristics were determined from the patch, class and landscape level metrics generated from the software. Landscape indices, their methods of calculation, symbols and units used are as defined in the FRAGSTATS user manual [21].

The Khangchendzonga massif presides over the physiography of KNP. The seven watersheds or river sub-systems namely the Lhonak, Zemu, Lachen, Rangyong, Rangit, Prek and Churong though located adjacent to one another, show significant variation in physiography and climate (Figure 1). Although the Greater Himalaya generally runs in an east-west direction, the chief ridge of Khangchendzonga range here is aligned in north-south inclination with west-east running transverse spurs. The monsoon winds blowing from the south-easterly direction bring heavy precipitation and are obstructed by successive west-east ridge formations, significantly reducing the precipitation towards the north. The annual rainfall decreases from 2.75 meter in the southeastern part to 0.75 meter in the north with the average being 2.14 meter [22]. While the southern part of KNP (Rangit, Prek and Churong), represents the wet part that is the Outer Himalaya, central part (Zemu, Lachen, Rangyong) represents the transitional inner Himalaya, and the high valley of Lhonak the Tibetan Himalaya [23]. Hence to highlight the unique characteristics of these watersheds, their landscape characteristics were aggregated including composition, shape, configuration and diversity (Table 6, Figure 1).

### Temporal change detection

The georeferenced Landsat time series data of 23<sup>rd</sup> January, 1977 [24] and 26<sup>th</sup> December, 2000 [25] 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 [26]. The 30m resolution Landsat ETM+ (2000) image was degraded to 60 meters using the utilities option in the image interpreter module of Erdas to match with the Landsat MSS (1977) image. Normalized difference vegetation index (NDVI) has been widely used as an indicator of the presence and condition of green vegetation. The NDVI helps compensate for changing illumination conditions, surface slope, aspect and other extraneous factors. 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 [27]. The decrease in winter snow and increase in illumination of shadow areas resulted in a positive biasing of the change detection, hence only the negative changes were used.

Landcover type	Extent in KNP					
	Greater Himalaya		Trans Himalaya		Total	
	km <sup>2</sup>	%	km <sup>2</sup>	%	km <sup>2</sup>	%
Snow	541.8	35.2	71.7	29.4	613.5	34.4
Rock	253.2	16.4	77.9	31.9	331.1	18.6
Alpine meadow	199.8	13.0	62.5	25.6	262.3	14.7
Alpine scrub	101.7	6.6	25.8	10.6	127.5	7.1
Subalpine thicket	150.5	9.8	3.6	1.5	154.1	8.6
Subalpine fir forest	100.3	6.5	2.7	1.1	103.0	5.8
Temperate forest	127.5	8.3	0.0	0.0	127.5	7.1
Bamboo thicket	51.1	3.3	0.0	0.0	51.1	2.9
Temperate scrub	5.9	0.4	0.0	0.0	5.9	0.3
Forest blank	8.0	0.5	0.0	0.0	8.0	0.5
<b>Total</b>	<b>1540</b>	<b>100</b>	<b>244</b>	<b>100</b>	<b>1784</b>	<b>100</b>

Table 1: Broad landcover types and their extent in KNP.

### Results

Analysis of the 30m resolution Landsat ETM+ (2000) provided interesting results which are indicated below:

#### Vegetation types and composition

Greater Himalaya comprises 86% of the KNP landscape (southern and central parts), while the remaining 14% (northern part) is trans-Himalayan in character. The final classified image of the study area had 10 classes or landcover types (Table 1, Figure 3), of these, temperate forest constituted 11%, subalpine forest 14%, alpine forest 22% and a high proportion (53%) of snow and rock. Amongst the vegetation classes, alpine meadows were the most extensive (14.7%, 262 km<sup>2</sup>), followed by temperate oak forests (10%, 179 km<sup>2</sup>) and subalpine thickets (8.6%, 154 km<sup>2</sup>).

#### Spectral separability and accuracy

The average separability was 158. Minimum class pair separability (25) was observed between subalpine thicket and alpine scrub followed by 37 between subalpine thicket and bamboo thicket (Table 2). 161 GPS points, in seven vegetation classes were used as a reference set for accuracy assessment. The confusion matrix generated had an overall

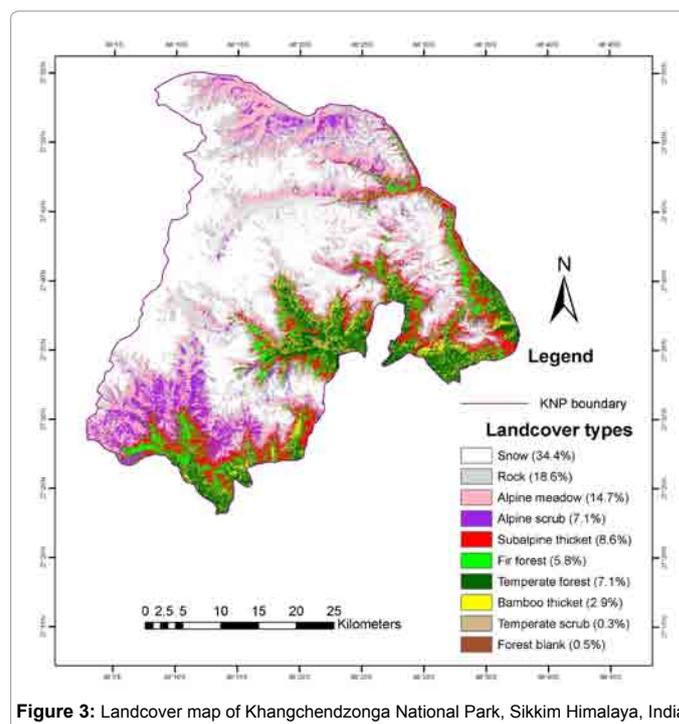


Figure 3: Landcover map of Khangchendzonga National Park, Sikkim Himalaya, India.

	Fir and oak	Bamboo thicket	Rock	Alpine scrub	Subalpine thicket	Alpine meadow	Snow
Fir and oak	X	75	88	38	44	92	387
Bamboo thicket		X	74	61	37	58	355
Rock			X	65	63	50	312
Alpine scrub				X	25	57	375
Subalpine thicket					X	53	367
Alpine meadow						X	346
Snow							X

Table 2: Spectral separability of the landcover classes across five bands in KNP.

classification accuracy of 74%. One drawback affecting the classification accuracy was that while the ground truth information was collected in summer the remotely sensed image was of winter. But, on correcting for the 12 ground truth points affected by snow cover, the overall classification accuracy improved to 81% with alpine scrub showing the lowest (64%) and alpine meadow the highest (89%) accuracy (Table 3). The mixing of the spectral signature of alpine scrub with alpine meadow and subalpine thickets in the transition zone results in its weak classification accuracy.

### Patch properties of the landscape

The total vegetated area of KNP (839 km<sup>2</sup>, 47%) is composed of 70 790 patches with a mean patch size of 1.2 ha with large variation. The perimeter area ratio (mean) was 1173 and the shape index (mean) 1.3, suggesting relatively compact patches. The landscape configuration had the euclidean nearest neighbour distance of 85 m, contagion was 39%,

Class Name	Reference Totals	Classified Totals	Number Correct	Producers Accuracy (%)	Users Accuracy (%)
Snow	11	11	11	100.00	100.00
Rock	18	20	14	77.78	70.00
Alpine meadow	68	63	56	82.35	88.89
Alpine scrub	22	25	16	72.73	64.00
Subalpine thicket	24	26	20	83.33	76.92
Fir forest	10	8	7	70.00	87.50
Oak forest	8	8	7	87.50	87.50
<b>Total</b>	<b>161</b>	<b>161</b>	<b>131</b>		<b>81.37</b>

Table 3: Accuracy totals with winter snow correction in KNP.

Category	Name	Symbol	Units	Value
Landscape composition	Total vegetated area	TA	km <sup>2</sup>	839
	Number of vegetated patches	NP	none	70790
	Patch density of vegetated patches	PD	km <sup>2</sup>	84.37
	Patch area (mean)	AREA_MN	ha	1.17
	Patch area (SD)	AREA_SD	ha	27.63
	Effective mesh size	MESH	ha	159
	Splitting index	SPLIT	none	2128
	Patch richness	PR	none	8
	Shannon's diversity index	SHDI	none	1.75
	Simpson's diversity index	SIDI	none	0.80
	Modified Simpson's diversity index	MSIDI	none	1.63
	Shannon's evenness index	SHEI	none	0.84
	Simpson's evenness index	SIEI	none	0.92
Modified Simpson's evenness index	MSIEI	none	0.78	
Landscape shape	Perimeter area ratio (mean)	PARA_MN	none	1173
	Perimeter area ratio (SD)	PARA_SD	none	264
	Shape index (mean)	SHAPE_MN	none	1.26
	Shape index (SD)	SHAPE_SD	none	0.82
	Perimeter area fractal dimension	PAFRAC	none	1.58
Landscape configuration	Euclidean nearest neighbour distance (mean)	ENN_MN	meter	85
	Euclidean nearest neighbour distance (SD)	ENN_SD	meter	74
	Contagion	CONTAG	percent	39
	Aggregation index	AI	percent	65
	Interspersion and juxtaposition index	IJI	percent	60

Table 4: Selected landscape indices measuring landscape composition, shape and configuration of KNP.

aggregation index was 65% and scattering at patch level as measured by interspersion and juxtaposition index was 60%. The landscape diversity was 1.8 as per the Shannon's diversity index and the evenness as measured by the Shannon's evenness index was 0.8. Further details of landscape level metrics for KNP measuring landscape composition, shape, configuration and diversity is given in Table 4.

### Patch properties of classes

The mean patch size for class metrics ranged from 0.8 ha (alpine scrub) to 12.2 ha (temperate forest) (Table 5). The alpine meadows had the largest number of patches and highest patch density (NP=21 471, PD=25.59) while the temperate forests were the most compact (NP=1030, PD=1.23). Landscape fragmentation as measured by the mean patch area was highest for alpine scrub (AREA\_MN=0.81) and fir forest (AREA\_MN=0.91) and lowest for temperate forest (AREA\_MN=12.24). Temperate forests exhibited a higher shape index compared to the other landscape classes. The disturbed vegetation classes namely forest blank and temperate scrub together comprise just 0.8% of KNP and generally had less number of patches, smaller patch size and lower patch density.

### Landscape characteristics of watersheds

Amongst the seven major watersheds in KNP, Churong chu, Prek chu, Rangit chu, Lachen chu, Rangyong chu and Zemu chu showed characteristics of greater Himalaya i.e., higher relief ratio, more snow cover and extensive *krummholz* formations. Lhonak chu watershed in the extreme north exhibits rain shadow areas typical of trans-Himalaya. Also Churong chu, Prek chu and Lhonak chu watersheds have been strongly influenced by valley glaciers which have receded while the Zemu chu watershed is dominated by the 26 km long Zemu glacier. Rangyong chu and Rangit chu valleys do not show strong influences by valley glaciers. Only a minor part of the Lachen chu watershed falls within the KNP and hence is not fully representative, while the true left bank of the Lhonak chu watershed is outside the KNP. The relief characteristics of these watersheds show that the relief ratio is lowest for the trans-Himalayan glaciated valley of Lhonak (RR=0.1), moderate for greater Himalayan glaciated valleys of Zemu, Prek and Churong (RR=0.2) and highest for the greater Himalayan non-glaciated valleys of Rangyong and Rangit (RR=0.3).

The patch density of vegetated patches was lowest for the trans-Himalayan glaciated valley of Lhonak (PD=30.05), moderate for greater Himalayan glaciated valleys of Zemu, Prek and Churong (mean PD=37.09) and highest for the greater Himalayan non-glaciated valleys of Rangyong and Rangit (mean PD=51.41). The trans-Himalayan, glaciated valley of Lhonak showed lower landscape diversity (SHDI=0.85) and evenness (SHEI=0.62) compared to greater Himalayan valleys (mean SHDI=1.58, mean SHEI=0.80). Within the greater Himalaya, the glaciated valleys of Zemu chu, Prek chu and Churong chu showed lower landscape diversity (mean SHDI=1.42) and evenness (mean SHEI=0.78) as compared to the non-glaciated valleys of Rangit chu and Rangyong chu (mean SHDI=1.78, mean SHEI=0.86). The clumpiness is lowest and scattering highest in the Zemu (CONTAG=30.92, IJI=89.59) and Rangyong watersheds (CONTAG=36.24, IJI=61.37) with the Churong chu watershed (CONTAG=47.94, IJI=44.54) being at the other end of the spectrum showing high clumpiness. The east-west orientation of the watershed results in dominant north south aspects which harbour different vegetation types, resulting in increased scattering. In north-south oriented valleys the role of aspect is comparatively subdued that suppresses scattering. This east-west orientation of watershed is high in Rangyong and dominant in Zemu where one can observe different

Landscape indices at class level				Natural vegetation classes					Disturbed vegetation classes	
Category	Name	Symbol	Units	alpine meadow	alpine scrub	subalpine thicket	fir forest	temperate forest	temperate scrub	forest blank
Landscape composition	Class area	CA	km <sup>2</sup>	262	127	154	103	179	6	8
	Percentage of KNP	PLAND	%	14.7	7.1	8.6	5.8	10.00	0.30	0.50
	Number of patches	NP	none	21471	15568	10582	11226	1030	2103	1636
	Patch area (mean)	AREA_MN	ha	1.21	0.81	1.44	0.91	12.24	0.28	0.49
	Patch area (SD)	AREA_SD	ha	24.82	13.17	24.99	11.30	170.12	0.76	1.57
	Patch density of vegetated patches	PD	per km <sup>2</sup>	25.59	18.56	12.61	13.38	1.23	2.51	1.95
Landscape shape	Shape index (mean)	SHAPE_MN	none	1.27	1.23	1.27	1.25	1.47	1.16	1.23
	Shape index (SD)	SHAPE_SD	none	0.73	0.72	1.05	0.72	2.20	0.39	0.46

**Table 5:** Comparison of selected landscape indices measuring landscape composition and shape across different vegetation classes in KNP.

Landscape indices				Watershed name							
Category	Name	Symbol	Unit	Lhonak	Rangyong	Rangit	Zemu	Prek	Churong	Lachen	
	Watershed characteristics			TH-G*	GH-NG*	GH-NG*	GH-G*	GH-G*	GH-G*	GH*	
Landscape composition	Watershed area	CA	km <sup>2</sup>	243	664	118	368	144	152	95	
	Percentage of KNP	PLAND	%	14	37	7	21	8	9	5	
	Highest elevation	HE	m	7459	8476	5825	8586	6691	7338	5064	
	Lowest elevation	LE	m	3100	1220	2200	2700	2200	2200	1800	
	Total relief	TR	m	4359	7256	3625	5898	4491	5138	3264	
	Basin length	BL	m	44065	31413	10747	42697	25626	23953	27171	
	Relief ratio	RR	none	0.10	0.23	0.34	0.14	0.18	0.21	0.12	
	Patch density of vegetated patches	PD	per km <sup>2</sup>	30.05	44.44	58.39	26.98	45.99	38.31	54.93	
	Patch area (mean)	AREA_MN	ha	1.28	1.01	1.25	0.77	1.50	1.76	1.42	
	Patch area (SD)	AREA_SD	ha	31.63	29.99	17.19	10.84	27.71	28.29	25.49	
	Patch richness	PR	none	4	8	8	4	8	8	8	
	Shannon's diversity index	SHDI	none	0.85	1.81	1.76	1.17	1.68	1.42	1.62	
Shannon's evenness index	SHEI	none	0.62	0.87	0.84	0.84	0.81	0.68	0.78		
Landscape shape	Shape index (mean)	SHAPE_MN	ha	1.29	1.26	1.27	1.22	1.27	1.29	1.29	
	Shape index (SD)	SHAPE_SD	ha	0.77	0.77	0.92	0.62	0.92	0.94	0.93	
	Landscape shape index	LSI	none	11.84	42.62	32.24	11.36	30.18	26.93	24.52	
	Perimeter area fractal dimension	PAFRAC	none	1.58	1.58	1.59	1.57	1.58	1.56	1.60	
Landscape configuration	Euclidean nearest neighbour distance (mean)	ENN_MN	meter	82.51	85.14	82.56	93.92	82.60	83.17	80.69	
	Euclidean nearest neighbour distance (SD)	ENN_SD	meter	97.96	72.63	60.32	95.84	63.22	65.80	59.01	
	Contagion	CONTAG	percent	49.81	36.24	37.07	30.92	40.86	47.94	41.64	
	Aggregation index	AI	percent	67.60	62.29	63.38	60.63	67.66	69.64	66.01	
	Interspersion and juxtaposition index	IJI	percent	51.01	61.37	58.12	89.59	51.49	44.54	49.64	

\*TH = Trans Himalaya  
 GH = Greater Himalaya  
 G = Dominant valley glacier  
 NG = No dominant valley glacier

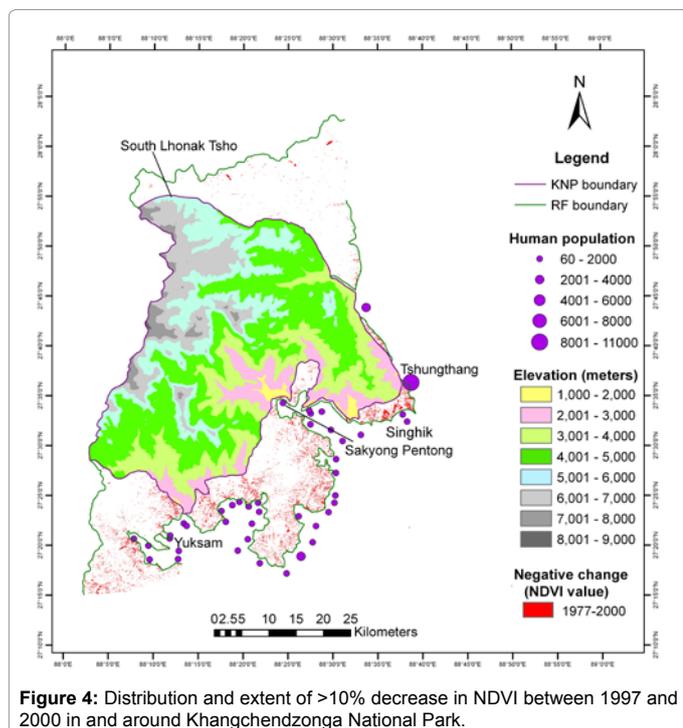
**Table 6:** Comparison of selected landscape indices measuring landscape composition, shape and configuration of watersheds in KNP.

vegetation types on either flank of the valley resulting in higher mixing or dispersal and consequently lower clumpiness in the landscape. Lhonak also being east-west oriented however shows high clumpiness since only the northern aspect of the watershed falls within the study area, reducing the influence of aspect. The euclidean nearest neighbour distance (mean) and aggregation index also show similar trends. In the mountain watersheds of KNP while elevation gradient plays a major role in determining landscape composition, the landscape configuration is largely determined by the orientation. Rangyong watershed with a very

high elevation gradient and a largely east-west orientation exhibits the highest overall landscape heterogeneity.

### Temporal change detection

The geo-referenced Landsat time series data of 23<sup>rd</sup> January, 1977 [24] and 26<sup>th</sup> December, 2000 [25] were used for temporal change detection. Out of a total 1203 km<sup>2</sup> of the park area below 5000 m elevation, 30 km<sup>2</sup> (2.5%) was found to be impacted by a decrease of greater than 10% in NDVI values (Figure 4, Table 7). However, this



**Figure 4:** Distribution and extent of >10% decrease in NDVI between 1997 and 2000 in and around Khangchendzonga National Park.

	Altitudinal zones			Total
	Less than 3000m	3000 – 3800m	3800 – 5000m	
Total area of KNP	194 km <sup>2</sup>	284 km <sup>2</sup>	726 km <sup>2</sup>	1203 km <sup>2</sup>
Area impacted by greater than 10% decrease in NDVI	14 km <sup>2</sup>	5 km <sup>2</sup>	11 km <sup>2</sup>	30 km <sup>2</sup>
% of total area impacted by greater than 10% decrease in NDVI	7.2	1.7	1.5	2.5

**Table 7:** Extent of areas with more than 10% decrease in NDVI between 1977 and 2000 in KNP.

change was not uniform. For instance, as much as 7.2% of the areas below 3000 m showed a decline in forest cover, while the vegetated areas in the subalpine and alpine zone showed only less than 2% change.

In the zone between 3000 to 5000 m the yak herders over the last 30 years have regularly set fire and burnt Juniper scrub in pockets at Lampokhri and Neer-pokhri Nikash converting the alpine scrub into grassy meadows, contributing to reduction in NDVI. A few alpine lakes such as South Lhonak Tsho in the trans-Himalaya show a substantial increase in size. In the subalpine zone the changes were mostly in the riverine areas possibly due to change in river course, glacial lake outburst floods or flash floods in the past. In the zone below 3000 m which showed largest areas impacted by negative change, substantial degradation was found close to the villages of Sakyong-Pentong, Singhik and Tshungthang in North Sikkim and Yuksam in West Sikkim. A large forest fire was reported from Payongchu ridge above Sakyong-Pentong in the spring of 1998, which could not be adequately contained due to the difficult terrain (T.B.Subba, *personal communication*, 18<sup>th</sup> March 2007). Also portions of KNP close to human habitations showed greater negative change in vegetation compared to parts that were shielded by a buffer of reserve forest.

## Discussion

High altitude protected areas such as KNP pose several challenges for

the natural resource ecologists and managers in terms of understanding linkages between the landscape features and spatio-temporal changes caused by natural and anthropogenic factors. A substantial proportion of the Eastern Himalaya remains largely inaccessible for physical verification. Despite the advantages of remote sensing tools, relief-induced factors limit utilization of potential of these tools [28]. Reflected signal values carry high variability and distortion 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 two-three months in early winter when the alpine zone can be adequately remotely sensed by satellites. Out of the 40 land cover classes segregated through unsupervised classification, 12 were of snow and ice, 11 were rock and glacier, 6 were shadow classes of vegetation and 11 non-shadow vegetation classes. The classified image was subset into contour intervals of less than 3000 m, 3000 to 3800 m, 3800 to 5000 m, 5000 to 6000 m and greater than 6000 m. For the shadow classes and oak and fir forests mixing, recoding was done to resolve this using elevation and ground truth information as a parameter. Mixing of subalpine thickets and temperate bamboo thickets was resolved by taking a buffer around the KNP to include more temperate forests. Extensive field surveys of vegetation structure and knowledge of altitudinal variation in major formations coupled with ground truthing proved necessary to enhance the accuracy of classification. The relative proportion of subalpine thickets (*krummholz*) and alpine scrub, which constitute suitable habitat for some of the endangered mammals including the Himalayan musk deer [29] was substantially higher as compared to the composition in the western Himalaya [30].

The landscape was found to be highly heterogeneous, with relatively compact patch shapes. This together with high values of aggregation, interspersions and diversity indices reflect rich landscape character, possibly not being heavily disturbed by unnatural forces. Disaggregating the landscape features of the KNP at watershed level was found to be very useful in identifying their character. Amongst the seven major watersheds, the Rangyong watershed, which covers 37% (664 km<sup>2</sup>) of KNP was found to be most heterogeneous. The high landscape heterogeneity in this area could be related to a high relief ratio, east-west orientation, greater Himalayan character and not being dominantly impacted by valley glaciers.

In the change detection analysis, the variation in NDVI could arise from differences in spatial and spectral resolution of the sensors, differences in shadow intensity, variability of snow cover, variability in atmospheric conditions, changes in the vegetation density and noise [27]. The challenge was to significantly mask out the changes due to variations other than those emanating from changes in vegetation density. In spite of taking into account atmospheric correction, a number of challenges were posed during the change detection analysis carried out on the Landsat images (year 1977, 2000). Though the spectral bands 2 and 4 of MSS and 3 and 4 of ETM+ sensors used to assess NDVI were spectrally similar and were taken less than a month apart, minor variations were found. The 2000 image had less snow cover in the alpine zone especially in the greater Himalayan part (south and centre) of KNP. Because of this reduction in winter snow cover, the alpine vegetation that was hidden under snow in the older image was visible in the new image, making 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 intensity or decrease in snow cover between the two images. In order to determine the optimal threshold level, change detection was carried out at 10%, 15% and 20% levels of decrease in NDVI. Comparing this with the ground truthing information and digital photographs it was found that the 10% threshold value was the most accurate.

A total of 14 glacial lakes in the state have been identified as potentially dangerous [31]. In the KNP, a few alpine lakes like the South Lhonak Tsho in the trans-Himalaya show a substantial increase in size. In the late 1980's, two glacial lake outburst floods (GLOF) were reported in the Pagala pokhri and Tinkune pokhri in southern part of KNP [32]. In the summer of 2007, following incessant rains, flash floods in Zemu chu and Rangyong chu washed away bridges and consequently a few frontier villages were cutoff for weeks altogether. In the subalpine zone the changes were mostly in the riverine areas possibly due to flash floods or glacial lake outbursts in the past. In mountain terrain the riverine zone is preferred for development of communication and tourism infrastructure. Trekking foot-paths, trekker's huts, camping sites and other tourism facilities should be created at a safe distance from the river.

A national park as defined in the Wildlife Protection Act of India is closest to the IUCN Category 1b – "Wilderness area" where the scope for meeting livelihood needs from activities other than tourism is limited [33]. In the KNP, a buffer of reserve forests around the park boundary helps in meeting the livelihoods needs of the people, thus shielding the park and reducing the chances of park people conflict. This could be related to the maximum degradation observed in the lower belt (1000 to 2500 m) adjacent to the villages of Sakyong-Pentong, Singhik and Tshungthang in North Sikkim and Yuksam in West Sikkim and the buffer of reserve forests.

## Conclusion

The challenges posed due to the hilly terrain, climate (cloud and snow cover), multi-layered vegetation structure and spectral characteristics of vegetation result in certain limitations in the accuracy of vegetation classification from remotely sensed satellite images in KNP. Though this results in certain uncertainty in the accuracy of vegetation classification, a hybrid approach using extensive field information in the form of ground truthing, digital photographs and knowledge about the spatial pattern of vegetation could improve the classification to acceptable limits for management purposes.

Remote sensing and GIS analysis provide useful insights in the conservation management of the KNP. Prioritizing conservation action to target the areas where maximum impacts have taken place will help in improving the effectiveness of conservation initiatives. Effective conservation of this landscape by forest staff alone is difficult due to its high altitude, remoteness, tough terrain, harsh climate and limited resources. The park management should consider enlisting the support of the villagers, practicing traditional subsistence livelihoods in this landscape, in conservation management. Also using watershed as a unit of management would be a practical approach to address their unique characteristics. Over the last three decades, possible impacts of climate change in the riverine zone and human pressure on the buffer and low-lying forests is visible. Buffer forests play a vital role in supporting the livelihood requirements of the local community and thus help in keeping the park inviolate. For the long-term security of this unique mountain landscape, the park management needs to evolve

innovative co-management models, take adequate safeguards while using the riverine zone, strengthen buffer zone management and focus conservation measures in high impact areas.

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