Modelling forest resilience in Hindu Kush Himalaya using geoinformation

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Resilience is the capacity of an ecosystem to absorb disturbance and undergo change while maintaining its essential structure, functions, identity and feedbacks. The forests of the Hindu Kush Himalayan (HKH) region are vulnerable to both natural and anthropogenic changes, and the forest land conversion and degradation. Using satellite-derived tree canopy cover percent data and precipitation as the explaining variable, we studied the forest cover resilience in a geospatial framework employing the logistic regression and polynomial equation fitting. Out of the 4.3 million km² geographical areas, 873,650 km² (20.20%) was under the forest in 2000 and experienced loss of 11,250 km² during 2000–2010. We could model the forest cover and treeless areas fairly than the scrub and grassland owing to the variation in precipitation pattern. The majority of the forest cover (59.3%) has been estimated to have less resilience owing to the receipt of <1650 mm of total annual precipitation, whereas only 375 km² forest area could change to scrub that shows the least resilience. About 94.4% of treeless areas were estimated to be stable, while only 1% (25,200 km²) area could accommodate the grassland. The resilient forest areas estimated and observed, owing to the mapping and modelling protocols used in this study, shall be useful in conservation planning in the HKH region.

Keywords. Remote sensing; forest cover change; logistic regression; precipitation; tree canopy cover.

1. Introduction

Ecosystems are subjected to spatio-temporal disturbances of both natural and anthropogenic nature. The conservation and management practices to mitigate such disturbances or to eliminate the impact of long-term large disturbances without perceiving the slower and rare ones could be a failure (Dale *et al.* 1998). Thus, the biodiversity

conservation could be a failure without incorporating slow change processes such as climate regime shift that may alter the ecosystem functions. The capacity of an ecosystem to absorb such disturbances while undergoing changes maintaining its essential structures, functions, identity and feedbacks is termed as ecological resilience (Holling 1973; Walker *et al.* 2004). The resilience of a system can be estimated by studying the

magnitude of disturbances it can absorb without undergoing significant transformational changes. In forests, the resilience is defined as the capacity to recover from severe disturbances, such as fire, logging, climate change, etc., to its original state and beyond which it experiences undesired shifts to the available alternative stable states. This definition of resilience therefore assumes the existence of alternative states in a forest ecosystem (e.g., forest to scrubland or from scrubland to grassland) and is primarily concerned with (i) how the changes in the structure of an ecosystem can alter its behaviour and (ii) how a given state persists over time (Holling 1973; Gunderson 2000). The resilience theory also states that the complex systems such as forests do not simply tend towards an equilibrium condition, but rather cycle dynamically based on the tension between forces that are selected for efficiency (Gunderson and Holling 2002).

Climate has major influence that defines the plant functioning as photosynthesis, respiration and other processes as well as forest structures, diversity and their growth rates. Forests have been adapting to the fast-changing climate and in course, abandoning the existing locations and migrating to newer locations leading to a shift in latitudinal and altitudinal gradients. Generally, most well-developed forests, especially primary old forests, are both resilient and resistant to changes. Drier forests are more vulnerable to climate change as they are more prone to fire and droughts (Anderson-Teixeira *et al.* 2013). Apart from the quantitative change, the forests are changing qualitatively by its density and connectivity (Roy *et al.* 2013; Behera *et al.* 2014). The forests are also vulnerable to anthropogenic alterations such as forest land conversion and degradation, fragmentation due to the construction of rail-road, urban encroachment, agriculture, mining, etc. (Chitale and Behera 2014). The loss of ecosystem resilience due to the reduction in the size of the basin of attraction is also been linked with the diversity loss as the more diverse system has the benefit of high complementarity gains (Folke *et al.* 2004). Thus, it also necessitates the biodiversity conservation to maintain the resilient ecosystem that ensures sustainable flow of ecosystem goods and services to the society.

The theory of alternative stable states in a forest ecosystem suggests that the regime shift among various forest formations of grass-shrub, savannas and woody plants is dependent on the mutual interaction and utility of competition to dry

season, precipitation, fire events, etc., with varied intensity and frequency (Folke *et al.* 2004). Bucini and Hanan (2007), Hirota *et al.* (2011) and Staver *et al.* (2011) have also studied the alternative stable states among forest, savanna and treeless states in reference to precipitation at continental and intercontinental scales in Africa, southeast Asia, Australia and South America. They observed that the tree canopy cover percent (TCC%) gradually increased with the precipitation following a double hysteresis curve corresponding to the resilient zones of three dominant forest types (Hirota *et al.* 2011). This implied that the forest cover that belonged to the wetter zones is more resilient and has one end transition probability towards savanna that received lesser precipitation. However, the savannas are resilient to moderate amount of precipitation, and have upper and lower end transition probabilities to forest and treeless states, with increase and decrease in precipitation, respectively. Treeless areas belonging to drier areas are more resilient, and showed change proneness towards the savanna with the increase in precipitation. Following this distribution pattern of TCC% w.r.t. the precipitation, Hirota *et al.* (2011) fitted the sigmoid curve and used the logistic regression to derive the resilience of each forest cover type, whereas Bucini and Hanan (2007) added the growing season length, soil properties, fire frequency, cultivation intensity, human population, cattle density into account. Staver *et al.* (2011) added the fire frequency, dry season length and soil properties to estimate the forest cover resilience while using a generalised additive model.

The forests of the Hindu Kush Himalayan (HKH) region are experiencing change of varied magnitudes due to the climate and anthropogenic disturbances, and different forest management policies practiced by different countries sharing the region (Das *et al.* 2017). The varied spatial distribution of precipitation and temperature makes the HKH region a unique mountainous landscape, where the southern aspect receives higher solar illumination and sub-tropical monsoon precipitation. On the other hand, the varied topography and high altitude mountains restrict the monsoon precipitation in the northern aspects, which are characterised by dry and cold waves in the Tibetan plateau. Moreover, the western part of this landscape is characterised by drier and warmer climate. This varied climate influenced the forest cover distribution pattern, restricting up to 5500 m along the elevation gradient (Singh and Singh 1987).

With the global climate change, the HKH region is also experiencing a temperature rise of 0.2°C per decade since 1960 (Chen *et al.* 2013). The rates of winter and autumn warming have been significantly faster than those of spring and summer in this region. Southern Asia ($5\text{--}50^{\circ}\text{N}$; $64\text{--}100^{\circ}\text{E}$) comprising the HKH region observed an increasing trend of 0.9°C per decade in mean annual temperature and 0.12 mm/decade in precipitation in the past century (Harris *et al.* 2014). The mean annual temperature is expected to rise by $2.6\text{--}5.2^{\circ}\text{C}$ by 2100 under two scenarios [Intergovernmental Panel on Climate Change (IPCC) A2 and B1; Chen *et al.* 2013]. Since 1960, although the precipitation trend has shown an overall minor increase, less seasonal and high inter-annual variation in precipitation has been experienced in the HKH region (Chen *et al.* 2013). Precipitation showed a significant increase during the winter and spring, but non-significant decrease during the summer and autumn seasons. Future projections of precipitation indicate a wetting trend with increases of 38 or 272 mm by 2100 under two scenarios (IPCC A2 and B1). Such climate diversity and possible future alteration estimated to modify the species richness pattern in this landscape where the impact of climate and topographic variability is identified as the major reasons (Panda *et al.* 2017; Tripathi *et al.* 2017).

With the advent of satellite remote sensing and related data products, and availability of several open source models, it is imperative to develop geospatial frameworks integrating different drivers of change and customise the analysis methods

and models. Forest cover monitoring and change assessment can rely on remote sensing technology with ground measurements for verification (Behera *et al.* 2014). This enables researchers to compare and analyse the consistent changes across landscapes. Researchers have used the moderate resolution imaging spectro-radiometer derived TCC% and the normalised difference vegetation index data to represent various forest formations and estimated their resilience in relation to the responsible variables (Bucini and Hanan 2007; Staver *et al.* 2011). The spatio-temporal changes in forest cover of the HKH region studied across the landscapes suggest that both the natural and anthropogenic forces played a key role (Houghton 2005; Rudel *et al.* 2005; Upadhyay *et al.* 2005; Roy *et al.* 2013; Murthy *et al.* 2016; Behera *et al.* 2018). In the current study, we have utilised the TCC% data to define various forest formations, and estimated their resilience by accounting to precipitation.

2. Study area

The HKH region encompasses all or parts of eight countries – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal and Pakistan (figure 1). This region lies between $16^{\circ}\text{N}\text{--}40^{\circ}\text{S}$ and $61\text{--}105^{\circ}\text{E}$ with $>3500\text{ km}$ stretch along the east–west direction. The HKH region consists of several parallel mountain ranges, i.e., the Karakoram, the Hengduan Mountains, the Himalayas, the Hindu Kush and the Tibetan Plateau. The sharp

Figure 1. HKH region is spread over eight countries with the elevation above MSL.

altitudinal gradient and topographic variations resulted in compressed ecoclimatic zones accommodating very rich biodiversity (Behera and Kushwaha 2007). The forest types vary along the elevation gradient such as tropical and sub-tropical rainforests; temperate broadleaf, deciduous or mixed; temperate coniferous, alpine moist and dry scrub; meadows; and desert steppe (Behera *et al.* 2002; Guangwei 2002). The forests of the HKH region support over 12% of the world's population and provide various ecosystem goods and services including freshwater, energy, timber, variety of bio-resources, etc. to one-fifth of world's population (Zomer *et al.* 2011; Ning *et al.* 2014). The rangelands of the HKH region are experiencing unprecedented pressure and deterioration due to four-fold increase in human and livestock population in the last 5–6 decades (Sharma *et al.* 2007).

3. Materials and methods

3.1 Tree canopy cover for the year 2000, loss and gain during 2000–2012

Here, we have estimated the precipitation-dependent forest cover resilience. The high-resolution TCC% data (30 m) for the year 2000 and the forest loss and gain data during 2000–2012 were downloaded from the Earth Engine Partner's database (<http://earthenginepartners.appspot.com/>). Mosaicking and extraction were done using the study area boundary to prepare the tree canopy cover and change maps (table 1). The tree canopy cover is defined as the canopy closure for all the vegetation taller than 5 m in height, and represented as the TCC% per 30 m grid cell ranging from 0 to 100% (Hansen *et al.* 2013). The TCC% map for the year 2000 represents the percent of tree canopy cover in each cell or pixel for the year 2000. The forest cover loss data was encoded ranging from 1 to 12, where the number indicates the year of TCC% loss during 2000–2012; whereas the forest cover gain data was encoded as 0 and 1 that corresponds to 'no change' and 'gain during 2000–2012', respectively,

having no information about the year-wise forest cover gain. The TCC% loss and gain data only indicates the spatial location of forest canopy cover change, and does not account to change in TCC%. All the data were resampled to 5 km for further analysis. The elevated Tibetan Plateau is almost devoid of forest cover beyond 5500 m elevation, and experiences $< -2^{\circ}\text{C}$ mean annual temperature and about 100 mm mean annual precipitation (Singh and Singh 1987). Hence, these areas were masked out using elevation [digital elevation model (DEM) from the shuttle radar topographic mission (SRTM)] and temperature data to avoid any bias in further analysis (Hirota *et al.* 2011). For elevation data, the SRTM-derived DEM data was downloaded from the database of 'Consortium for Spatial Information (CGIAR-CSI)'. The spatial resolution of the data is 90 m (table 1). Mosaic and extraction by masking was done to extract the data for the HKH region.

3.2 Climate data description and source

The global precipitation and temperature data was downloaded from the climate research unit (CRU) database for the year 2000. The CRU (version TS3.21) data was constructed using the monthly observations from the meteorological stations across the world's land areas, primarily from three sources, i.e., (i) World Meteorological Organization (around 2200 stations during 2002–2009 and >2800 stations for unique precipitation measurements), (ii) Monthly climatic data for the world produced by US National Oceanographic and Atmospheric Administration (via its National Climatic Data Center) (average number of stations: 1500 during 2002–2009 with 2600 precipitation measurement stations), and (iii) World Weather Records decadal data publications that are exchanged between National Meteorological Services (around 1700 stations during 1991–2000) (Harris *et al.* 2014). The mean annual temperature and total annual precipitation were derived using the monthly data, which was then clipped using the study area boundary in the ArcGIS

Table 1. *Data specifications as utilised in the study.*

Data	Year	Resolution	Data source
Canopy cover, forest loss–gain	2000 and 2000–2012	30 m	Earth-engine partners
Temperature and precipitation data	2000–2010	0.5°	CRU data
SRTM DEM	2000	90 m	CGIAR-CSI

CRU: climate research unit; CSI: consortium for spatial information.

platform. The total annual precipitation varied between 13 and 5299.8 mm during 2010 (defining the variation in precipitation observed between all measured data in this region), where the moderate-to-high precipitation areas were observed in north-east India, Myanmar, Bangladesh, Bhutan and northern Nepal; while the least precipitation was observed in Pakistan, Afghanistan, north India and northern part of China (figure S1). The range of mean annual temperature varied between 12° and 27°C, where the negative mean annual temperature was observed in the northern part of China, which are mostly cold desserts with no vegetation above 5500 m altitude.

3.3 Estimation of forest cover resilience

The tree canopy cover map was categorised into four forest categories depending on the dominance TCC% (0% as treeless state, 1–10% as grass savanna, 11–39% as scrub and $\geq 40\%$ as forest). To estimate the forest cover resilience, we have adopted the same technique as [Hirota et al. \(2011\)](#), where they performed logistic regression and which then used to fit to a second-order polynomial equation to derive the corresponding resilience. We have used the ArcGIS platform to convert the TCC% data in vector and further to extract the corresponding precipitation values. We performed the logistic regression and then fitted the second-order polynomial equation. Using the coefficients of the polynomial equation, we calculated the value of z (precipitation-dependent parameter) and the corresponding resilience probability using the following equations:

$$P(\text{category} = y) = \frac{1}{1 + \exp(-z)},$$

$$z = \beta_0 + \beta_1 x + \beta_2 x^2,$$

where y is either treeless, grassland, scrub or forest; β_0 is a constant; $\beta_{1,2}$ are coefficients; and x is the precipitation.

Similarly, we also tried computing the resilience probability accounting ‘ z ’ to temperature as an independent variable. The basic principle of the logistic regression is that it transmits the input–output relations using the binary presence ($Y = 1$) and absence ($Y = 0$) data or here, a particular forest cover type with the independent variable, i.e., precipitation and temperature. Now, the linear or non-linear regression can be used to find the unknown parameters in the function.

Table 2. Area estimates of tree canopy cover for the year 2000.

Class (TCC%)	Area in km ² (area%)
Treeless (0)	3,450,100 (79.79)
Grass (1–10)	13,600 (0.32)
Scrub (11–39)	92,850 (2.15)
Forest (40–100)	767,200 (17.74)
Total	4,323,750

4. Results and discussion

The HKH region is dominated by treeless area with 79.79% of the total geographical area (table 2; figure 2). The remaining 20.21% area was covered by forest, scrub and grasslands with 767,200 km² (17.74%), 92,850 km² (2.15%) and 13,600 km² (0.32%), respectively. The country-wise forest area statistics showed that the maximum contribution was by Myanmar (263,775 km²) followed by India (201,550 km²) and China (199,975 km²) and the least contribution was by Afghanistan (2000 km²) (table 3). In case of both scrub and grassland spread, the maximum contribution was by China followed by India and Myanmar (figure 2). The maximum treeless area was accounted to China, which was >62% of the total treeless area (table 3). The HKH region experienced an overall loss of 11,250 km² forests during 2000–2010 that can be separated to 13,225 and 1975 km² forest loss and gain, respectively ([Murthy et al. 2016](#)). Out of the total forest loss, Myanmar alone accounted to 51% forest loss, whereas in India 24% forest loss took place (table 3). According to the Forest Survey of India report (FSI 2013), in Arunachal Pradesh alone, nearly 1000 km² forest loss took place during the study period. [Behera et al. \(2018\)](#) studied the deforestation in the entire northeast India, and observed a combined loss of 3300 km² of forest, scrub and grassland during 1985–2005. In Myanmar, 0.31 m ha of forest loss was observed during 2000–2010 due to the overuse of forest resources ([FAO 2010](#)). On the other hand, 3.41% increase in net forest cover is reported in China during 2000–2013. Similarly, Bhutan has reported forest gain of 0.22% per year during 1990–2010 ([Gilani et al. 2015](#); [Li et al. 2017](#)).

Since we observed a better regression value (R^2) for precipitation than temperature, we used only precipitation to predict the resilience in this study. The scatter plot of TCC% w.r.t. precipitation is given in figure 3 with the corresponding curve of

Figure 2. Tree canopy cover map categorised into four vegetation types of the HKH region.

Table 3. Country-wise area estimates of tree canopy cover for the year 2000 (in km²).

Country name	Treeless	Grass	Scrub	Forest
Afghanistan	415,381	175	2225	2000
Pakistan	424,664	1225	5325	6325
India	297,522	3275	21,300	201,550
Nepal	79,145	1000	8325	58,600
China	2,168,143	4850	35,400	199,975
Bhutan	13,497	175	1700	24,525
Bangladesh	3616	325	1150	10,450
Myanmar	48,132	2575	17,425	263,775

resilience probability (Pr) estimated by applying the logistic regression. The corresponding β coefficient values for each forest type and the Nagelkerke R^2 of logistic regression are given in table 4. With the R^2 values noted as 0.42, 0.11, 0.12 and 0.44 for forest, scrub, grass and treeless, respectively, in table 4, it can be inferred that the precipitation was able to explain the TCC% distribution for forest and treeless areas fairly, but failed to explain the distribution of grassland and scrub. This could be due to two possible reasons: (i) the presence of large treeless data points even at higher precipitation areas where the occurrence of scrub and grassland data points was least, and (ii) the absence of gradual increasing trend in TCC% with the precipitation, as observed by

Hirota *et al.* (2011). Moreover, the HKH region has large variations due to frequent alteration in elevation, which makes it a topographically rugged landscape and creates sharp transition in the closely spaced climatic zones supporting different forest cover formations at very short intervals. Further, the distinct climate condition was observed in the southern and northern aspects. In the HKH region, large forest data points were observed at 500–1700 mm precipitation range, coinciding with larger distribution of both scrub and grasslands. The overlapping precipitation ranges of treeless and forest cover with the scrub and grassland could have led to their insignificant presence in the HKH region. However, the presence of sufficient forest cover data points even at higher precipitation zones compared to scrub and grassland allowed in modelling their presence. The mid-value of forest cover resilience (i.e., $\text{Pr} = 0.5$) was observed around 1650 mm precipitation, below which a larger proportion of forests lies and estimated to have lower resilience. The mid Pr value for treeless state was observed around 1470 mm, which indicates that the change prone treeless areas have higher precipitation value than this. However, the maximum Pr values for scrub and grassland were estimated to be 0.15 and 0.25, respectively, which could be attributed to their overlapping in precipitation ranges with forest and treeless areas.

Figure 3. Probability of resilience (secondary axis) of different vegetation types (TCC% in primary axis) w.r.t. total annual precipitation (mm) (horizontal axis).

Table 4. Estimated coefficients and the Nagelkerke R^2 of the logistic regressions predicting vegetation types as a function of total annual precipitation and mean annual temperature.

Vegetation					
Variable	type	β_0	β_1	β_2	R^2
Rainfall	Forest	-3.316	0.002	0.000	0.42
	Scrub	-4.127	0.001	0.000	0.11
	Grass	-6.126	0.001	0.000	0.12
	Treeless	3.238	-0.002	0.000	0.44

The estimated resilience probabilities of four forest types are given in table 5 and figure 4. The values of Pr were categorised at an interval of 0.05 and their corresponding area spread was mentioned. About 375 km² (<0.05% of the total forest cover) area was estimated to have Pr < 0.05, indicating the forests with the highest tendency of transition to its alternative stable state of scrub with 14,875 km² having Pr between 0.05 and 0.1 (figure 5). Around 59.3% of the total forests showed Pr < 0.5 owing to their presence in the lower precipitation range (<1650 mm) in north-east India, northern part of India, Nepal, Bhutan and Pakistan, southeastern parts of China and Myanmar. Rest of the forests (around 40.65%) with Pr > 0.5 were mostly found in north Nepal, Bhutan, northeast India, Bangladesh, western and

north Myanmar having wetter climate. About 25,200 km² treeless areas were identified as having least resiliency (Pr < 0.05), and could exhibit transition tendency to its alternative stable state of grassland (figure 6). These treeless areas were mostly seen in western Myanmar, northern India and Bangladesh. Only 4.6% of the total treeless areas showed the lower resilience (Pr < 0.5) observed in areas with sufficient amount of precipitation, whereas rest 94.4% areas exhibited the higher resilience probability to be in the same state as can be seen in the drier parts of China, north India, Pakistan and Afghanistan (figure 6).

The majority of the scrub and grasslands observed to have less resilience probability indicate their transition to the alternative forest state with lower TCC%, whereas the moderate and

Table 5. Area estimate (in km²) of treeless and various meta-stable states of tree canopy cover (grass savanna, scrub savanna and forest savanna) resilience probabilities (inversely, change proneness) for the year 2010.

Resilience Probability	Treeless to Grass	Grass to Treeless & Scrub	Scrub to Grass & Forest	Forest to Scrub
0-0.05	25200	13375	80650	375
0.05-0.10	11350	200	10950	14875
0.10-0.15	7100	25	1025	61950
0.15-0.20	11625		125	51500
0.20-0.25	8550		100	68950
0.25-0.30	12875			35700
0.30-0.35	8050			80175
0.35-0.40	9025			53275
0.40-0.45	20875			50475
0.45-0.50	26800			37875
0.50-0.55	32425			21700
0.55-0.60	61025			22450
0.60-0.65	68025			42100
0.65-0.70	61175			35700
0.70-0.75	107050			22500
0.75-0.80	166825			13050
0.80-0.85	172100			19650
0.85-0.90	354600			23750
0.90-0.95	866400			54100
0.95-1	500775			57050

Rest of the treeless areas (918,250 km²) belongs to cold deserts with 0% TCC located above 5000 m altitude received <1200 mm precipitation and below <−2°C temperature. Colour is used to highlight the major observations as: (i) treeless to grass – orange colour: least resilient treeless area (highest change proneness to grass); cream colour: less resilient treeless area (low change proneness to grass); light brown: resilient treeless area; (ii) grass to treeless and scrub – cream colour: change prone grass towards treeless; orange: resilient grass cover; yellowish: change prone grass towards scrub; (iii) scrub to grass and forest – orange: change prone scrub towards grass, dark yellow: resilient scrub cover; yellowish green: change prone scrub towards forest; (iv) light shade of dark yellow: highly change prone forest cover towards scrub; olive green: less change prone forest towards scrub; green: resilient forest cover.

fewer areas were observed to have higher probability values. Keeping either-end transition probability, the scrub and grasslands with the highest range of resilience probability were attributed to change-proneness to forest and scrub with 100 and 25 km², respectively (table 5). On the other end, with the lowest resilience probability range, 13,375 km² grassland and 80,650 km² scrubs showed change-proneness to treeless and grassland state, respectively. Scrub areas change-proneness to forests was observed in zones with the higher precipitation in Myanmar, Nepal, Bhutan and northeast India and change proneness to grassland was observed in the drier parts of northern India, Nepal and Pakistan and Eastern China (figure 7). A similar pattern was also seen for grassland, where they occupied the wetter zones of northeast India and Myanmar showing the transition probability to scrubs, and drier areas of China and north India showing the transition tendency to treeless state (figure 8).

Timely deforestation and afforestation in the parts of China, Myanmar, northeast India and Nepal are very common according to the countries forest management policies (www.forestlegality.org/). Murthy *et al.* (2016) identified an overall deforestation of 11,250 km² in HKH region; where TCC% was decreased by 13,225 km², whereas TCC% was increased by 1975, 50, 650 and 5375 km² in treeless, grassland, scrub and forest areas, respectively, during 2000–2010. The Pr values of these points where TCC% changed were examined through these changes and attributed to possible anthropogenic activities (table 6; figure 9). From table 6, it can be observed that majority (7050 km²) of the TCC% loss took place in forest areas having less resilience (Pr < 0.5), whereas 5625 km² forest areas have undergone TCC loss while having higher resilience probability (Pr > 0.5). Only 25 km² forests with least resilience probability have experienced TCC loss during 2000–2010. However, change in TCC%

Figure 4. Tree canopy cover resilience map.

Figure 5. Forest cover resilience map.

was observed negligible in grassland and scrub in comparison to forest and treeless areas. About 325 and 1000 km² treeless areas having least

(Pr<0.05) and moderate (0.05<Pr<0.5) resilience probability values, respectively, have undergone TCC rise, which has 875 km² area estimation

Figure 6. Resilience map of treeless state.

Figure 7. Resilience map of scrub.

under the higher resilience probability. Increases in TCC% in forest areas were observed as 2225 and 3275 km² having the moderate and higher

resilience. Most of the changes in TCC% were observed in northeast India and Myanmar, which could be due to the anthropogenic activities such

Figure 8. Resilience map of grassland.

Table 6. Area estimate (in km²) of points where TCC% increased and decreased during 2000–2010 with the corresponding resilience in the year 2000.

	TCC% Decreased				TCC% Increased			
Resilience Probability	Treeless to Grass	Grass to Treeless & Scrub	Scrub to Grass & Forest	Forest to Scrub	Treeless to Grass	Grass to Treeless & Scrub	Scrub to Grass & Forest	Forest to Scrub
0-0.05	0	50	300	25	325	50	50	0
0.05-0.10		0				0		
0.10-0.15		0	175			0	225	
0.15-0.20			0				0	
0.20-0.25				7050 (MC:1)	1000 (MC:3)			2225 (MC:5)
0.25-0.30	0							
0.30-0.35								
0.35-0.40								
0.40-0.45								
0.45-0.50								
0.50-0.55								
0.55-0.60								
0.60-0.65								
0.65-0.70								
0.70-0.75				5625 (MC:2)	875 (MC:4)			3275 (MC:6)
0.75-0.80	0							
0.80-0.85								
0.85-0.90								
0.90-0.95								
0.95-1								

Map code (MC) w.r.t. figure 9.

as shifting cultivation practices, rubber and other forest plantation in northeast India, and higher annual allowable cut with intense anthropogenic

activities in Myanmar (figure 9) (Maithani 2005; Ramakrishnan 2007; Songer *et al.* 2009; Saha *et al.* 2010; Mon *et al.* 2012).

Figure 9. Map showing some location points where TCC% changed (increased/decreased) during 2000–2010.

5. Conclusions

The arrangement of mountains in the HKH region makes it a highly variable landscape that created distinct differences in the spatio-temporal distribution in precipitation and temperature, i.e., climate zones and the corresponding forest types. Around 873,650 km² forest area was observed in the HKH region in the year 2000, which experienced change (both loss and gain) in TCC% of 13,225 and 8025 km², respectively, during 2000–2010. In the HKH region, places having extreme temperature with low precipitation were mostly devoid of forest cover as seen in Pakistan, Afghanistan and northern parts of China. The results clearly showed that the precipitation has much bearing on forest and treeless state resilience in comparison to scrub and grassland. The forest cover resilience ($Pr > 0.5$) was observed having >1650 mm precipitation. The majority of forest cover ($>59.3\%$) observed as less resilient is correlated with the lower precipitation range. Around 1% of treeless areas observed to have least resilience and more than 94.4% of the areas with <470 mm precipitation

were observed to be resilient ($Pr > 0.5$). The resilient and change proneness estimation proved that the utility of the method to be more fitting for forest and treeless categories than the grassland and scrub. However, the model performance for the grassland and scrub could be improved by examining more factors or employing the more critical process-based models as dynamic vegetation models. The higher variability in input data in the present study also could lead to the lesser sensitivity of the analysis for grassland and scrub. This may need a landscape level analysis for better performance of the model.

5.1 Management and forest resilience

Globalisation and climate change have an increasing influence on the stability of fragile mountain ecosystems and the livelihoods of mountain people. In 2007, the IPCC recognised the HKH region as a ‘data-deficient area’. In the last few decades, the HKH region has undergone rapid economic, social and environmental changes triggering changes in forest cover, land use, ecosystem and their services.

This study utilised a geospatial framework to estimate the precipitation-driven tree canopy cover resilience or proneness in the HKH region. The tree canopy cover change proneness and resilience map showed clearly the areas having different levels of change and resilience potentials. Interestingly, most areas in northeast India, western Myanmar, Bhutan and Nepal showed resilient to forest change owing to climate attributes. The areas showing high forest change proneness are located in lower Siwalik foothills and Myanmar, and hence qualify urgent attention for conservation.

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