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Forest fragmentation and human population varies logarithmically along elevation gradient in Hindu Kush Himalaya - utility of geospatial tools and free data set

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Abstract: Hindu Kush Himalaya (HKH) is the largest and the most diverse mountain region in the world that provides ecosystem services to one fifth of the total world population. The forests are fragmented to different degrees due to expansion and intensification of human land use. However, the quantitative relationship between fragmentation and demography has not been established before for HKH vis-à-vis along elevation gradient. We used the globally available tree canopy cover data derived from Landsat-TM satellite to find out the decadal forest cover change over 2000 to 2010 and their corresponding fragmentation levels. Using SRTM-derived DEM, we observed high forest cover loss up to 2400 m that highly corroborated with the population distribution pattern as derived from satellite observation. In general, forest cover loss was found to be higher in south-eastern part of HKH. Forest fragmentation obtained using 'area-weighted mean radius of gyration' as indicator, was found to be very high up to 2400 m that also corroborated with high human population for the year 2000 and 2010. We observed logarithmic decrease in fragmentation change (area-weighted mean radius of gyration value), forest cover loss and population growth during 2000-2010 along the elevation gradient with very high R^2 values (i.e., 0.889, 0.895, 0.944 respectively). Our finding on the pattern of forest fragmentation and human population across the elevation gradient in HKH region will have policy level implication for different nations and would help in characterizing hotspots of change. Availability of free satellite derived data products on forest cover and DEM, grid-data on demography, and utility of geospatial tools helped in quick evaluation of the forest fragmentation *vis-a-vis* human impact pattern along the elevation gradient in HKH.

Keywords: Tree canopy cover; Topography; Diachronic analysis; Biogeography; Human impact

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Introduction

Forests provide critical social, economic, health and environmental benefits to humankind, including food, timber, recreation, climate regulation and biodiversity conservation (Gao and Liu 2011). Many studies pointed that forest ecosystems have been significantly degraded or depleted as a consequence of human disturbances in many places of the world (Matin and Behera 2017; Gustafsson et al. 2012). The degradation of forest ecosystems are typically due to forest loss and fragmentation (Onojeghuo and Blackburn 2011; Behera 2010). Forest fragmentation refers to the progressive process of subdividing original large and intact forest patches into smaller isolated and geometrically irregular ones. Forest loss and fragmentation generating various negative environmental and ecological consequences, have become widespread phenomena across the globe (Behera and Roy 2010; Riitters et al. 2000). Fragmentation of natural and semi-natural habitats constitutes major extinction threats as they reduce the availability of suitable habitats for many species, also leading to regime shift in biodiversity (Pardini et al. 2010; Behera et al. 2005). Fragmentation may also have negative effects on species richness by reducing the probability of successful dispersal and establishment (Hagen et al. 2012), as well as by reducing the capacity of a patch or habitat to sustain a resident population (Habel and Zachos 2012). Therefore, it creates high priorities on the agenda of local and regional government in formulating forest protection policy or land use planning using inputs from forest fragmentation studies (Roy et al. 2013; Behera 2000).

The ecological consequences of fragmentation can differ depending on the pattern or spatial configuration imposed on a landscape and how they vary, both temporally and spatially (Wickham et al. 2007). The spatial distribution of forest patches and their association and connectivity identified on satellite imagery are linked to fragmentation analysis, is an established technique for assessing the degree of threat to ecosystems (Roy et al. 2013; Behera 2010). Monitoring of forest patches and their spatial arrangements in temporal scale provides insight to qualitative and quantitative evaluation of landscape fragmentation in defined time interval. Remote sensing combined with geographic information systems (GIS) and landscape ecological analysis can successfully provide spatially consistent and detailed information about landscape structure such as fragmentation: a prerequisite to study ecosystem services, sustainable resources management and land use planning (Liu et al. 2014; Coops et al. 2010; Roy and Behera 2002).

The characteristics of patches and their temporal variations in a landscape can be measured by studying the spatio-temporal changes of patch sizes (Giriraj et al. 2010; Behera et al. 2005). Numerous landscape indices have been developed to quantify landscape structure and spatial heterogeneity based on the composition and configuration of landscapes (Šímová and Gdulová 2012; Behera et al. 2005). Traditional patch metrics like patch area, number of patches (NP), mean patch size (MPS), largest patch index (LPI), patch density (PD) etc. are used in estimating landscape fragmentation (Kadıoğulları 2013; Başkent and Kadioğullari 2007). However, spatially landscape fragmentation can be studied by employing spatially explicit parameters such as radius of gyration (Molina et al. 2015). Baker et al. (2015) examined the metrics that quantifies the connectivity and fragmentation in landscape ecology concluded that the radius of gyration has distinct significance which the other metrics lack. Again, the area-weighted mean radius of gyration (also known as correlation length), signifies that staying in a particular patch the expected distance to traverse starting from a random point and moving in a random direction (Keitt et al. 1997). It is often interpreted as a measure of the physical connectedness of the landscape (McGarigal et al. 2002). Echeverria et al. (2006) studied the spatio-temporal deforestation and fragmentation using the area-weighted mean radius of gyration (measures of both fragment extent and habitat connectivity) and highly recommended this parameter for the physical continuity analysis of forest patches across the landscape and over time.

Like other mountain landscapes deforestation, overgrazing, human activities, infrastructural development and steep slope cropping practices in high-altitude rangelands contributes to fragmentation in Hindu Kush Himalaya (HKH) region (Rueff 2014; Wu et al. 2013). Road accessibility, population proximity and temperature increase are found as the major drivers of forest cover change in Hindu Kush Himalaya (Murthy et al. 2016). The slowly changing climatic conditions and rapid population growth causes forest fragmentation, often at the forest boundaries (ICIMOD 2013; Behera 2010). However, the influence of human disturbance has not generally been the focus in fragmentation studies (Hobbs and Yates 2003). Forest fragmentation and elevation defines the forest structure and composition, and it regulates the ecology and distribution of its organisms (Garbarino 2013). Sharma and Roy (2007) reported from a study in central Himalaya that the forests that escaped fragmentation were either inaccessible to humans or had rigorous legal protection. Cayuela et al. (2006) studied the forest clearance and corresponding fragmentation in the highlands of Chiapas, Mexico; and attributed human population, increasing demand for cropland area and timber to their causes. Forest fragmentation along elevation gradient due to anthropogenic activities is poorly understood in HKH landscape. This differential fragmentation creates unnatural heterogeneous habitats altering patterns of species richness. The current study aims to identify the spatio-temporal variation of the fragmented landscape in the HKH region to find out the pattern of variation along elevation gradient incorporating the effects of human population, as human caused fragmentation could be managed with various acts.

1 Study Area

The study area, HKH region with 4.3 million km^2 area is known as the ‘Roof of the World’ comprises of dense forests, dry to cold deserts with barren lands. It spreads over eight countries such as the whole of Nepal, Bhutan; and partly India, Myanmar, China, Bangladesh, Pakistan and Afghanistan (Figure 1). The elevation varies from the mean sea level in Myanmar to 8848 m (above mean sea level) at the Everest, the world’s tallest mountain peak. It is the largest and the most diverse mountain region in the world, comprising of 3500 km long complex landscape of mountains, plateaus, river gorges, and plains (Murthy et al. 2016). With 30% of the world’s glacier, this region is also regarded as the 'Third Pole' (ICIMOD 2013). The region has been experiencing above-average warming and climatic variability during the 20th century with significant implications for both environment and vast population (Kulkarni et al. 2013). Recent studies identified that about 54% of the HKH are rangelands, whereas agricultural lands and forests cover about 26% and 14% respectively (Chettri et al. 2008; Bajracharya and Shrestha 2011; Öztürk et al. 2015). Out of the rest, 5% areas are seen to be permanently covered with snow-glaciers and 1% area is identified as water body (Ning et al. 2014). The complex topography and diverse climatic conditions of HKH defines its unique landscape, accommodating around 25,000 plant and animal species with rich biodiversity (ICIMOD 2011). This region also includes all or part of the four global biodiversity hotspots, 330 important bird sanctuaries, two mega-diversity countries (in India and China), and 60 eco-regions (Karki et al. 2012). With a total of 488 protected areas covering 39% of the HKH Mountain, this landscape supports more than 210 million inhabitants those depend directly and indirectly for essential ecosystem services. This region supplies food, water, ecosystem services, bio resources, energy and timber to one fifth of the total world population (Ning et al. 2014). Yet, the region has been recently suffering from forest cover loss due to various anthropogenic and natural causes (Murthy et al. 2016).

2 Data and Methodology

We used the tree canopy cover (TCC) data to derive the fragmentation, the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) for elevation information and population data for entire HKH region. The SRTM DEM data collected in a 11-days mission in the year 2000, was used for elevation analysis owing to its higher vertical accuracy and reliability over ASTER; and higher spatial resolution over GTOPO (Varga and Bašić 2015; Rexer and Hirt 2014) (Figure 1). The 90m DEM data was downloaded from ‘Consortium for Spatial Information (CGIAR-CSI)’ database. The individual DEM tiles were mosaicked and the HKH region was extracted

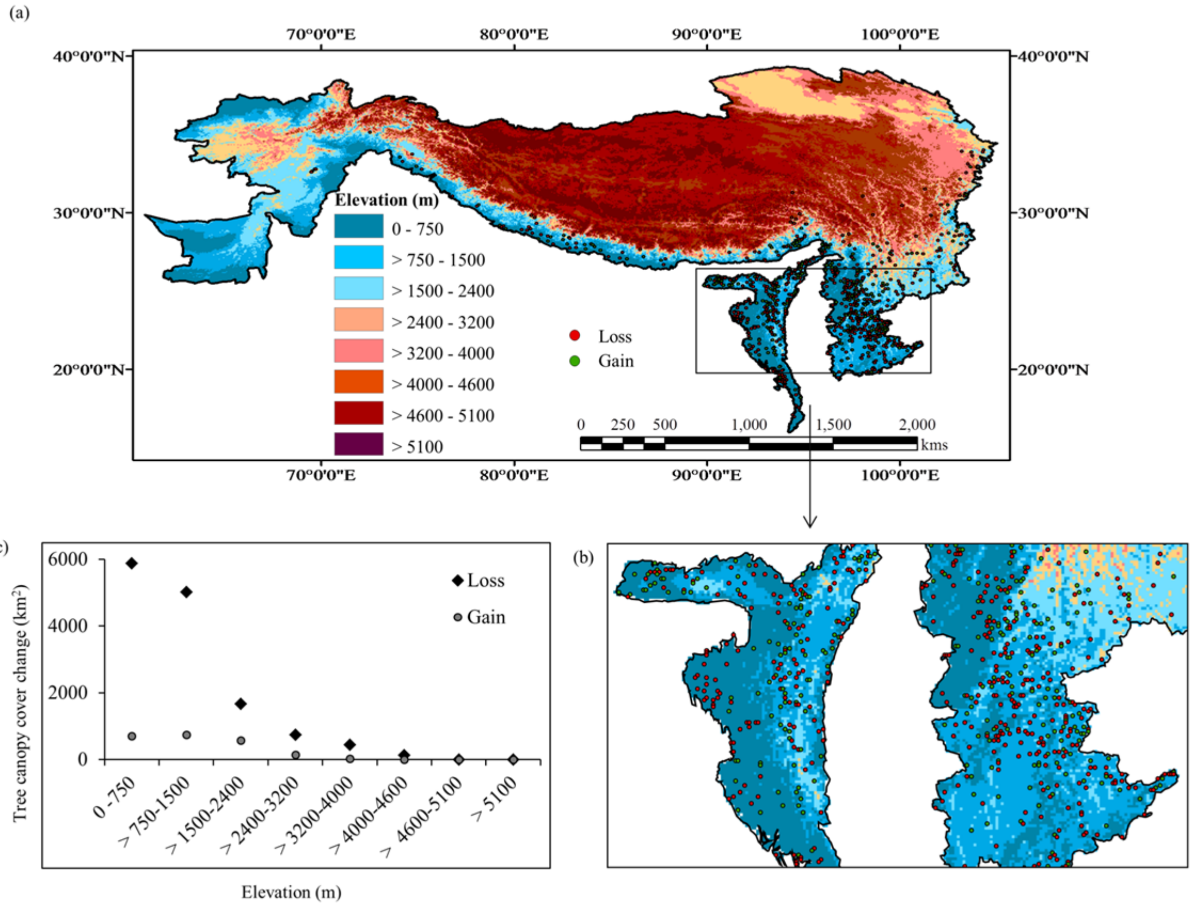

Figure 1 (a) Elevation map of Hindu Kush Himalaya (HKH) region spread over 8-Asian countries with TCC change points during 2000-2010, (b) South-Eastern region of HKH has been zoomed to highlight the change locations, and (c) change in TCC at 8 elevation gradients.

using ArcGIS (10.0 Version) software. Using raster calculator, the *No data* values were removed from the DEM data. The whole elevation range was categorized into eight divisions (hereafter the divisions are referred as elevation gradients) for further analysis (Table 1; Figure 1). The population count data at 5 km resolution (i.e., 5 km × 5 km = 25 km^2 grid size) representing the total population were downloaded from Socioeconomic Data and Applications Center (SEDAC) database for the year 2000 and 2010; and elevation gradient wise change was calculated (Figure 2; Table 1) (Doxsey-Whitfield et al. 2015). The settlement location data was collected from the Socioeconomic Data and Applications Center (SEDAC) database (Balk et al. 2006), which was available for the year 2000 only, demotes the location having population more than 5000 (Figure 2). To extract the cropland areas in the study area, 500 m MODIS land cover data (Product name: MCD12Q1) for the year 2000 and 2010 were downloaded from the Reverb website (Friedl et al. 2010). The MODIS data was mosaicked and projected into UTM projection with WGS84 datum using the MODIS reprojection tool (MRT) (Figure 2).

Landsat-derived 30 m resolution tree canopy cover (TCC) maps with more than 99% overall accuracy at global scale for TCC loss and gain published by Hansen et al. (2013) were used for tree cover change and fragmentation analysis. The loss and gain observed in the data were validated using a probability-based random sample in each biome with 120 m blocks (Hansen 2013). Total 1500 blocks were taken, where in each biome 150 blocks for no change and 90 for change and 60 for gain. Assistance was taken from low resolution Moderate Resolution Imaging Spectroradiometer (MODIS) and high resolution Google Earth imagery. The LiDAR (light detection and ranging) data from Geoscience Laser Altimetry System (GLAS) instrument of IceSat-I satellite was also incorporated to calculate the tree height. The

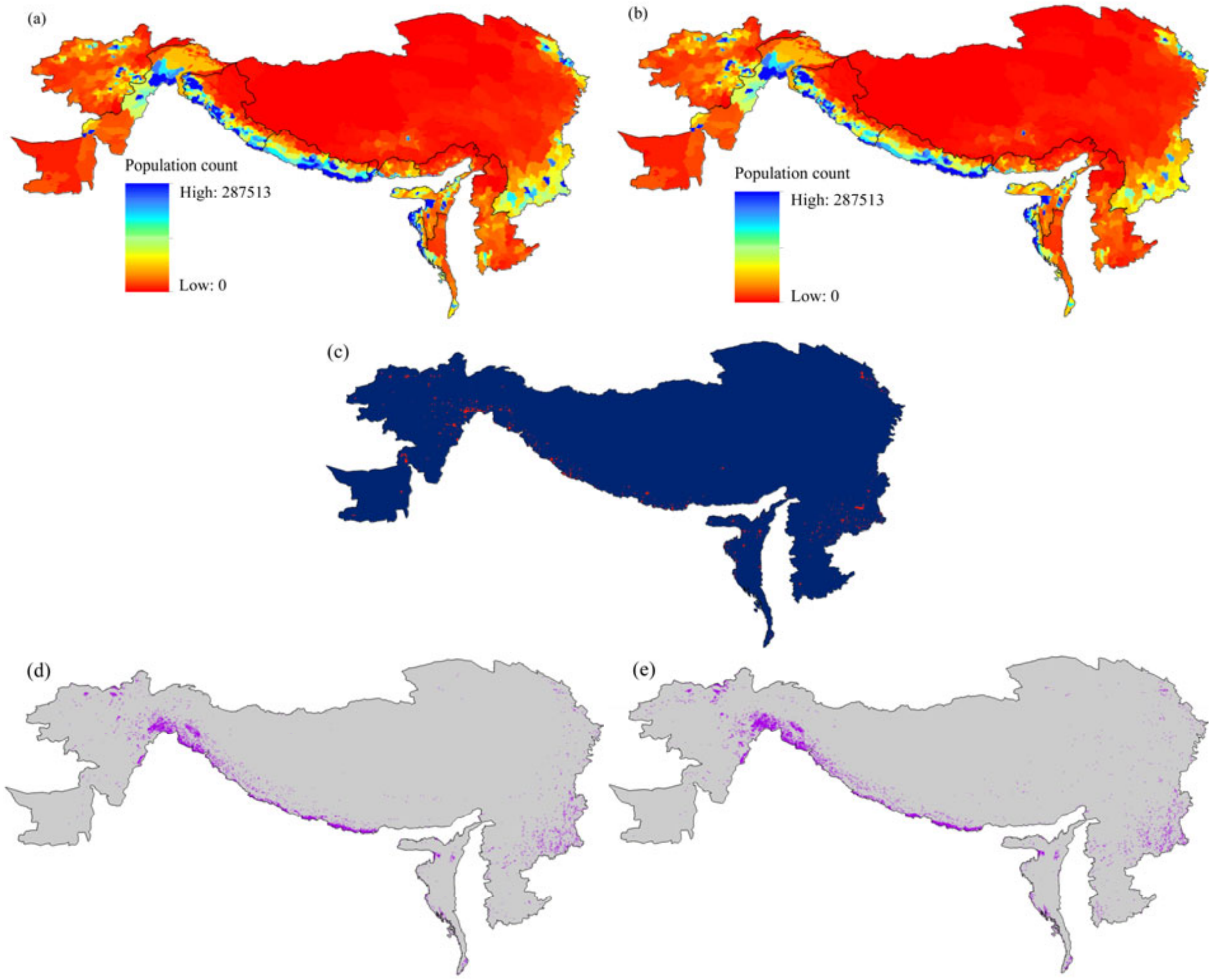

Figure 2 Total population count at 5 km × 5 km pixels for the year (a) 2000 and (b) 2010 in Hindu Kush Himalaya; (c) Urban areas [red pixels]; cropland covers [purple pixels; 500m resolution] for the year (d) 2000 and (e) 2010 in Hindu Kush Himalaya.

Landsat scene of before and after forest loss was integrated with the GLAS data, that confirmed the forest loss and the year of disturbance. In tropical, sub-tropical and temperate climate zones, 628, 295 and 298 points were validated respectively, which showed >99% overall accuracy in all climate zones. The TCC data values range from 0 to 100% denoting the tree canopy taller than 5m in height, has been expressed in percentage at each 30 m × 30 m pixel; and is available only for the year 2000 in the 'Earth Engine Partners' database (Hansen et al. 2013). The year-wise *TCC loss,* and the entire *TCC gain* data during 2000 to 2012 data were available in 'Earth Engine Partners' database in binary format (Hansen et al. 2013). To calculate the TCC for the year 2010, the *TCC loss* for the period of 2010 to 2012 was eliminated using year wise loss data; and the *TCC gain* during 2000 to 2012 were added to the TCC data of 2000. Here onwards, the tree canopy cover term has been used as a surrogate of forest cover.

The TCC raster data for the year 2000 and 2010 were used as input data to calculate fragmentation in 'Fragstats' (version 4.0), a statistical program (McGarigal et al. 2012). The dynamics of patch area is one of the key factors for analyzing the landscape fragmentation. Being non-spatial, the analysis of patch area was expressed via a spatial parameter as radius of gyration, which is a measure of patch extent. The larger the patch, the greater the radius of gyration, i.e., higher value corresponds to less fragmented patches and vice-versa. The area-weighted mean (AMN) considers the patch structure using a landscape-centric perspective to provide better measure of landscape dynamics in comparison to mean patch characteristic provides path-centric perspective. AMN equals to the sum across all patches in a landscape of the corresponding patch metric value multiplied by the proportional abundance of the patches (i.e., patch area divided by the sum of patch areas; McGarigal et al. 2012). As AMN is the ratio of patch area to the sum of patches; with fragmentation, the patch area and AMN value reduces. Landscapes with a smaller mean patch size can be considered as more fragmented than one with larger mean patch size. Mathematically, AMN can be expressed as follows:

$$AMN = \sum_{i=1}^{m}\sum_{j=1}^{m}\left[x_{ij}\left(\frac{a_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{m}a_{ij}}\right)\right]$$

where, x_{ij} = value of a patch metric for patch ij, a_{ij} = area of patch ij.

The AMN radius of gyration also known as correlation length was computed at landscape level to analyze fragmentation. Using a moving window algorithm, this metric calculates the exact pattern included in the window. Lower the correlation length, lesser is the landscape connectivity and vice-versa. The change in correlation length with time gives the temporal change in landscape connectivity (Keitt et al. 1997). The forest cover maps of 2000 and 2010 were resampled at 5km resolution to reduce the data computation time. A window size of 5 × 5 pixels was used to calculate the AMN radius of gyration for the year 2000 and 2010 in Fragstat software. In similar window size the other indices as number of patches (NP), mean patch size (MPS), largest patch index (LPI) and patch density (PD) were derived for the years 2000 and 2010 in Fragstat software. The fragmentation change maps were derived by using map algebra tool in ArcGIS software and their mean values were extracted, incorporating the elevation gradient raster. As the value of correlation length is reversely correlated to fragmentation, the reduction in the correlation length value during 2000 to 2010 signifies reduction in patch size or increase in fragmentation; and the increase in correlation length value signifies increase in patch area or decrease in fragmentation. To find the nature of fragmentation with the variation in elevation, the change in fragmentation (including decrease and increase) for all the indices, percentage of forest cover change (including loss and gain), and the response variables as cropland cover change, urban area change and percentage population change was extracted for each elevation gradient. Changes in the total number of patches during 2000 to 2010 was derived; however, mean values of change were derived for AMN radius of gyration, mean patch size, largest patch index and patch density. Before, regression analysis for relationship establishment, collinearity test was carried out among the fragmentation indicators, and responsible variables. Then after, results were used to regress with the mean elevation in *Statistica* software v10.0 (StatSoft Inc. 2011). The non-linear estimation tool was used to add the user defined function as logarithmic function with least square regression method at 95% confidence interval. The Gauss-Newton method with 50 iterations was applied. We observed logarithmic function to be best fitted between for fragmentation change (AMN radius of gyration), percent forest cover loss and percent population growth during 2000-2010 along the elevation gradients.

3 Results and Discussion

We divided the whole elevation range in to 8 elevation gradients and found that maximum geographical area is occupied in the elevation range of 4000-5100 m accounting about 20% area of the entire HKH. This region is almost devoid of vegetation cover (Table 1; Figure 1). The total population and total cropland cover for the years 2000 and 2010; and the total urban areas in the year 2000 are shown in Figure 2, observed similar to one another. We derived the percent of population, total cropland cover and total numbers of urban area (>5000 population) in each elevation gradient (Table 1). We have observed that the percent of population was collinear (R^2 > 0.95) with both the cropland covers and urban areas, therefore the total population was only selected as a responsible variable for forest change analysis further (Figure 3). The forest cover change map was generated using subtraction of TCC data for the period of 2000-2010 (Table 1; Figure 1). Forest cover area changes in each elevation gradient are

Table 1 Land surface area, total population, total cropland area, total urban area, forest cover area along the elevation gradient for the year 2000, 2010 and corresponding change

Elevation (m)	Area (km^2)	Population (millions)			Cropland area (km^2)		Urban area (km^2)	Forest cover (km^2)				
								Area		Change		
		2000	2010	Change	2000	2010		2000	2010	Loss	Gain	Overall Change
0-750	540575	35.44	45.04	9.6	6274.37	7514.25	37567.49	242800	237625	5875	700	- 5175
>750-1500	539050	21.42	26.64	5.22	2474.75	3354.66	16771.65	228525	224250	5025	750	- 4275
>1500-2400	507875	26.04	31.77	5.73	3334.67	3659.63	18296.34	167275	166175	1675	575	- 1100
>2400-3200	517850	11.27	13.43	2.16	1159.88	949.91	4749.05	106900	106300	750	150	- 600
>3200-4000	519200	5.63	6.78	1.15	474.95	394.96	1974.61	81800	81375	450	25	- 425
>4000-4600	681700	3.37	4.04	0.66	144.99	169.98	849.83	36925	36800	125	0	- 125
>4600-5100	967325	1.5	1.78	0.28	40.00	50.00	249.95	8150	8150	0	0	0
> 5100	552025	1.18	1.41	0.22	40.00	10.00	49.99	1275	1275	0	0	0

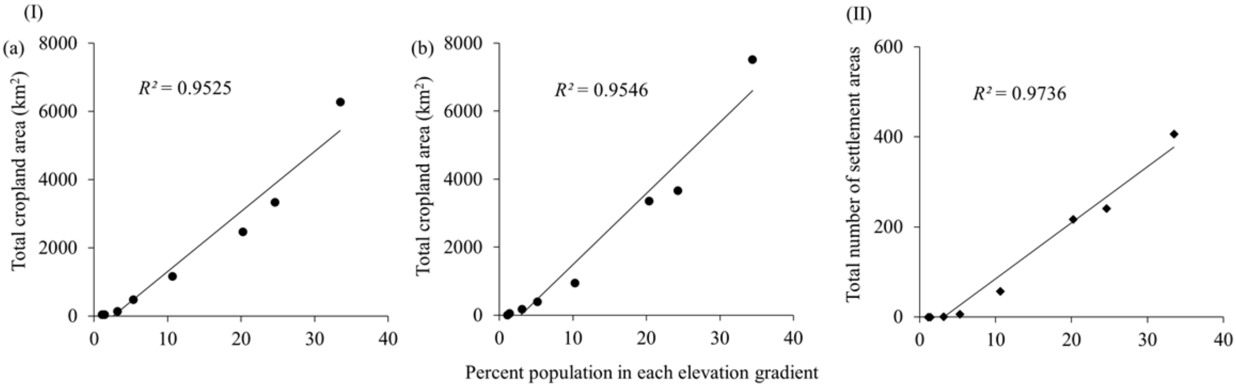

Figure 3 Scatter plot and linear relation of (I) percent population (X-axis) in each elevation gradient with total cropland area (Y-axis) for the years (a) 2000 and (b) 2010; and (II) percent of population (X-axis) with the total number of settlement areas (>5000 population) for the year 2000 (Y-axis) in Hindu Kush Himalaya.

summarized in Table 1. It can be inferred that during the study period, population and forest cover were drastically decreased along the elevation gradients. Interestingly, above 2400 m, the percent of forest cover area proportionated to the percent of population density and *vice versa*. We observed high population increase and forest cover loss up to 2400 m elevation during 2000-2010; while there was minor increase in population beyond 4600 m, without recognizable loss in forest cover (Table 1). Severe loss of forest cover was observed in the North-East India, Myanmar and Bangladesh part of HKH, followed by southern part of Nepal and China (Figure 1). These areas mostly coincide with dense population at low elevations (Figure 1a, b).

It was observed from the Landsat satellite derived TCC images that there has been very less/ no change in forest cover over the parts of Afghanistan, Pakistan and Bhutan covering HKH (Figure 1). Interestingly, in HKH, both forest cover gain (afforestation/regeneration) and loss (depletion/conversion/deforestation) happened simultaneously, though the percent of later event was more than the former (see the zoomed portion of north-eastern India in Figure 1). This can be attributed to the higher rate of deforestation or degradation of natural forest cover than afforestation or natural forest growth in this region. Reddy et al. (2016) studied the forest cover change in Bangladesh, observed 0.77% annual deforestation rate during 2006 – 2014. They attributed higher deforestation in dense forest (compared open forest) to increased anthropogenic pressure. According to FAO (2012), during 2000 – 2010 the rate of deforestation in Myanmar was 0.93% of its total forest cover. It was observed that the country has undergone afforestation during the past decade. Deforestation in North East India was mostly attributed to shifting cultivation practices, conversion to agriculture lands, overuse of forest products, etc. (FAO 2012; Sheikh et al. 2011; Behera and Roy 2005). The region has also undergone afforestation such as rubber and other native species (Roy et al. 2015). Along the elevation gradient, it was observed that more than 90% forest cover loss and 92% forest cover gain took place below 2400 m elevation during 2000 to 2010 (Table 1, Figure 1c). Forest cover loss followed a decreasing trend from the lowest elevation gradient, whereas the highest gain in forest cover was observed at the elevation range of 750 – 1500 m; however, the overall forest cover change followed the same trend as forest cover loss. During 2000 to 2010, 13900 km² area undergone forest cover loss via deforestation or depletion in canopy cover and 2200 km² area undergone forest cover gain via afforestation or regeneration; with an overall loss of 11700 km² tree covered areas in HKH during this period. The first two elevation gradients (up to 1500 m) holding 54% of the total tree cover area experienced 81% of total forest cover loss. This is followed by two mid-elevation gradients (1500-3200 m) holding 35% tree cover area experienced 14.53% of forest cover loss.

The changes in mean patch size (MPS), largest patch index (LPI), number of patches (NP) and patch density (PD) are shown in Figure 4 and the elevation gradient-wise change statistics are given in Table 2. From Table 2, it can be inferred that lowest MPS was observed in the elevation gradient of 1500-2400 m; whereas MPS was higher below 750 m compared to 750-1500 m elevation gradient. MPS decreased in all the elevation gradients except the elevation gradient 2400-3200 m, and above 4600 m. Highest decrease in MPS was observed in the lowest elevation gradient as 8.53 km² followed by the second elevation gradient of 5.35 km². It could be attributed to the anthropogenic activities that reducing forest patch size at its periphery mostly at flat terrain of lower elevation for agriculture land expansion. However, the changes of MPS in the rest of the elevation gradients were observed very low (<0.56 km²). LPI denotes the percentage area of the largest patch to the landscape area i.e., percentage area occupied by the largest patch. It can be seen that lowest LPI value was observed in the elevation gradient of 1500-2400 m, denotes the largest patch in this elevation gradient was smallest among all the elevation gradients; which corroborated the lowest mean patch size in this elevation gradient. Nearly similar pattern was observed with LPI, where maximum LPI was decreased in the first and second elevation gradients, and changes in the upper elevation gradients were observed low. From the Table 2, this could be attributed that the largest patches in the first and second elevation gradients reduced by 0.84% and 68% respectively. However, the total number of patches and patch density increased in

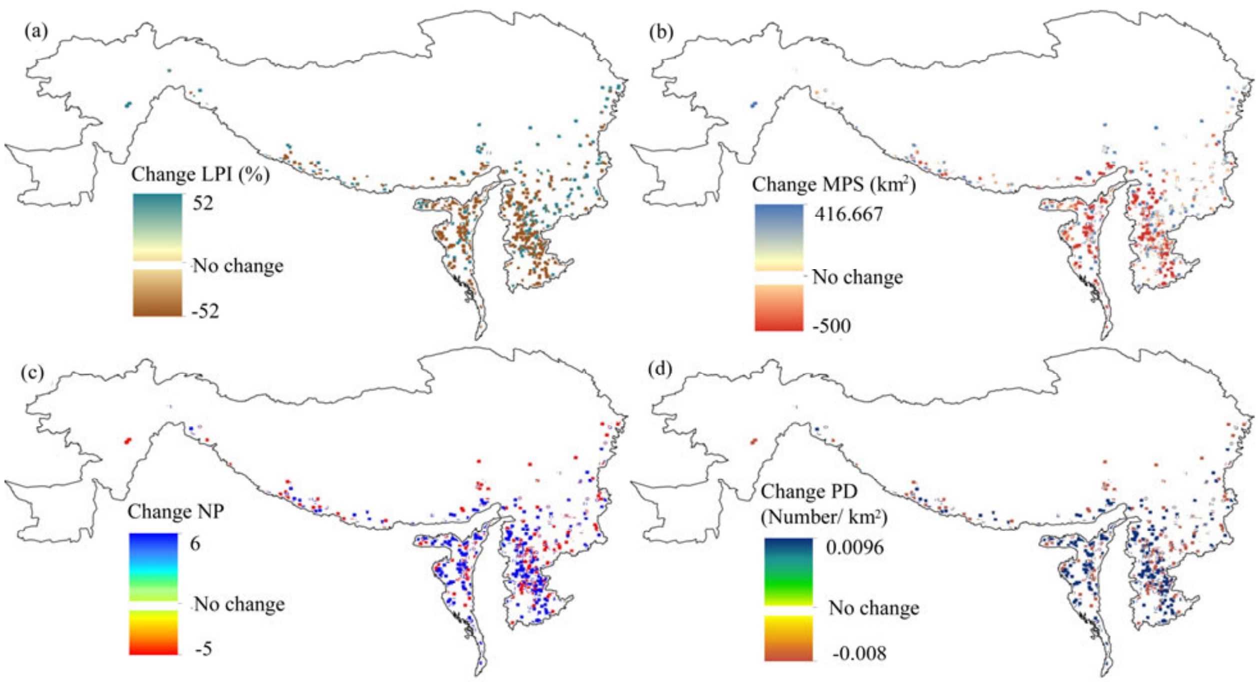

Figure 4 Change in (a) largest patch index (LPI), (b) mean patch size (MPS), (c) number of patches (NP) and (d) patch density (PD) during 2000 – 2010.

all the elevation gradients, where the majority of changes were observed in the first two elevation gradients. With the lowest MPS and LPI values, highest number of patches was observed in the elevation gradient of 1500-2400 m. Again, the number of patches in the elevation gradient of 1500-2400 m was significantly higher compared to the patches below 750 m having higher MPS and LPI values. Maximum numbers of patches were increased i.e., 1620 in the second elevation gradient of 750-1500 m compared to 1523 number of patches in the first elevation gradient of 0-750 m. Patch density is a surrogate of total number patches. The lower values of patch density in the lowest elevation gradient shows that the number patches in this gradient were lesser with higher mean patch size and having larger patch area i.e., higher LPI values. With this same reason, the patch density of elevation gradient 750-1500 m was lesser than the former due smaller patch size and lesser LPI values. Highest patch density observed for 1500-2400 m with lowest MPS and LPI values. In contrast to total number of patches, maximum change in patch density observed in the first elevation gradient, followed by the second gradient, and then reduces above 1500 m. The fragmentation as indicated by these indices showed majority of the fragmentation took place below 1500 m, and low up to 4600 m, and significantly low beyond 4600 m. These results clearly show the impact of anthropogenic activities on at below 1500 m was significantly higher than above 1500 m. The AMN radius of gyration computed in Fragstat and the corresponding change in fragmentation are given in Figure 5a and 5b. The mean AMN radius of gyration for the year 2000 and 2010 with corresponding change in mean value with the percentage change in forest cover in each elevation gradient are shown in Figure 6a and 6b, Table 2. The AMN radius of gyration value varied from a minimum of 4994 to a maximum of 9589 at 3200-4000 m elevation, indicating the maximum and minimum levels of fragmentation respectively for the year 2000 and 2010 (Table 2; Figure 6). The changes in the AMN radius of gyration value during the decade were dominantly observed in the South Eastern region of HKH, eastern part of Myanmar and North East India: moderately in South East China, Bangladesh and Nepal (Figure 5). This corroborates with the significant increase in number of patches in North East India during 1975 to 2005 by Reddy et al. (2013). Similar trend of high forest fragmentation in these regions were also observed by Roy et al. (2013) and Murthy et al.

Table 2 Area-weighted mean radius of gyration, mean of patch size, mean of largest patch index, total number of patches, mean of patch density value distribution along the elevation gradient for the year 2000 and 2010 and their change during 2000-2010

Elevation (m)	Mean area-weighted mean radius of gyration (m)					Mean of patch size (km²)		
	2000		2010		Change in Mean	2000	2010	Change
	Range	Mean	Range	Mean				
0 -750	5463-9500	8863	5463-9500	8825	-38	385.18	376.65	-8.53
>750-1500	5215-9563	8699	5183-9563	8671	-28	345.48	340.13	-5.35
>1500-2400	5198-9575	8573	5198-9575	8565	-8	326.51	325.95	-0.56
>2400-3200	5282-9526	8829	5282-9526	8830	1	416.51	416.66	0.15
>3200-4000	4994-9589	8833	4994-9589	8831	-2	417.33	417.04	-0.29
>4000-4600	5000-9574	9068	5000-9574	9067	-1	497.58	497.32	-0.26
>4600-5100	5756-9481	9277	5756-9481	9285	0	582.30	582.34	0.04
> 5100	5992-9472	9332	5992-9472	9332	0	603.77	603.81	0.04

Elevation (m)	Mean of largest patch index (%)			Total number of patches			Mean of patch density (number/km²)		
	2000	2010	Change	2000	2010	Change	2000	2010	Change
0 -750	85.75	84.91	-0.84	45336	46859	1523	0.005046	0.005216	0.000170
>750-1500	79.77	79.09	-0.68	74486	76106	1620	0.006467	0.006608	0.000141
>1500-2400	75.29	75.16	-0.13	78962	79014	52	0.007233	0.007237	0.000005
>2400-3200	82.59	82.60	0.01	59190	59246	56	0.005347	0.005352	0.000005
>3200-4000	84.64	84.61	-0.03	54464	54525	61	0.004913	0.004919	0.000006
>4000-4600	92.63	92.59	-0.04	48574	48670	96	0.003320	0.003327	0.000007
>4600-5100	98.27	98.26	-0.01	42667	42684	17	0.002060	0.002061	0.000001
> 5100	99.42	99.42	0.00	20565	20566	1	0.001776	0.001776	0.000000

Notes: Decrease in the mean values of area-weighted mean radius of gyration indicates increase in fragmentation.

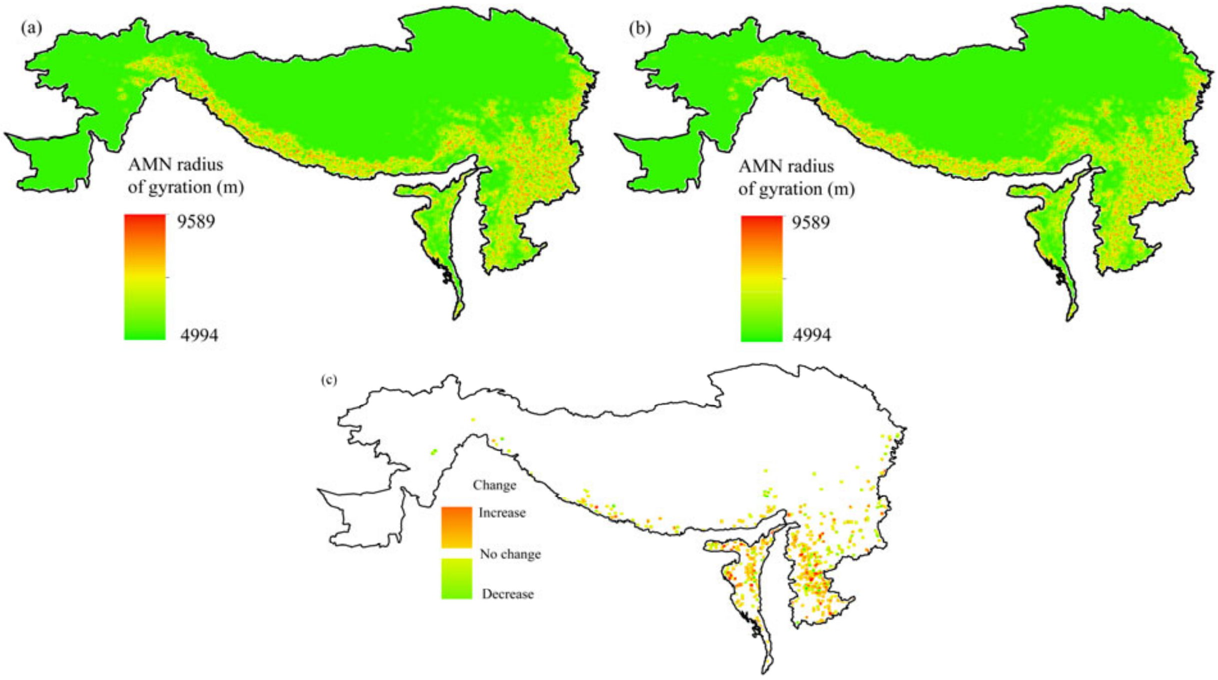

Figure 5 Area-weighted mean radius of gyration shows extent and connectivity of forest patches across the HKH during (a) 2000, (b) 2010 and (c) change during 2000-2010.

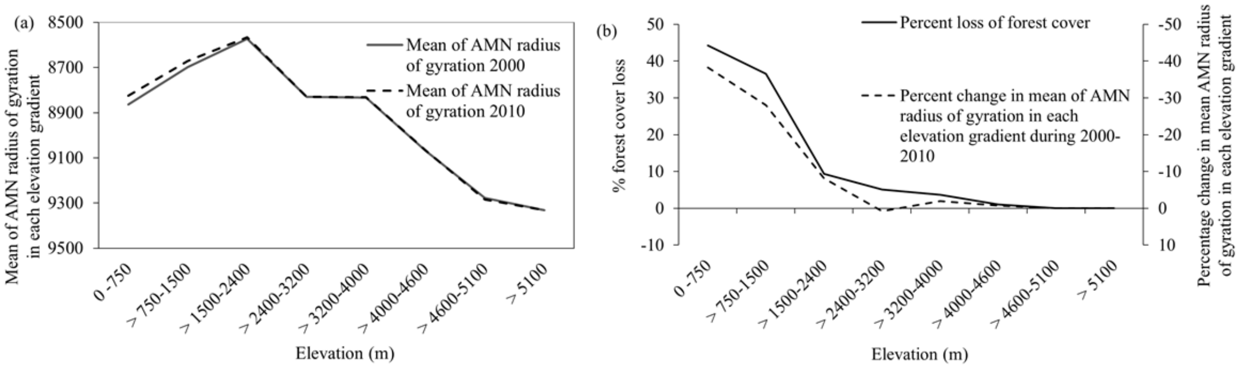

Figure 6 (a) Change of mean of AMN radius of gyration in each elevation gradient indicates higher level of fragmentation up to 2400 m; (b) Percent change in mean of AMN radius of gyration in each elevation gradient during 2000-2010 is plotted with percent of forest cover loss. The sharp decrease in forest cover loss was proportional to forest fragmentation till 2400 m that slowed down further and halted by 4000 m.

(2016) who attributed that shifting cultivation, population pressure, forest logging, agricultural land expansion were the main reasons. Dong et al. (2014) studied the forest cover change and associated fragmentation in Southeast Asia, and observed higher number of fragmented patches in Myanmar. Shrestha et al. (2016) observed higher fragmentation in large core and perforated forest while studying the deforestation, due to cropland and grassland expansion in Nepal during 1990 to 2009. Along the elevation gradient, the mean AMN radius of gyration value decreased up to 2400m, indicating increase in fragmentation; marginally increased at 2400 – 3200 m, indicating decrease in fragmentation; decreased at 3200-4600 m indicating minimal fragmentation; and beyond 4600 m indicating no fragmentation during 2000-2010 (Table 2; Figure 6a). In general, the mean AMN radius of gyration value decreased in 2010 in comparison to 2000 indicating overall landscape fragmentation restricted up to 2400 m (Table 2). The change in minimum AMN radius of gyration value was only observed at the elevation range of 750 – 1500 m indicating further fragmentation of the exiting fragmented patches at this elevation during 2000 – 2010. Whereas, the maximum AMN radius of gyration values was observed to be static, indicating no change in least fragmented patches. Higher fragmentation at lower elevation could be due to high anthropogenic activities like shifting cultivation, agriculture land expansion, forest logging and lopping etc. triggered by higher rate of population growth (Table 1 and Figure 6). However, at 1500 m - 2400 m, the population growth was about 22.88%, but the intensity of fragmentation change was not so high as compared to the lower elevation (Table 1). The forest cover loss and increasing fragmentation level showed a unanimous decreasing pattern along the elevation gradient (Figure 6b). The highest fragmented patches observed at 1500-2400 m elevation could be attributed to intense anthropogenic activities that only allow occurrence of smaller vegetation patches. Similar result was also observed by Mendoza et al. (2005) in Mexico due to presence of small vegetation patches at mid-elevation range. In a special report by ICIMOD, Ning et al. (2013) have discussed about the loss of vegetation at high altitude rangelands of HKH, and concluded that the human activities like expansion in agriculture, settlements, road and other infrastructure are the major reasons. At very high elevations, the cold deserts support no vegetation cover and the harsh climatic conditions and complex terrain provides inaccessible and unsuitable living conditions. Thus, with increase in elevation, the anthropogenic activity gradually decreases due to less population and low growth rate leading less forest cover loss (Murthy et al. 2016), consequently lower or no fragmentation. All the indices showed that majority of the landscape fragmentation occurred in the first two elevation gradients i.e., below 1500 elevation during the study period.

Prior to establish the relationship between fragmentation and population count along elevation gradients, collinearity test was also carried out as done with the response variable. The changes in the fragmentation indices in the elevation gradients are summarized in Table 2. We observed high linear correlation ($R^2 > 0.93$) among AMN radius of gyration, mean patch size, largest patch index, number of patches and patch density. Therefore, we have chosen one fragmentation indicators as AMN radius of gyration as the traditional indicators lacks sensitivity and consistency, and have limitation in evaluating habitat fragmentation across all the phases of fragmentation process (Jaeger 2000).

The scatter plots of fragmented points (AMN radius of gyration; hereafter the fragmentation refers to the changes in AMN radius of gyration) during 2000 - 2010 are given in Figure 7a, showing the grid locations, where fragmentation has increased and decreased respectively with the mean and standard deviation of fragmentation shown at each elevation gradients. The corresponding change in population has been shown in Figure 7b. It can be observed that, at all the elevation gradients both the increase and decrease in fragmentation occurred during the study period. The overall change in mean fragmentation including both the increase and decrease in fragmentation with the corresponding percentage change in forest cover loss and population growth have been plotted in Figure 8. According to the applied regression functions, we found the negative logarithmic function to be the best fitted with high R^2 values of 0.889, 0.895 and 0.944 for fragmentation, forest cover loss and population growth respectively, indicated significant decreasing pattern in population growth along elevation gradient followed by forest cover loss and fragmentation. As per the characteristics of negative logarithmic function, the initial components contributed most with rapid decreasing trend that quickly saturates further. From Figure 8, it can be seen that the contributions from the initial two elevation gradients were around 85% of the total fragmentation (triangle boxes), and with the addition of the third elevation gradient, the contribution raised to around 95%, which thereafter reduced subsequently. The lower proportion of natural tree cover at high altitudes could be misinterpreted when assessing the landscape fragmentation. Therefore, in the current study we evaluated the change in fragmentation instead of fragmentation of individual years.

Different countries have varied rules for forest cover management. The current study on forest fragmentation in HKH with reference to population growth along the elevation gradients has advantages for framing conservation policies. In HKH, most deforested and fragmented landscape was observed Myanmar, which has also shown afforestation during 2000 – 2010. It is noted that Myanmar has colonial-style centralized

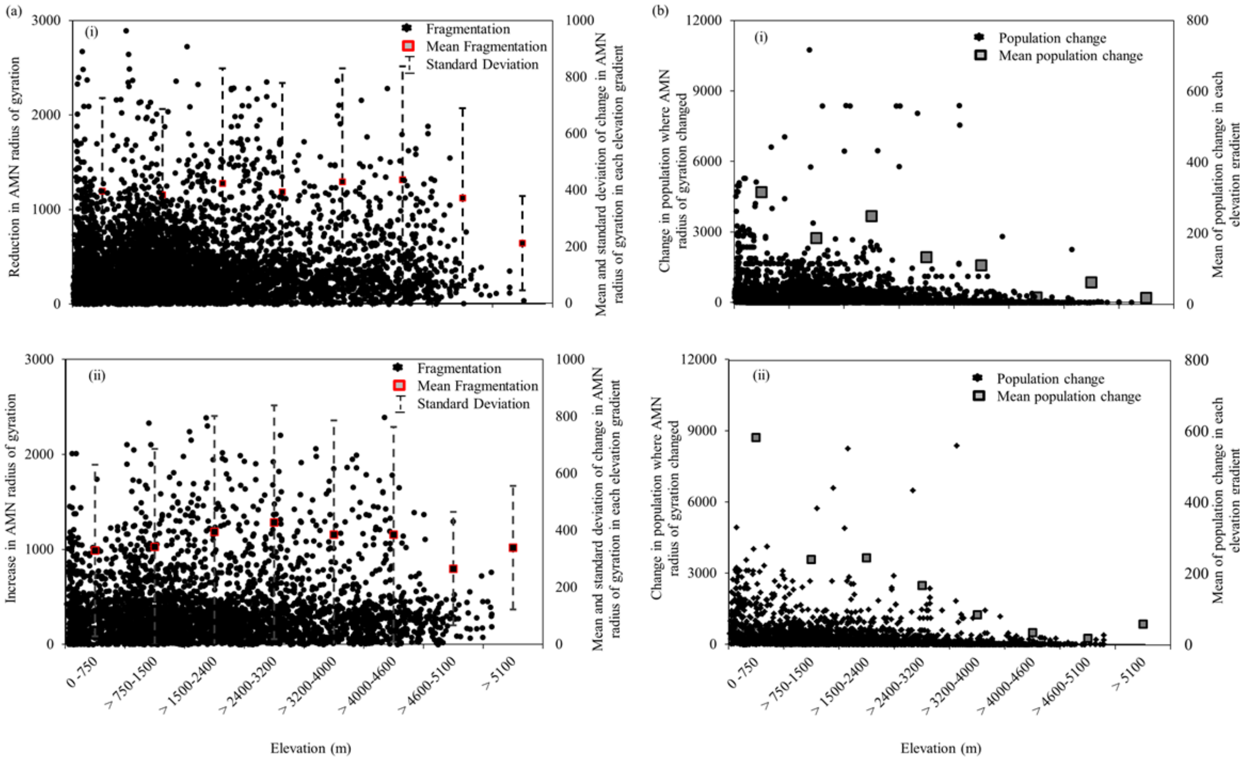

Figure 7 (a) Scatter plots of the points where fragmentation (i) increased (reduction in AMN radius of gyration) and (ii) decreased (increase in AMN radius of gyration) [Y-axis], mean and standard deviation of change in AMN radius of gyration in each elevation gradient [Y'-axis] along elevation gradients [X-axis] took place during 2000-2010; (b) scatter plots of corresponding change in population and mean population for (i) increased and (ii) decreased fragmentation locations.

forest ownership and control by the national government. Forest-management in Myanmar prioritizes timber extraction for export, and both illegal logging and conversion for commercial agriculture is widespread (Brandt et al. 2017); and therefore has shown the highest deforestation. The Annual Allowable Cut (AAC) which defines the allowable limit of forest use was set to 179,000 numbers of Teak trees and 1,366,000 number of hardwood trees till 1992-1993; further, it was modified to 124,000 and 1,795,000 number for teak trees and hardwood trees respectively. The AAC was again revised in 2010 to set 147,300 teak trees and 1,131,461 hardwood trees to reduce the limit by 33.4% (Woods and Canby 2011). According to the updated forest conservation act of India, 2003, the diversion of forest areas for non-forestry purposes needs prior approval from central government; mostly allowed for development of drinking water, irrigation projects, road-rail transmission lines, power projects, defense use and mining with compensatory afforestation and plans for catchment area treatment, biodiversity and wildlife conservation, rehabilitation etc. India's Recognition of Forest Rights Act (RFRA), 2006, was enacted due to democratic processes driven by demand for recognition of forest rights by forest dwellers. RFRA represents a political, demand-based effort to reform forest governance through a provision of rights to forest-dependent people (Kumar et al. 2015). Deforestation and associated fragmentation were observed very less for Bhutan, could be attributed to the forest policies for sustainable conservation and management. According to the forest and nature conservation rules 2006, all forests in Bhutan to be government reserved forests, provides land allotment and rights, allows leasing of parts of reserved forests. The nationalization of forests eliminated legal status for traditional forest management, although such practices remain in Bhutan (Brandt et al. 2017). Moderate rate of deforestation and afforestation with corresponding fragmentation was seen in Nepal. The introduction of community forestry protects local forests and allows sustainable use of forest products along with rural developments

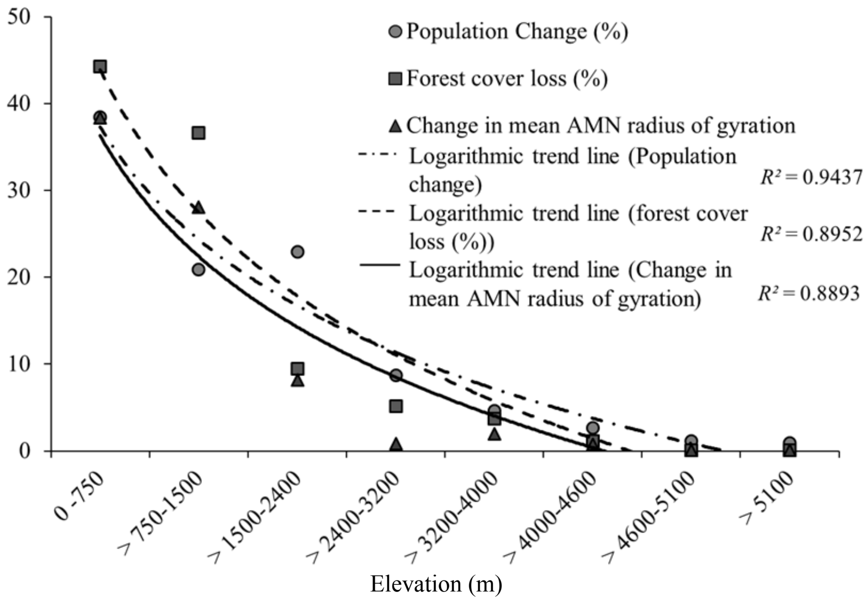

Figure 8 Logarithmic decrease (high R^2 values) in fragmentation level change (AMN radius of gyration; triangle box), forest cover loss (square box) and percent population growth during 2000-2010 (circle) along 8-elevation gradients in HKH; [lines showing the regression curves as: solid line for AMN radius of gyration, dashed line for forest change and dashed with dotted line for population change].

including poverty alleviation. According to Brampton and Cammaert (2007), nearly two million people of Terai population in Nepal benefited from community forestry which provides 100% rights of forest products, imparted under the Forest Act (1993), Forest Regulations (1995) and 1st Amendment (1998). In China, the deforestation and associated fragmentation were observed in the eastern part. High population density in China imposes high timber and wood products demand. Community forests are managed through China's collective forestry program, which has historically focused on timber extraction. In 1998, China implemented the National Forest Conservation Plan (NFCP), which banned commercial logging in southwestern China, but allowed harvesting by collectives, primarily for economic development (Brandt et al. 2017).

4 Conclusions

The aim of this study was to provide the pattern of fragmentation, forest cover change dynamics and demographic condition along the altitude of the world's largest mountainous region. The spatio-temporal remote sensing data product by Earth Engine Partners was used as the primary data greatly helped in understanding the status forest cover change and corresponding fragmentation status in the HKH landscape. The pattern of landscape fragmentation is illustrated along the elevation gradients as well as spatially with five indices as area-weighted mean radius of gyration, mean patch size, largest patch index, total number of patches and patch density. The spatially explicit results on landscape fragmentation across elevation gradients would help the managers and planners for additional assessment, prioritization and conservation of landscape ecology via disturbances, change in patch connectivity. The analysis shows that the South East part of the HKH is the most disturbed regime, which is one of the most important regions both economically and ecologically. Our finding on the pattern of fragmentation, forest cover dynamics, and demography across elevation gradient will have policy level implications for this HKH region. Though, forest cover loss is expected to trigger forest fragmentation due to its origin from the former, reverse pattern was also noticed at 2400m. Increases as well as decrease in patch fragmentation observed in all the elevation gradients during the study period, with a net increase in fragmentation. We observed higher mean patch size, larger patches with significantly less number of patches below 750 m compared to the 750-1500 m elevation gradient. More than

3100 patches were reduced in the study area below 1500 m during 2000 to 2010. The changes in largest patch index values showed reduction in largest patches below 1500 m. Similarly, all the derived landscape indices showed that majority of landscape fragmentation occurred in first two elevation gradients i.e., below 1500 m, which was then reduced with increase in elevation due to less anthropogenic pressures. Since the elevation wise landscape fragmentation and demography is related logarithmically, it would be wise to accelerate plantation and gap-filling afforestation activities at low and mid-elevation areas. As the forest loss, population increase and fragmentation were seen to follow negative logarithmic trend, this signified that lower elevation ranges contributed to the most fragmentation. With this outcome, the fragmentation needs to be mitigated by afforestation activities to diminish forest gaps and to enhance patch connectivity at lower altitudes to reduce the threats of further fragmentation, habitat loss, local species extinction, biodiversity loss, etc. Moreover, ecosystem resilience and forest connectivity is also on stack by fragmentation, which is a key indicator of reforestation. With the results, it can be concluded that anthropogenic activities such as deforestation, forest looping, cropland expansion, shifting cultivation, urbanization, rail-road construction etc. has high impact on forest cover at low altitudes compared to higher altitudes (Murthy et al. 2016). Therefore, it is required to monitor the population growth at lower altitudes to estimate the possible threats to hotspots, which need different conservation and management policies compared to the hotspots at higher altitudes. Availability of satellite derived data products on forest cover and DEM, grid-data on population growth and utility of GIS helped in quick evaluation of the fragmentation pattern along the HKH elevation gradient. Our analysis on forest fragmentation and population corroboration through maps and statistics, would be useful to all the countries (falling under HKH region) in formulating their conservation measures. More such studies and integration of other drivers would provide better insight into the fragmentation study in future days.

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