Assessment of the alpine plant species biodiversity in the western Himalaya using Resourcesat-2 imagery and field survey

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In the alpine ecosystem of the Himalaya, an observation of species diversity with habitat heterogeneity predicts some important factors that govern them. Information theory-based species biodiversity at the community level and habitat heterogeneity at the landscape level were studied. Resourcesat-2 linear imaging self-scanning sensor (LISS-III and LISS-IV)-based spectral diversity indices and species diversity indices of four summits with increasing elevation gradients were estimated. The species richness decreased with an increase in elevation. The southern aspect of the sub-alpine zone has the highest biodiversity having a 3.5 Shannon' entropy (H). Despite receiving higher insolation, the increase in elevation leading to coldness and dominance of a few species make the southern aspects less diverse at the higher elevation. Both elevational gradients and microclimatic conditions define biodiversity in the Himalaya. Resolution from coarser (LISS-III) to finer (LISS-IV) to micro (field) scale showed an increasing range of values, $H = 0.1, 0.2$ and 2.1 , respectively. There is significantly less correlation between field and satellite measured biodiversity indices ($r, -0.5$ to 0.3). To go closer to the field level of biodiversity assessment, there is a need to use satellite data having a higher spatial resolution. Spectral variation hypothesis does not hold good in the alpine ecosystem of the Himalaya.

Keywords. Mountain; alpine ecosystem; elevation; habitat heterogeneity; spectral variation hypothesis; entropy.

1. Introduction

Alpine ecosystems are found along elevational gradient tree species that change from lowland to dwarf shrubs (*krummholz*) and meadows dominated by herbaceous plants. An imaginary line

connecting the uppermost or the most northern patches of *krummholz* called the treeline is the lower limit of the alpine zone, and the area lying above is called the alpine zone (Körner 2012). Himalaya is one of the hotspots of biodiversity (Mittermeier *et al.* 2011). It is considered the most

vulnerable to climate change than the other regions throughout the globe (Field *et al.* 2014). It harbours a large number of endemic species. The anthropogenic impact on land use and land cover changes has caused a decrease in these species biodiversity in recent decades (Pandit 2013). The treeline species have shifted to a higher elevation due to global warming and glacier retreat (Grabherr *et al.* 1994; Singh *et al.* 2012, 2015; Mohapatra 2015a). It causes the major extinction of the alpine species above the treeline as the herb and shrub species do not get a habitable place to survive in competition with the thermophilic species (Gottfried *et al.* 2012; Mohapatra 2015b). The species distribution model of *Betula utilis* D. Don in the Himalaya shows a significant elevational shift of fundamental niche in future scenario (Singh *et al.* 2013).

The remotely sensed image from satellites is considered as a fundamental input data for the conservation model and can be used as a proxy for biodiversity monitoring with field-based information. Remote sensing metrics and indices provide a great amount of information for ecological studies. Little work has been carried out so far for modelling biodiversity from space (Lauver 1997; Gillespie *et al.* 2008). Satellite-derived vegetation indices, such as the normalised difference vegetation index (NDVI) is a direct measure of photosynthesis and productivity, which is used to quantify spatial heterogeneity or diversity at the landscape level (Turner *et al.* 2003; Levin *et al.* 2007). The Resourcesat-2 imagery provides a synoptic view of the Earth's surface with a temporal resolution of 24 days. In particular, the linear imaging self-scanning sensor (LISS-III) and higher resolution LISS-IV provide multispectral data at a spatial resolution of 23.5 and 5.8 m, respectively. These resolutions are appropriate for studying biodiversity at a landscape level, providing both fine-scale information and large area coverage.

An understanding of the impact of climate change on both community species diversity and landscape diversity is important for conservation decision-making (Gould 2000). The spatio-temporal modelling of landscape heterogeneity is considered as one of the most efficient methods for observing the changes in the biotic and abiotic components of an ecosystem (Rocchini 2007). The assessment of species diversity at the landscape level is often a challenging task due to the difficulty in judging the completeness of species and in undertaking sufficient and appropriate sampling. It

is a time-consuming and tedious task involving an observer's inaccuracy. Therefore, remote sensing could be used as one of the proxies of biodiversity that allows the derivation of large-scale biodiversity assessment in a short period. These coarser-scale assessments focus on relatively large spatial areas, which is required for implementing conservation strategies (Gillespie *et al.* 2008; Mairota *et al.* 2015). According to the spectral variation hypothesis (SVH), the higher the spectral variability, the higher the habitat and species diversity. Many researchers (Nagendra *et al.* 2010; Oldeland *et al.* 2010; Rocchini *et al.* 2015) have studied SVH at different ecosystems. The utility of SVH for the conservation biogeography study of the alpine ecosystem in the Himalaya is lacking (Gairola *et al.* 2013).

Direct (species diversity) and indirect (spectral diversity) approaches to habitat heterogeneity are useful for effective biodiversity monitoring. Landscape heterogeneity derived from satellite images can be related to field-based information (Nagendra 2001; Rocchini *et al.* 2013, 2015). Many researchers have previously adopted such an approach for studying both flora (Rocchini *et al.* 2004, 2016; Kalkhan *et al.* 2007; Nagendra *et al.* 2010) and fauna (Jørgensen and Nøhr 1996). Heterogeneity in spectral information has been correlated with species richness (Gillespie *et al.* 2008). Assessment of biodiversity at the landscape level using Resourcesat data in the Himalaya and other regions has previously been done (Chandrashekhar *et al.* 2003; Roy and Behera 2005; Singh *et al.* 2010; Rashid *et al.* 2013; Behera *et al.* 2016). However, this is the first study in which information statistics indices from satellite imagery are used for the assessment of landscape diversity in the Himalaya. In this study, both landscape spectral diversity from Resourcesat-2 images and community species diversity are studied to understand the patterns of biodiversity in different elevations and aspects.

2. Materials and methods

2.1 Study area

The state of Jammu and Kashmir in India is located in the western part of the Himalaya (figure 1) with a total geographical area of 222,236 km². The vertical and horizontal distance is 546 and 727 km, respectively. The elevation reaches up to 8564 m a.m.s.l. and slopes vary between 0° and

Figure 1. Location map of the study area. The swath footprints of Resourcesat-2 linear imaging self-scanning sensors, LISS-III and LISS-IV images used in the study are shown in green colour shades. The selected summits are in the Gulmarg site indicated by the red point.

89° evaluated from the digital elevation model (DEM). The forest cover is 10.34% having 4061 km² of highly dense forest, 8815 km² of moderately dense forest and 10,112 km² of open forest, excluding 625 km² of shrubland (SFR 2015). The Gulmarg site is located in the western part of Jammu and Kashmir that has been selected and permanently established for long-term monitoring. The region has well-defined seasonality viz., summer from the month of June–August, autumn from September–November, winter from December–February and spring from March–May (Wani 2001). The mean total rainfall for a year is 1566 mm with 98 days of mean rainy days per year. Most of the precipitation is dry with snowfall during the winter. The annual mean daily minimum and the maximum temperatures are 2.3°C and 11.8°C, respectively. The lowest and the highest daily temperatures were in the month of January and July, respectively. During the studied period, the soil and air temperature of Gulmarg ranged from an average daily mean of −2.5 to 12.1° and 7–19.5°C, respectively. The coolest and warmest months are January and July, respectively.

The four summits selected for the study were GUL1 (34°01′54″N, 74°20′59″E; elevation 3528 m), GUL2 (34°01′54.7″N, 74°20′50.2″E; elevation 3598 m), GUL3 (34°01′50.6″N, 74°20′44.8″E; elevation 3671 m) and GUL4 (34°01′47.16″N, 74°20′38.64″E, elevation 3733 m). These summits are in the alpine zone of the Gulmarg target region that was selected using the criteria specified by the Global Observation Research Initiative in the Alpine Environment

(GLORIA) field manual (Pauli *et al.* 2015). These summits were considered for long-term monitoring of biodiversity because of being least attracted to mountain tourism and anthropogenic activities. The four summits are with increasing elevational gradient ranging from 3528 to 3733 m as shown in the map (figure 2). The studied summits have an elevational range of 205 m; it extends from the sub-alpine zone where treeline species are dominant to the alpine/nival ecotone where the vegetation is mostly dominated by herbs and shrubs.

2.2 Field survey

In mountain summits, the biodiversity of the alpine plant species is determined by the local topography and microclimatic conditions (Winkler *et al.* 2016). Microtopographical features in summits create variable microclimates that are adaptive to different species as per their physiology and tolerance capacity. To understand this phenomenon in the alpine ecosystem of the Himalaya, biodiversity was estimated along the elevational gradient and in different slope aspects. For this purpose, species occurrence data from the study area were collected in the month of August in the year 2015 based on the multi-summit approach of GLORIA (Pauli *et al.* 2015). Each summit was divided into eight summit area sections, four covering the area at 5 m contours from the highest summit point (HSP) and other four covering the area below 5 m contour and above 10 m isocline for the north, east, south and west aspects. Within the 5-m summit area section,

1 m² permanent plots, arranged in clusters of four quadrats forming 3 m² were established in each cardinal direction (figure 3). This allows the inter-comparative studies of species biodiversity in the mountain summits as a function of slope exposure to radiation and moisture. The size and an optimum number of quadrats were decided such that they are sufficiently large to capture the typical species of a community and small enough that sampling could be made without trampling inside the quadrats (Pauli *et al.* 2015). The list of plants and their composition expressed as percentage cover was recorded in all 1-m² quadrats and summit area sections.

Different diversity indices were quantified, as a single diversity index cannot characterise all the aspects of diversity (Ricotta 2005). The assessment

of species diversity was done using different information statistics indices. Simpson's reverse dominance (D ; Simpson 1949) was calculated as

$$D = 1 - \sum_{i=1}^S P_i^2, \quad (1)$$

where S is the total number of species and P_i is the relative proportion of total individuals in the i th species. Shannon's entropy (H ; Shannon 1948) was calculated as

$$H = - \sum_{i=1}^S P_i \ln(P_i), \quad (2)$$

where $0 \leq H \leq \ln(S)$. The normalisation of H with respect to maximum entropy takes into account

Figure 2. Resourcesat-2 LISS-IV atmospherically corrected reflectance image (false colour composite; date of acquisition: 20 November 2014) covering the alpine zone of Gulmarg, Jammu and Kashmir, India (path 91, row 46). In the satellite imagery, the red colour shows the vegetation and the white colour, the snow cover.

Figure 3. Sampling design of summits with contour lines (yellow lines) of 1 m distance. The yellow and blue shaded regions show 5 and 10 m summit area sections, respectively. The black shaded areas are 1-m² sampling quadrats.

the evenness as Pielou's evenness (J ; Pielou 1966) calculated as

$$J = \frac{-\sum_{i=1}^S P_i \ln(P_i)}{\ln(S)}, \quad (3)$$

where $0 \leq J \leq 1$. Rényi's generalised entropy (H_α ; Rényi 1961; Kindt and Coe 2005) is highly flexible, as many popular diversity indices are special cases of H_α . It was calculated as

$$H_\alpha = \frac{1}{1-\alpha} \ln \sum_{i=1}^S P_i^\alpha, \quad (4)$$

where α is the parameter that changes the formula to generate a continuum of diversity, i.e., generates different diversity indices. The α values 0.25 and 0.50 were used for the analysis. These were measured using the 'vegan' package (Oksanen *et al.* 2015) in the R statistical language (R Core Team 2017).

2.3 Quantification of spectral diversity

Spectral diversity was quantified from both LISS-III and LISS-IV imagery using information statistics indices. The entropy of species communities can be translated to spectral diversity by considering the distribution of individual pixels among total reflectance values (N). The entropy metrics incorporate this information taking into account the relative proportion (P) of each reflectance value within the image. Orthorectified and terrain-corrected cloud-free data of Resourcesat-2 LISS-III (path 92 row 47; date of acquisition (DOA): 9 September 2015) and LISS-IV (path 91 row 46; DOA: 20 November 2014) covering the Gulmarg region was used for the quantification of landscape diversity. Cartosat-1 DEM (CartoDEM; Muralikrishnan *et al.* 2011) with a spatial resolution of 10 m was used for elevation variable. Satellite images are prone to atmospheric contamination because of atmospheric gasses, aerosols and viewing angle of the sensors. Therefore, the imagery were calibrated to radiance, and then atmospherically corrected to retrieve surface reflectance. Resourcesat-2 LISS-III and LISS-IV images were atmospherically corrected using the fast line-of-sight atmospheric analysis of spectral hypercube module (Matthew *et al.* 2000; Saini *et al.* 2016) embedded in ENVI v 4.4 (Exelis Visual Information Solutions, Boulder, Colorado). These atmospherically corrected reflectance data were then used to compute the NDVI. The spectral variability was measured using the information theory-based

statistics of landscape diversity using the module 'r.diversity' (Rocchini *et al.* 2013, 2016) written in Python language (van Rossum 1995). The dependent modules were *r.li.simpson*, *r.li.shannon*, *r.li.pielou*, *r.li.renyi* of open source geographic resources analysis support system Geographic Information System (GIS) software (Neteler *et al.* 2012). The input was the sensor-derived NDVI map. Given a certain number (N) of digital numbers (DNs), the entropy can be calculated as

$$D = 1 - \sum_{DN=1}^N P_{DN}^2, \quad (5)$$

$$H = - \sum_{DN=1}^N P_{DN} \ln(P_{DN}), \quad (6)$$

$$J = \frac{-\sum_{DN=1}^N P_{DN} \ln(P_{DN})}{\ln(N)}, \quad (7)$$

$$H_\alpha = \frac{1}{1-\alpha} \ln \sum_{DN=1}^N P_{DN}^\alpha, \quad (8)$$

where N is the total number of DN values and P_{DN} as the relative proportion of each DN value. The pixel to be considered for extracting the landscape diversity values for comparison with the species diversity was defined by the ground-based measurements. The surface (planar) distance from the HSP to the corner points of the 10 m summit area was measured; this is used to calculate the horizontal distance from HSP to the points where the 10 m vertical measurements fall. These distances were then used to define required pixels from the satellite data that will be used for comparison with the field analysis. The diversity values from the specified pixels were then extracted within those pixels using the 'raster' package (Hijmans 2015) and plotted (figures 5 and 6) using the 'sp' package (Pebesma and Bivand 2005) in R statistical language (R Core Team 2017). We analysed the inter-sensor comparison of spectral diversity and their correlation with the species diversity on the ground using the 'stats' package in R.

2.4 Upscaling biodiversity from the community to landscape scale

Habitat diversity supports species diversity in a landscape (Rosenzweig 1995), irrespective of the area (MacArthur and MacArthur 1961). The species richness predicted in a larger region allows

comparing biodiversity with the satellite remote sensing sensor (Turner *et al.* 2003) that represents differential habitat. Upscaling biodiversity from the local to the regional scale was done for multi-scale biodiversity monitoring using the concept of species–area relationship (SAR; equation 9; Arrhenius 1921; Rosenzweig 1995) as

$$\ln(S) = z \ln(A) + \ln(c), \quad (9)$$

where S is the species richness, A is the area and z and c are constants. On transforming both sides of equation (9)

$$e^{\ln(S)} = e^{z \ln(A) + \ln(c)}, \quad (10a)$$

$$e^{\ln(S)} = e^{\ln(cA^z)}, \quad (10b)$$

$$S = cA^z. \quad (10c)$$

SAR was evaluated from the field measured species record of 1 m × 1 m quadrats of the four summits. The coefficients z and c of the power law (equation 10c) were estimated. SAR was used to predict biodiversity from the community level (A_{original}) to the landscape level (A_{new}), the equation (Turner *et al.* 2003; Koh *et al.* 2010) used was

$$\frac{S_{\text{new}}}{S_{\text{original}}} = \left(\frac{A_{\text{new}}}{A_{\text{original}}} \right)^z, \quad (11)$$

where S_{original} and S_{new} represent the species richness in the community and landscape level, respectively. The continuous values of the NDVI were converted to 8-bit values. The predicted values of species richness were compared with the number of unique pixels in the given sampled area of NDVI.

3. Results and discussion

3.1 Species diversity on the ground

The total number of flora recorded at the four summits in the month of August 2015 was 127, including vascular plants, bryophytes and lichens. The month of August was the peak season of vegetation growth in Gulmarg. The number of species in the summits varies with seasons. In GUL1-3528 m, the most dominant species were *Rhododendron anthopogon* D. Don. (16.4%) and *Sibbaldia cuneata* Hornem. ex Kuntze (10.6%). In GUL2-3598 m, the most dominant species were *Juniperus squamata* Buch. Ham. ex D. Don (25.7%) and *S. cuneata*

Hornem. ex Kuntze (11%). In GUL3-3671 m, the most dominant species were *J. squamata* Buch. Ham. ex D. Don (23.5%) and *R. anthopogon* D. Don. (18.3%). In GUL4-3733 m, the most dominant species were *R. anthopogon* D. Don. (20.6%) and *J. squamata* Buch. Ham. ex D. Don (12.5%).

The lowest summit was mostly dominated by treeline species, while the other three summits were mostly composed of dwarf shrubs (*krummholz*), grasses, mosses and lichens. The GUL1-3528 m summit represents the sub-alpine forest mostly dominated by treeline species like *R. anthopogon* D. Don. The GUL2-3598 m summit represented a lower alpine zone, which is an open grassland dominated by *J. squamata* Buch. Ham. ex D. Don, *S. cuneata* Hornem. ex Kuntze, *R. anthopogon* D. Don, *Persicaria affinis* Wall. ex Meisn and grasses. The GUL3-3671 m summit represents the upper alpine zone dominated by *J. squamata* Buch. Ham. ex D. Don, *R. anthopogon* D. Don, *P. affinis* Wall. ex Meisn., *Potentilla atosanguinea* Lodd. ex D. Don and grasses. The highest among the summits, GUL4-3733 m represents alpine/nival ecotone dominated by cryophilic species like *J. squamata* Buch. Ham. ex D. Don, *S. cuneata* Hornem. ex Kuntze, *Swertia petiolata* D. Don and grasses.

The species diversity varied in all aspects of different summits (table 1). In all aspects of the summits studied, the species richness ranged from 37 to 79 species. There was a 26% drop in species richness from the lowest to the highest summit with a rise of 205 m elevation. Simpson's reverse dominance ranged from 0.4 to 0.9, Shannon's entropy from 1.4 to 3.5, Pielou's evenness from 0.4 to 0.8, Rényi's generalised entropy ($\alpha = 0.25$) from 3.1 to 4.1 and Rényi's generalised entropy ($\alpha = 0.50$) from 2.6 to 3.9. The total number of species in GUL1-3528 m, GUL2-3598 m, GUL3-3671 m and GUL4-3733 m were 96, 81, 68 and 71, respectively. In GUL1-3528 m, the north aspect has the lowest values of all the diversity indices compared to other aspects of the summit because of low species richness (45 species). The south aspect in GUL1-3528 m has the highest values of diversity with high species richness of 79. In GUL2-3598 m, the south aspect has the lowest diversity in spite of having high species richness of 58 because of the dominance of *J. squamata* Buch. Ham. ex D. Don (74%). The north aspect in this summit has the highest diversity with species richness of 51 with evenly dominant species. In GUL3-3671 m, the south aspect has the lowest diversity with the lowest species richness of 37. The east aspect of the summit has the highest diversity

Table 1. Species diversity at the principal cardinal directions (N, E, S and W) of the four summits.

Summit	Aspect	Species richness	Simpson's reverse dominance	Shannon's entropy	Pielou's evenness	Rényi's entropy	
						($\alpha = 0.25$)	($\alpha = 0.50$)
GUL1 (3528 m)	N	45	0.7	2.2	0.6	3.5	3.1
	E	58	0.9 ^a	3.2	0.8 ^a	3.9	3.6
	S	79 ^a	0.9 ^a	3.5 ^a	0.8 ^a	4.1 ^a	3.9 ^a
	W	57	0.9 ^a	2.9	0.7	3.8	3.5
GUL2 (3598 m)	N	51	0.9 ^a	3.0	0.8 ^a	3.7	3.9 ^a
	E	52	0.9 ^a	2.9	0.7	3.6	3.3
	S	58	0.4 ^b	1.4 ^b	0.4 ^b	3.5	2.8
	W	47	0.9 ^a	2.7	0.7	3.5	3.2
GUL3 (3671 m)	N	43	0.8	2.4	0.7	3.4	3.1
	E	54	0.9 ^a	2.9	0.7	3.7	3.3
	S	37 ^b	0.4 ^b	1.4 ^b	0.4 ^b	3.1 ^b	2.6 ^b
	W	47	0.9 ^a	2.7	0.7	3.6	3.2
GUL4 (3733 m)	N	48	0.8	2.5	0.7	3.5	3.2
	E	40	0.8	2.5	0.7	3.4	3.1
	S	50	0.8	2.6	0.7	3.6	3.2
	W	46	0.9 ^a	3.1	0.8 ^a	3.6	3.4

The highest (^a) and the lowest (^b) index values for each site are indicated.

with the highest species richness of 54. In the GUL4-3733 m, the east aspect has the lowest diversity having the lowest species richness of 40. In this summit, the west aspect has the highest diversity even though the south aspect has higher species richness of 50. This is because of the dominance of *R. anthopogon* D. Don. (37%) in the south aspect. Hence, the biodiversity of the alpine community is determined by the presence of dominant tree species like *J. squamata* Buch. Ham. ex D. Don and *R. anthopogon* D. Don. The south aspect of the lowest summit (GUL1-3528 m) has the highest diversity and south aspect of GUL3-3671 m has the lowest diversity compared to the other summits and their aspects in all the diversity indices were computed. The southern aspect gets maximum insolation and rainfall, which is a factor that enhances the proper growth and development of species leading to the higher dominance of an individual species and therefore to lower overall biodiversity in most cases. This is in contrast to the species–energy relationship (Wright 1983), which assumes that the higher the availability of energy (like the solar insolation), the higher is the biodiversity. This inference is not the same for the entire four summits along the elevational gradient. It has been speculated that in the lowest summit GUL1-3528 m, the south aspect has the highest biodiversity because of shading from other adjoining summits being at the lowest elevation compared to other summits studied. The difference in the biodiversity of the highest

summit GUL4-3733 m in all four aspects was the least. This is because, with an increase in the elevation of summits, the aspects receive nearly about the same proportion of solar insolation due to the least shading. These results indicate that slope aspects, steepness and variable microclimatic conditions are important factors that govern the patterns of biodiversity at high elevation. A variety of topography in the mountain ecosystem provides local refugia to plant species survival in the alpine ecosystem. As a different aspect of the mountain summit receives a differential amount of insolation and moisture, variation in the species diversity is observed. The Himalaya mountain is topographically complex compared to other mountain systems in the globe. Therefore, the relationship of species biodiversity and elevation is not simply a function of a decrease or a increase in temperature gradient along the elevational gradient in the Himalaya. The shading of mountain summits by adjoining summits make the interpretation more complicated. The exposure of summits to insolation and rainfall are important factors that govern biodiversity.

3.2 Landscape diversity calculated from the Resourcesat-2 LISS-III and LISS-IV sensors

Spectral diversity maps generated from the LISS-III and LISS-IV sensors are shown in figures 4 and 5, respectively. A high correlation or

Figure 4. Map of (a) elevation from Cartosat-1 DEM, (b) normalised difference vegetation index (NDVI), (c) Simpson's index (D), (d) Shannon's entropy, (e) Pielou's evenness, (f) Rényi's entropy ($\alpha = 0.25$) and (g) Rényi's entropy ($\alpha = 0.50$) derived from Resourcesat-2 LISS-III sensor imagery. The cross points show the four different summits GUL1-3528 m, GUL2-3598 m, GUL3-3671 m and GUL4-3733 m sequenced from the right.

multicollinearity was observed in the comparison of diversity indices of the same sensors (figure 6). However, less correlation was observed when the diversity indices were compared between the two sensors. Different spectral diversity indices were

quite similar and hence provided similar information on habitat heterogeneity.

There was a less significant correlation between the spectral diversity indices of LISS-III and LISS-IV because of the differences in the spatial

Figure 5. Map of (a) NDVI, (b) Simpson's index (D), (c) Shannon's entropy, (d) Pielou's evenness, (e) Rényi's entropy ($\alpha = 0.25$) and (f) Rényi's entropy ($\alpha = 0.50$) derived from Resourcesat-2 LISS-IV sensor imagery. The cross points show the four different summits GUL1-3528 m, GUL2-3598 m, GUL3-3671 m and GUL4-3733 m sequenced from the right.

resolutions of sensors, similar to the report by Nagendra (2001). The probable cause of the difference could be due to the temporal difference in the LISS-III and LISS-IV data products as well. The acquisition of LISS-III and LSS-IV sensor imagery of common date synchronous to field sampling was difficult. This was because of the non-availability of optical cloud-free imagery in the Himalaya region on the same date. If not cloud, many times snow covers the major portions of the alpine ecosystem in the Himalaya on non-monsoon days. Although NDVI normalises the differential solar irradiation and radiation detected by the satellite sensor on different dates, species turnover and growth variations might be the cause for the difference in spectral diversity in LISS-III and

LISS-IV imagery. Nonetheless, using two different resolutions can be advantageous in understanding heterogeneity due to the biodiversity at various scales independently, which may also increase the probability of correlation with species diversity (Rocchini *et al.* 2015).

3.3 Comparison of species and spectral diversity

The correlation and its significance level between the spectral and species diversity indices were assessed by Pearson's correlation coefficients (figures 7 and 8). Locally weighted regression (LOWESS; Cleveland 1979; Cleveland and Devlin 1988) was used instead of linear regression for observing the trend in the relationship between

Figure 6. Correlations among the landscape diversity indices measured from Resourcesat-2 LISS-III and LISS-IV. Si, reverse Simpson's index (D); Sh, Shannon's entropy; Pi, Pielou's evenness; Re_0.25, Rényi's generalised entropy ($\alpha = 0.25$); Re_0.50, Rényi's generalised entropy ($\alpha = 0.50$); L.III, LISS-III sensor; and L.IV, LISS-IV sensor. This correlation matrix is generated by the 'corrplot' (Wei and Simko 2016) package in the R statistical language.

species diversity and spectral diversity (Nagendra *et al.* 2010; Rocchini *et al.* 2011).

Based on the combined information of spectral diversity and species diversity, the sites clustered into different groups. GUL1-3528 m (lowest summit) site has the highest biodiversity compared to that of other summits. All aspects of the GUL1-3528 m summit except its north aspect showed a distinct cluster because of similar species occurrences. The GUL2-3598 m and GUL3-3671 m south aspects have the least diversity compared to other summits and their aspects along the elevational gradient. Similarly, all aspects of GUL2-3598 m clustered except the south aspects that have the least diversity in both species and spectral indices. A similar trend in GUL4-3733 m has also been observed wherein all aspects showed near cluster patterns except west. Among all the five indices used in the study, Shannon's entropy is the best diversity index as it showed the highest discriminating values for the sites in both the species and spectral variability.

The effect of resolution from coarser (LISS-III) to finer (LISS-IV) to micro (field) level can be clearly seen in figures 7 and 8. All five biodiversity

indices showed the increasing range of values from the coarser to the finer and to the field scale. Therefore, to get a closer elucidation to the field level biodiversity assessment, there is a need for the use of similar spatial resolution from the satellites. Moreover, different hyperspectral indices capable of separating one species from others based on biochemical differences may also be utilised for better results (Annece *et al.* 2017).

Species diversity increases as the environmental heterogeneity increases and so the regions that are homogeneous or dominated by a few species are likely to be less diverse. The spectral diversity at the lower summit is more due to the mosaics of trees and shrubs giving spectrally different features. The regions having the dominance of a few species have the least diversity. High insolation and warmth at the south aspects of lower elevations lead to the dominance of a few shrubs leading to less biodiversity. Similar species composition defined by the elevational gradient makes distinct cluster groups. All the five species and spectral diversity indices showed low and non-significant Pearson's correlation coefficients with nearly flat LOWESS curves for both LISS-III and LISS-IV

Figure 7. Scatterplots of species diversity indices *vs.* Resourcesat-2 LISS-III spectral indices for (a) Simpson's index (D), (b) Shannon's entropy, (c) Pielou's evenness, (d) Rényi's entropy ($\alpha = 0.25$) and (e) Rényi's entropy ($\alpha = 0.50$). Locally weighted regression (LOWESS) functions were fitted to show the trends in the relationship between species and spectral-based diversity indices. Pearson's correlation coefficient (r) and their associated P -values are represented in each panel.

sensors. Such similar observations of less significant correlation between species and spectral diversity indices with no common trend have been previously reported (Jørgensen and Nørh 1996; Nagendra *et al.* 2010; Rocchini *et al.* 2011; Schmidtlein and Fassnacht 2017). The spectral diversity map did not provide the exact values of diversity that were obtained from the field, but quite distinctly showed a relative difference in the biodiversity between the sites.

The SAR (figure 9a) of the alpine ecosystem in the Indian Himalaya has z and c values of 0.4 and 16.4, respectively (figure 9b). This z value is similar to that reported in many islands (Rosenzweig 1995). The alpine ecosystem is similar to islands because of its isolated summit peak habitat surrounded by the sea of sub-alpine forests and dense woody vegetation downslope. The diversity in the

landscape leads to the diversity of species. Similar to the SAR curve measured from the field study, the number of unique NDVI pixels (representative of differential habitat) increased with the increase in the area and finally got saturated for the LISS-III (figure 9c) and LISS-IV (figure 9d) imagery. The predicted species richness derived using the z value (upscaling biodiversity) showed a correlation with the number of unique NDVI pixels of LISS-III ($r = 0.95$; figure 9e) and LISS-IV ($r = 0.65$; figure 9f) imagery as the larger area is sampled progressively. The value of z in SAR is scale-dependent (Rosenzweig 1995). The extrapolated species richness in an area may not be precise and close to the true value, but can be used to see whether the species richness is related to the environmental gradient (Palmer 1990) and habitat heterogeneity.

Figure 8. Scatterplots of species diversity indices *vs.* Resourcesat-2 LISS-IV spectral indices for (a) Simpson's index (D), (b) Shannon's entropy, (c) Pielou's evenness, (d) Rényi's entropy ($\alpha = 0.25$) and (e) Rényi's entropy ($\alpha = 0.50$). LOWESS functions were fitted to show the trends in the relationship between species and spectral-based diversity indices. Pearson's correlation coefficient (r) and their associated P -values are represented in each panel.

In contrast to many low land forest ecosystems, the alpine ecosystem is not continuous but rather present in discrete patches in the summit peaks of mountains and hence upscaling biodiversity is rather complicated here. Microclimatic studies using moderate resolution satellite sensors in the low area alpine ecosystems in the peak of the summit of the Himalayan mountains is a difficult task. A detailed study of variations in insolation, moisture availability, temperature, soil characteristics and the nutrient availability in different slope aspects of summits is essential to understand the patterns of community biodiversity in the Himalaya. A consolidated study of soil temperature regime in different aspects of the summits (Winkler *et al.* 2016) would enrich the understanding of variations in species biodiversity at high elevation in the Himalaya.

Herbs and shrubs rather than trees mostly dominate the alpine zones. Therefore, coarse-scale data provide little information on their heterogeneity. Some of the species in the field sample used were very small like lichens and bryophytes that are mainly found under canopy cover. The areas that are dominant in tree cover may not be able to detect the spectral variability of understory species, and their heterogeneity could not be detected in spectral indices. Moreover, the mixed pixels may not represent pure entities; therefore, both the approach of field species diversity and landscape diversity is essentially important in their own ways for observing the diversity patterns. Hence, the spectral diversity approach should be used as an aid for deciding the area to be conserved or for optimising field-based studies, but not as a replacement of species diversity measurement from field survey. It is useful in

Figure 9. (a) Species–area relationship (SAR) of the alpine ecosystem measured in the field; (b) natural logarithm transformed SAR; (c) number of unique NDVI pixel derived from LISS-III imagery *vs.* area of sample; (d) number of unique NDVI pixel derived from LISS-IV imagery *vs.* area of sample; (e) predicted species richness *vs.* number of unique NDVI pixel in LISS-III imagery and (f) predicted species richness *vs.* number of unique NDVI pixel in LISS-IV imagery. Pearson's correlation coefficient (r) and their associated P -values are represented in the panel.

deriving information on the species–habitat relationships at the landscape level (Stohlgren *et al.* 1997) for the purpose of conservation.

4. Conclusions

Microclimatic condition is an important factor that governs the pattern of biodiversity other than elevation or other aspects. Habitat heterogeneity is largely due to relief and topographic variations. Species occurrence and biodiversity are largely defined by elevational gradients. Species richness decreases with an increase in elevation. The south aspect is found to be the least diverse when both species and spectral diversity are taken into account. In the lowest summit, habitat heterogeneity is higher which can harbour many species leading to high biodiversity. The sites with evenly distributed species have higher biodiversity. The presence of some dominant species like *J. squamata* Buch. Ham. ex D. Don and *R. anthopogon* D. Don.

make the sites less diverse although the respective sites have higher species richness.

The mapping of landscape diversity patterns over a large area using Resourcesat-2 imagery provides useful information for conservation decisions. The spatial resolution of satellite data might not correspond to the data that have been collected in the field in which actual spatial heterogeneity exists. However, remote sensing can provide species diversity maps at different spatial and temporal scales. Areas with higher spectral diversity can be prioritised for conservation. Hyperspectral data and high-resolution satellite images could solve many such problems of sub-pixel heterogeneity with better spectral information.

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