Long-term ecological and biodiversity monitoring in the western Himalaya using satellite remote sensing

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The IPCC in its Fourth Assessment Report (AR4) described the Himalayan Region as data-deficient in terms of climate monitoring. This is a serious impediment to global research initiatives and thus necessitates long-term ecological monitoring (LTEM) across the Himalaya. Being governed by low temperature conditions, the high-altitude regions in Himalaya are more responsive to changing environmental conditions and hence serve as better indicators. We identified few Protected Areas (PAs) and selected forest core area and ecotones along the temperate, sub-alpine, alpine and cold desert ecosystems in Himachal Pradesh to establish a network of permanent monitoring plots (PMPs). Land and vegetation cover map of three selected PAs has been prepared using Landsat TM satellite data. Among the 10 PMPs, the temperate and tree line forests in the GHNP were found to have the highest tree diversity with *Taxus wallichiana* showing good stand density and regeneration. The soil pH was found to be higher for cold desert and lower for tree line forests and alpine meadows. Soil total carbon and nitrogen contents ranged from 1.08% to 13.37% and 0.094% to 1.14% respectively. It was observed that the herbs diversity showed a positive trend with increasing soil carbon and nitrogen concentrations. Satellite remote sensing proves to be a useful tool in an LTEM study, including biodiversity assessment and climate change research in complex terrains such as the Himalaya.

Keywords: Climate change, ecotone, forest vegetation, permanent plots.

Introduction

LONG-TERM ecological studies not only enhance our understanding of the relationship between vegetation and environment, but are a pre-requisite for documenting responses of global climate change. These continued studies help distinguish between pathways, causes and mechanisms of vegetation change[1]. Permanent monitoring plots (PMPs) indicate different stages of succession and also generate hypotheses on its pace and causes[2]. These have become an essential tool for monitoring vegetation[3–5] and presently, there is a renewed emphasis on establishing PMPs for monitoring changes in mountain vegetation that are early indicators of climate change[6]. Mountain ranges play a significant role in influencing the regional and global climate. Further, being governed by low temperature, high-altitude regions of the world are more responsive to the changing climatic conditions and hence better indicators of the same[7,8]. The growth and reproduction of plant communities here are mainly controlled by temperature[9] that gives rise to steep ecological gradients and narrow ecotones[10]; and any minor change in temperature may lead to change in tree line and nival zones. PMPs of different designs have been established in different parts of the globe and consequently a number of long-term ecological research (LTER) networks have recently evolved, viz. SI/MAB (Smithsonian Institution/Man and Biodiversity program), CONECOFOR (CONtrolli ECOsistemi FORestali), MONITO (MONItoraggio Intensivo delle foreste, TOscane (Intensive Monitoring of Forests in Tuscany)), RAINFOR (Amazon Forest Inventory Network), DIVERSITAS (an international programme of biodiversity science established by three international organizations, viz. the United Nations Educational, Scientific and Cultural Organization (UNESCO), the Scientific Committee on Problems of the Environment (SCOPE) and the International Union of Biological Science (IUBS)), GLORIA (Global Observation Research Initiative in Alpine Environments), ILTER (International Long Term Ecological Research), ICP (International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests) and TEAM (Tropical Ecology Assessment & Monitoring Network) (Table 1). These have been established for analysing patterns of succession as well as recording imprints of climate change on ecosystems ranging from tropical evergreen rainforests, coastal dunes, temperate forests to alpine meadows. These programmes focus on vegetation succession, forest dynamics and climate change and have varying plot designs for assessment of plant population. A number of studies resulting from these programmes have generated and compiled quality

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data for different ecosystems in Europe, America and Africa, and provided valuable insights into the dynamics of global change[11–15].

Despite being a mega-diverse country with rich vegetation types, long-term ecological studies are lacking in India. Thus, there is an urgent need of establishing a LTER network in different ecoregions of the country, where detailed ecological observations on abiotic parameters (viz. topographic, climatic, edaphic), vegetation patterns, including phenological observations, community structure, forest disturbance and evolutionary patterns as well as the decomposition, mineralization and fine root dynamics can be recorded[16]. On a priority basis, these LTER sites could be established in the two Indian biodiversity hotspots. The Himalayas with two different ecoregions (western and eastern) is one of them[17]. The western Himalaya is structurally complex with elevations ranging from 300 to over 6000 m, and the drainage system is composed of rivers, lakes and glaciers. The mountains rise abruptly, resulting in a diversity of ecosystems that range from alluvial grasslands, subtropical broadleaved forests to dominance of conifers in the temperate zone to alpine meadows above the tree line. High-altitude cold desert ecosystems encompass a significant area of the region. The region supports a number of glaciers that are key source of water for sustaining downstream ecosystems and the world's largest human population.

It has been shown that global mean temperature has increased by 0.6° ± 0.2°C over the last century with the 1990s being the warmest decade, and 1998 and 2002 the warmest years[18]. Further, the rate of annual warming of global land area over the 1901–2001 period is estimated to be 0.07°C per decade[18]. Nogues-Bravo *et al.*[19] observed that the temperature would increase by 0.4°C per decade in the first half of 21st century and by 0.25°C per decade in the second half in different mountain systems of the world. Using climate modelling, they predicted a latitudinal gradient of temperature change in which mountains at high and medium latitudes (viz. the Himalaya, +1.2°C for 2055 or +0.15°C/per decade) show the greatest temperature rise. Thus, global warming inflicts dramatic effects on the climate of the Himalayan region. The temperatures here are increasing faster than the global average and the monsoon system is weakening with reduced precipitation. Majority of the glaciers are retreating and monsoon rains are becoming less predictable. The IPCC in its Fourth Assessment Report has described the Himalaya as a 'white spot' due to lack of sufficient data on natural ecosystems[20] and climate in the western Himalayan region is poorly understood due to logistical difficulties in maintaining observational networks at high elevations. Recently, there have been some reports on temperature rise in the western Himalayan region. Bhutiyani *et al.*[21] observed that the Indian western Himalayan region has warmed significantly during the last century at a rate of 1.6°C, which is higher than that of India (0.5°C)[22] and the global average (0.76°C)[23]. Dash *et al.*[24] found an increase of 0.98°C in annual maximum temperatures over the western Himalaya. The seasonal maximum and minimum temperatures of the region have been increased up to 0.8–1°C and 0.6–3.4°C respectively[25]. The initiative of Council of Scientific and Industrial Research (CSIR), India towards long-term monitoring of the ecosystems is all the more important in this region which is more vulnerable to the effects of climate change[26–28].

The present study focuses on Himachal Pradesh in the western Himalayan region. The state covers an area of 55,673 sq. km, of which 57% is under high altitude (elevation > 1800 m). This zone comprises temperate, subalpine, alpine, cold desert areas, glaciers and mountain peaks. Also, the state has a good representation of Protected Areas (PAs), and therefore, the PMPs are being established in the Great Himalayan National Park (GHNP), Pin Valley National Park (PVNP), Rupi-Bhabha Wildlife Sanctuary (RWLS), Dhauladhar WLS, Kugti WLS, Sechu Tuan Nala WLS and Lippa-Asrang WLS (Figure 1 *a*). Anthropogenic disturbances are least or negligible in GHNP due to restricted entry of locals and their livestock in the core area. GHNP supports undisturbed forests around Jiva, Sainj and Tirthan streams and their tributaries, which extend from the base of the valley to around 3300 m (ref. 29). The area above the tree line forms alpine meadows. The Tirthan valley in the northern aspects has dense forests, dominated by *Pinus wallichiana* (Blue Pine), *Picea smithiana* (Himalayan spruce) and diverse deciduous broadleaf forests on moderately sloping areas, and *Abies pindrow* (silver fir) on the steep areas. There are small areas of oak forests (*Quercus semecarpifolia* and *Q. incana*). The southern aspects are generally more open and stands of *Cedrus deodara* are interspersed with grassy and shrub-clad hillsides, with a zone of *Q. semecarpifolia* (Kharsu oak) forest above 2800 m. Stands of *Taxus wallichiana* in Jiva and Tirthan valley are under constant threat due to its medicinal properties. A total of 832 species belonging to 427 genera and 128 families have been reported from GHNP[30]. Woody communities were segregated and studied for species diversity along an altitudinal gradient and it was observed that tree species density increased with increasing altitude, whereas the species diversity was reduced[31]. PVNP is characterized by alpine pasture or dry alpine scrub forest. Juniper scrub and *Betula utilis* (birch) trees are on the verge of extinction. Valley bottoms have regenerated naturally with *Salix* sp. and *Myricaria* sp. *Myricaria* shrubs are eaten by the snow leopard during the crucial winter season. A total of 513 plants species belonging to 243 genera were reported from this area[32]. The area is rich in rare and medicinal herbs. With wide variations in altitude, RBWLS supports a large diversity of habitats and wildlife. A total of 313 plants have been reported from Bhabha valley of WLS and their altitudinal distribution was described[33].

Table 1. An overview of current, major long-term ecological programmes for monitoring of vegetation across the globe

Monitoring programme	Study area	Targeted biome/ ecosystem	Objectives	Plant groups	Design (plot and sampling)	Parameters studied
Gloria (Global Observation Research Initiative in Alpine Environments; http://www.gloria.ac.at)[13]	Global Network	Alpine ecosystems Focus: climate change	Population dynamics and migration	Vascular plants (herbaceous) bryophytes and lichens	Summit area sections (5 and 10 m summit areas) 16 of 1 × 1 sq. m quadrats distributed in four 3 × 3 sq. m clusters	Visual estimation of forest cover and abundance; soil temperature measurements
Smithsonian Institution/Man and the Biosphere (MAB) Biological Diversity Monitoring Program using Biodiversity Plot (BDP)	Africa, South America (23 countries across the globe)	Forest ecosystems Focus: succession	Species diversity and population dynamics	Vascular plants	25 ha plot divided into 25 plots of 1 ha. Basic layout is 1 ha plot and is widely adopted as a single unit. Each 1 ha plot subdivided into 25 quadrats 20 × 20 sq. m	Species count, tree DBH
Monitoring using modified Whittaker plots (MWPs)[38,69]	Rocky Mountain National Park, Colorado, USA	Lowland tropical rainforest; also includes Ponderosa pine, Lodgepole pine, Aspen woodlands, Meadows Focus: climate change	Species composition and community structure; ecotonal variations	Vascular plants	Three plots of 50 × 20 sq. m (Ten sub-plots 2 × 0.5 sq. m, two sub-plots 5 × 2 sq. m, one sub-plot 20 × 5 sq. m); the centre plot placed in ecotone region; two plots to separate the above three and for collection of environmental data	Species richness, species diversity and species migration
Takamanda Forest Reserve, Cameroon (modified BDP method)[70]	Cameroon, Nigeria, Africa; Amazonian forests, Peru	Tropical rainforests Focus: succession	Species population dynamics	Vascular plants	1 ha BDP with four surrounding MWPs	Herbaceous species counts, trees > 10 cm DBH
GEO-BON; Group on Earth Observations – Biodiversity Observation Network	Worldwide	Varying ecosystems	Species diversity, forest structure, dynamics and turnover; phenology, Litter fall, community composition	Plant and animal groups; ecosystems and their services	A coordinated network that allows for information exchange and access, and seeks to identify and help fill gaps in observations	–
CONECOFOR (http://www.enveurope.eu/partners/conecofor[15]	Italy	Forest ecosystem	Plant community; population dynamics	Higher plants, ferns, lichens bryophytes	A network of ICP–forests Level I and II plots	Species cover
MONITO[11]	Tuscany, Italy	Forest ecosystem	Species diversity and structure	Vascular plants, macro-fungi, bryophytes, lichens	50 × 50 sq. m plot subdivided into one 500 sq. m, ten 10 sq. m, ten 100 sq. m and twenty 1 sq. m plots	Forest cover, species richness and abundance; habitat hetero-geneity index
Central African Regional Programme for the Environment (CARPE) (http://carpe.umd.edu)	Central Africa, Congo basin	Tropical forest ecosystem	Community structure and species diversity	Plants	1 ha BDP with 25 sub-plots of 20 × 20 sq. m	Tree DBH, height, species richness and diversity, species density and IVI

(*Contd*)

Table 1. (*Contd*)

Monitoring programme	Study area	Targeted biome/ ecosystem	Objectives	Plant groups	Design (plot and sampling)	Parameters studied
TEAM (http://www.teamnetwork.org/en/protocols/bio/vegetation)	Worldwide (12 CI hotspots and wilderness areas)	Tropical ecosystems	ABG biomass, forest structure, dynamics and turn over phenology, litter fall and community composition	Plant and animal (vertebrates) groups	20×20 sq. m sub-plots	Species abundance, phenological observations, tree parameters, litter-fall traps
Carolina Vegetation Survey (CVS)[71]	Carolina, Georgia and Tennessee, USA	Coastal dune vegetation to montane forests	Species richness	Vascular plants	0.1 ha (50×20 sq. m) plots with a nested design	Species counts
Amazon Forest Inventory Network (RAINFOR) (http://www.geog.leeds.ac.uk/projects/rainfor/pages/manuals_eng.html)	Amazonia	Tropical rainforests	Forest structure, biomass and dynamics relation to local climate and soil	Vascular plants	1 ha plot with 20×20 sq. m sub-plots	Species abundance, edaphic factors, climate parameter recording
DIVERSITAS (http://www.diversitas-international.org/)	Worldwide	Varying ecosystems	Forest structure, biomass and dynamics relation to local climate and soil	Plants and animals	A coordinated network	–
Warra LTER Programme	Tasmania wilderness, World Heritage Area Tasmania, Australia	Tropical rainforests Focus: Succession and climate change	Species diversity and distribution	Vascular plants and invertebrates	50×20 sq. m floristic plot divided into ten 10×10 sq. m sub-plots, within which are also present pitfall and malaise plots ten pitfall traps along altitudinal transect malaise traps, light traps	Species cover, tree DBH (for > 10 cm), slope, aspect, area of exposed rock (rock cover), disturbance variables, etc.
Mpanga and Budongo Forest Reserves Programme[72]	Uganda	Tropical rainforests	Species population dynamics and diversity	Vascular plants	Four 1.86 ha plots and one 2.12 ha plot and a 0.64 ha plot	Species richness, species diversity basal area, ABG biomass
Holt Research Forest Monitoring Programme[73]	Maine, UK	Oak–pine forest ecosystem	ABG biomass, forest structure, dynamics; and community composition	Plant and animal groups	Contiguous 40 1 ha plots subdivided into four 50×50 sq. m quadrats that are again subdivided into 25×25 sq. m quadrats	Height and tree DBH, canopy cover
Ponderosa Pine Forests Monitoring Programme[74,75]	Arizona, New Mexico, USA	Ponderosa pine forests Focus: Succession studies and livestock effects on grazing	Species dynamics, tree regeneration	Vascular plants	1.01 ha sub-plot within each historical plot (varying in sizes from 2.0 to 6.1 ha); each sub-plot divided into 25 grid cells, each cell of 1 square chain (20.1×20.1 sq. m); a number of 20×2 0 sq. m plots for livestock effects on grazing.	Species composition, tree DBH

(*Contd*)

Table 1. (*Contd*)

Monitoring programme	Study area	Targeted biome/ ecosystem	Objectives	Plant groups	Design (plot and sampling)	Parameters studied
Christchurch Indigenous Forests Monitoring Programme	New Zealand	Indigenous forests Focus: Forest dynamics	Species population; tree regeneration	Vascular plants	20 × 20 sq. m plots sub-divided into 5 × 5 sq. m plots	Species abundance; tree DBH
Tropical ecosystems 50 ha plots[76]	Tropical forest ecosystems	Focus: Examining theories on maintenance of species diversity and monitoring community change at species level in response to climate change	Species population tree regeneration	Vascular plants	50 ha plot, census for trees	Stand parameters, species frequency and density
Monitoring plots in Western Ghats, India[56]	Madumalai Wildlife Sanctuary, Nilgiris, Western Ghats, India; Varagaliar, Anamalais, Western Ghats	Tropical evergreen forest	Species diversity, forest dynamics, tree growth and recruitment patterns	Vascular plants	50 and 30 ha (600 × 500 sq. m) plots respectively, in the two areas	Census of plants for their abundance
Monitoring plots in Eastern Ghats, India[55]	Kolli hills, Eastern Ghats, India	Tropical evergreen forest	Species diversity, forest dynamics, tree growth and recruitment patterns	Vascular plants	Four 2 ha plots sub-divided into 200 10 × 10 sq. m grids for over-storey spp. and 2 × 2 sq. m quadrat for measuring the under-storey species in every grid	Species abundance, tree DBH, IVI
CSIR Network Programme on 'Exploratory studies on climate change and adaptation of species complexes'	Western Himalaya (IHBT, IIIM); Central India (NBRI); Western coast (CSMCRI)	Temperate, alpine, cold desert, tropical and coastal saline ecosystems	Population dynamics and phenology; forest cover change, elevated CO_2, temperature metabolome and proteome dynamics; development biology	Vascular plants, bryophytes, mosses, lichens, microbes, genes and pathways	1 ha plots in tropical and temperate ecosystems, for western Himalaya see below. FACE/FATI remote sensing and GIS	A range of variables for studying the effect of climate change on gene to protein to metabolites to processes to organism to community to ecosystem level
Proposed LTEM programme in Himachal Pradesh, Western Himalaya	Western Himalaya	Temperate, alpine, cold deserts; plant community dynamics, phenology, productivity and climate change; exploration of vegetation–environment relationships	Species population dynamics, stand parameters, environmental factors (climatic, topographic edaphic, litter decomposition, etc.)	Vascular plants, mryophytes, mosses, lichens	A network of integrated plots (vegetation plots and modified Whittaker plots) in forest core areas and in ecotonal areas along altitudinal transects. A 1 ha VP in homogenous forest patch and transect of three 0.1 ha MWPs in ecotonal areas in the upper and lower edges	Species count and forest cover, tree DBH, litter fall traps and litter decomposition, soil sampling and physio-chemical analysis, physiognomy, AWS measurement

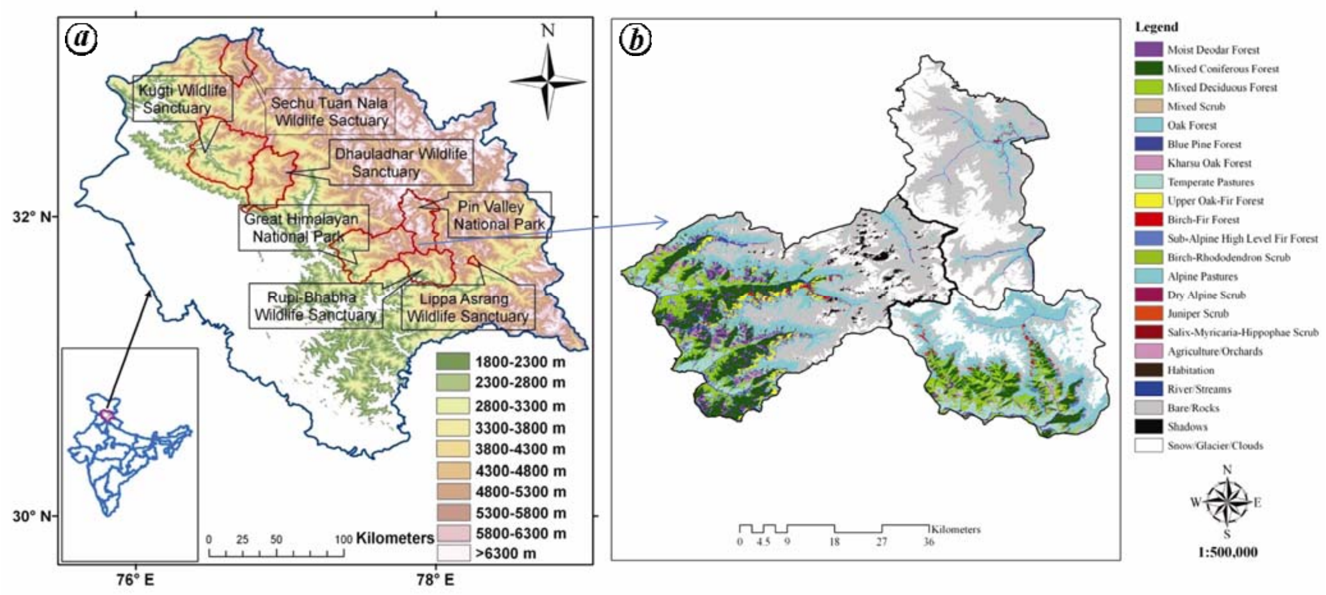

Figure 1. ***a***, Study area and location of selected protected areas (PAs). Elevation beyond 1800 m is shown at 500 m interval. ***b***, Land and vegetation cover map of Great Himalayan National Park (Landsat TM 5 dated 22 October 2010), Rupi Bhabha Wildlife Sanctuary (Landsat TM 5 dated 12 October 2010) and Pin Valley National Park (Landsat TM 5 dated 7 September 2009).

The initiative under a network programme entitled ‘Exploratory studies on climate change and adaptation of species complexes’ of CSIR is focusing on select ecosystems of the country, viz. western Himalaya, western coastal region and tropical ecosystems of central India. This is a coordinated programme to study the effect of changing climate on plant species complexes from ecosystem to gene level, and involves the Institute of Himalayan Bioresource Technology (IHBT, Palampur, HP) and Indian Institute of Integrative Medicine (IIIM, Jammu), both focusing on the western Himalayan region, the National Botanical Research Institute (NBRI, Lucknow), on tropical ecosystems of central India, and Central Salt and Marine Chemicals Research Institute (CSMCRI, Bhavnagar, Gujarat) on coastal saline ecosystems. This coordinated effort aims to study the changes in population dynamics and phenology in plant species, and soil micro flora in different ecosystems, and the effect of CO_2, temperature and other climatic factors on primary and secondary metabolism under native and Free Air CO_2 Enrichment (FACE) and Free Air Temperature Increase (FATI) environments; time-series analysis of changes in natural vegetation using remote sensing and GIS techniques; transcriptome dynamics and utilization of genes for plant adaptation under climate change, and developmental biology of key and vulnerable high altitude species. Here, we present an LTER design for the establishment of PMPs in the western Himalaya and their site characteristics; the preliminary results obtained on remote sensing-based land and vegetation cover mapping, edaphic and phytosociological characteristics and try to correlate and compare them.

Methods

The study sites lie in Himachal Pradesh that has a good representation of PAs, i.e. GHNP, PVNP, RWLS, Dhauladhar WLS, Kugti WLS, Sechu Tuan Nala WLS and Lippa-Asrang WLS, of which the first three are discussed here (Table 2). GHNP includes a core area of 754.4 sq. km surrounded by a 5 km wide buffer area of 326.6 sq. km with about 120 small villages, comprising 1600 households with a population of about 16,000, called the eco-development project area (ecozone). PVNP is a high-altitude national park in the trans-Himalaya with dry alpine scrubs and alpine meadows in the higher reaches. RBWLS is present in Kinnaur District and spans an area of 269.15 sq. km and an elevation range of 909 to 5650 m amsl. There are 15 villages inside RBWLS, with a population of 2420 people[34].

Reconnaissance surveys were conducted in the study area to collect signatures of different landscape features using a high-accuracy Global Positioning System (GPS) receiver. A USGS Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) of 90 m resolution was used for getting the elevation map for the study area in ArcGIS software (Figure 1 *a*). Landsat TM-5 satellite imageries were used to classify the vegetation types of the three PAs following supervised classification technique and classification accuracy was estimated in ERDAS Imagine software (Figure 1 *b*). The spectral signatures of ground objects, i.e. vegetation communities and other landscape features were identified on the satellite imageries using ground truthing points collected from several locations using GPS handsets for all land and

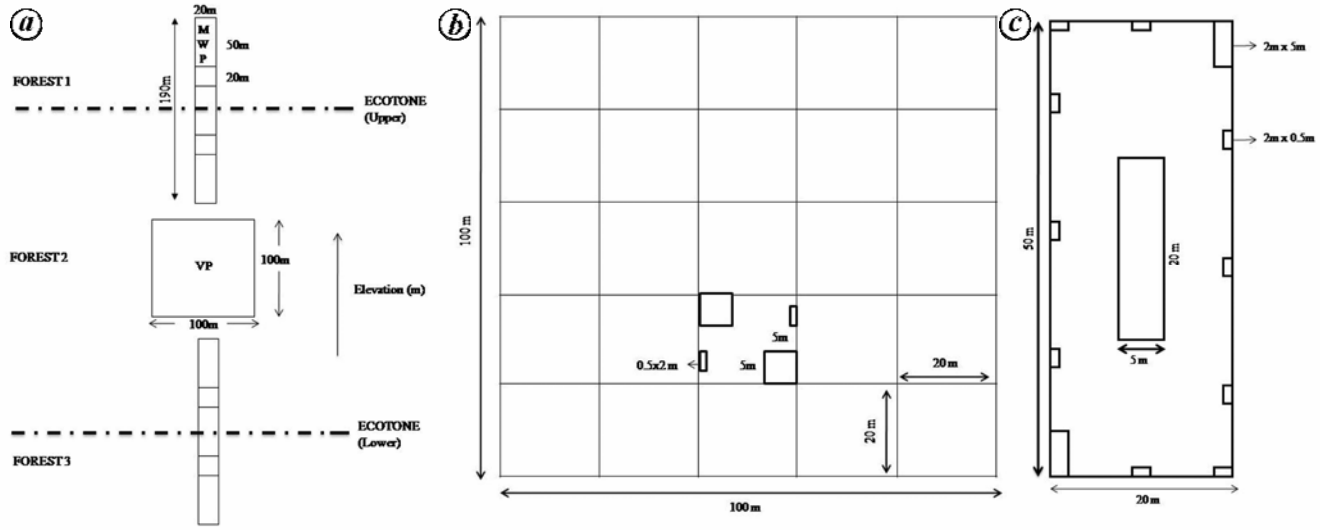

Figure 2. ***a***, Design of permanent monitoring plots (PMPs). ***b***, The 1 ha PMP established in the core of a forest type for recording of biodiversity and environmental parameters. ***c***, The 0.1 ha modified Whittaker plot (MWP)[38].

vegetation classes. The classification was performed using supervised techniques with maximum likelihood classifier. PMPs were established using probabilistic sampling method with the help of GIS analysis of physiognomy so as to represent different elevation zones. The geographical coordinates of the four corners of the larger 1 ha plot were noted using GPS.

The study of stand parameters and community dynamics of the forest ecosystems is important for the overall assessment of health of an ecosystem. The environment determines the composition, structure, health and dynamics of an ecosystem. A 1 ha vegetation plot (VP) was laid in the interior of a forest type in the core area[35–37]. Further, transects of 0.1 ha modified Whittaker plots (MWPs) were laid on either edges of forests, scrublands and grasslands[38,39] that represent patches of ecotones (Figure 2 *a*), distributed over 1800–5500 m elevation range. Vegetation in the plots for species diversity and tree recruitment was assessed thrice a year with litter sampling performed monthly. A 1 ha (100 × 100 sq. m) VP was laid in a homogenous forest area having buffer zone of 10 m around. Further, the 1 ha plot was subdivided into 25 quadrats of 20 × 20 sq. m size (Figure 2 *b*). A set of two 0.5 × 2 sq. m quadrats and one 5 × 5 sq. m quadrat were laid and marked in 12 quadrats of 20 × 20 sq. m. These sub-plots were selected by random number generation and were permanently marked. The 12 sub-plots were considered for monitoring and therefore were not utilized for sampling of soil, litter fall and decomposition analysis. A transect (0.1 ha) of MWPs was established across an elevation gradient in the ecotone such that both the terminal sections could fall in homogenous stands of their own forest types (Figure 2 *c*). MWP in the middle cuts through the ecotone area represented the transition zone between the two relatively homogenous forest types[39]. MWP has ten 0.5 × 2 sq. m subplots arranged systematically inside and adjoining the plots, two 2 × 5 sq. m subplots at the diagonally opposite ends, and one 20 × 5 sq. m subplot in the centre. All trees ≥ 10 cm were enumerated, tagged and marked. In the two 10 and 25 sq. m subplots, all shrubs were identified and counted. The individual plants of herbaceous species (including graminoids) were identified and counted in the 1 sq. m plots and their ground cover estimated according to Braun–Blaunquet scale.

Soil represents the basic support system for terrestrial ecosystems because of its role in providing nutrients, water, oxygen, heat and mechanical support to vegetation. Any environmental stress that alters the natural function of the soil has the potential to influence the productivity, species composition and hydrology of the corresponding ecosystem. Temperature data loggers (Thermochrons) were placed in soils at a depth of up to 20 cm (ref. 40). Three samples were collected around each sampling point, which is randomly generated in the buffer zone and in non-monitoring sub-plots of VP, representing the entire plot area. Forest floor material including moss was removed before sampling and samples were taken with a sliding hammer bulk density sampler of volume not less than 100 cm^3 for bulk density[41]. The organic layer at the soil surface was sampled separately from the underlying mineral soil for organic carbon determination[42]. Organic layer was sampled by an auger with a diameter of 8 cm. Due to high spatial variability of mineral horizon thickness in the forest soils and difficulty in identification of horizon boundaries, sampling was done with fixed depth and depth increment[43,44]. In mineral soil, the soil samples were collected by a core sampler at depths of 0–10, 10–20 and 20–40 cm. Soil samples were analysed for the estimation of various physical and chemical properties.

Results

All the three PAs accommodate temperate to sub-alpine forests and scrubs, with the dry alpine scrub unique to the PVNP. A total of 10 PMPs have been established in GHNP, RBWLS and PVNP that represent temperate and tree line forests, alpine meadows and cold deserts (Table 2). High-resolution recent satellite images were used to classify the forest types in these PAs. Selected cloud-free satellite data from Landsat-TM 5 with 30 m spatial resolution were used for supervised classification (Figure 1 *b*; Tables 3 and 4). For GHNP, satellite data of 22 October 2011 were used and a land use/vegetation cover map was prepared with an overall accuracy of 91.02% (Kappa statistics = 0.903). Among the dominant forest types are mixed coniferous forest (14,879.16 ha) and grasslands (22,673.16 ha). The tree line species, viz. *B. utilis*, *A. spectabilis* and *Q. semecarpifolia* also cover a significant area of the landscape. Similarly, satellite data of 7 September 2009 were used for the classification of vegetation of PVNP, and a classified map was prepared with an overall accuracy of 86.72% (Kappa statistics = 0.848; Table 4). Out of the six vegetation classes, alpine pastures span the maximum area of the landscape (18,101.97 ha; Table 3). Important medicinal species, viz. *Ephedra gerardiana*, *Arnebia euchroma*, etc. form the dry alpine scrub community. Among larger woody shrub species found in PVNP are *Salix* sp., *Myricaria* sp. and *Juniperus* sp. The RBWLS landscape was classified using satellite image of 12 October 2010, with an overall accuracy of 91.02% (Kappa statistics = 0.89; Table 3). The forest landscape is dominated by mixed coniferous forests. Like GHNP, the high-altitude forest communities cover a significant area of the vegetation landscape besides the alpine pastures, which spans the largest area.

The area under the three PAs forms a continuous landscape accommodating alpine pastures, tree line forests, mixed broadleaf and coniferous forests, moist Deodar forests, Kharsu oak forest, lower western Himalayan temperate forest and cold desert plant communities (Table 2; Figure 1 *b*). Populations of many threatened plant species that include *Jurinea dolomiaea*, *A. euchroma*, *B. utilis* and *T. wallichiana* are being assessed through this programme (see Table 5 for preliminary data of species populations from 1 ha plots). Distribution of dominant tree species in the plots was uniform (above 90% in most of the cases; Table 6), the number of mature stands per hectare suggests that the density of the forest and the growth of trees are fairly unaffected by a wide range of stand densities[45]. One noteworthy observation is the good stand density and regeneration of *T. wallichiana* trees in GHNP (plot #8; Tables 2 and 5). Knowledge of

Table 2. List of 1 ha permanent monitoring plots (PMPs) established in the Great Himalayan National Park (GHNP), Pin Valley National Park (PVNP) and Rupi Bhabha Wildlife Sanctuary (RBWLS) in Himachal Pradesh

Plot no.	Locality	Forest type	Dominant species	Altitude (m)	Latitude	Longitude	Aspect
1	Marour, Sainj, GHNP	Western Himalayan birch-fir forest	*Abies pindrow*	2694	31°47′3.9″N	77°27′ 43.1″E	NE
2	Raktisar, GHNP	Alpine meadow	*Potentilla*, *Allium*, *Pedicularis* spp.	3780	31°48′32.6″N	77°39′34.0″E	N
3	Naina Thach, GHNP	Western Himalayan high level birch–fir forest	*Betula utilis*, *Acer* sp.	3382	31°47′17.6″N	77°36′37.1″E	SW
4	Parkachi, GHNP	Temperate parkland	*Rosa* scrub	3085	31°47′52.7″N	77°36′17.4″E	NW
5	Teerath, GHNP	Alpine meadow	*Jurinea*, *Potentilla*, *Saussurea* spp.	3738	31°42′20.4″N	77°37′20.0″E	N
6	Shilt, GHNP	Western mixed coniferous forest	*Taxus wallichiana*, *Picea smithiana*	3019	31°42′20.4″N	77°37′20.0″E	NE
7	Serun, Pin Valley (PVNP)	Dry alpine scrub	*Arnebia euchroma*	3962	32°02′13.8″N	77°55′28.7″E	W
8	Sumna, Pin Valley (PVNP)	Dry alpine scrub	*Arnebia euchroma*, *Ephedra gerardiana* *Caragana* sp.	4224	32°01′28.6″N	77°56′19.0″E	E
9	Mulling, Bhabha Valley, RBWLS	Birch–Rhododendron scrub	*Betula utilis*, *Rhododendron campanulatum*	3350	31°41′28.2″N	77°59′34.1″E	E
10	Mulling, Bhabha Valley, RBWLS	Alpine meadow	*Morina*, *Potentilla*, *Thymus* spp.	3392	31°41′50.7″N	78°00′2.3″E	W

Table 3. Area estimate of land and vegetation cover classification

Class	Area (ha) GHNP	PVNP	RBWLS
Mixed deodar forest (*Cedrus deodara*)	3,029.04	–	1,667.7
Mixed coniferous forest	14,879.16	–	6147
Mixed deciduous forest	9,460.98	–	7,297.65
Mixed scrub	–	–	478.08
Oak forest (*Quercus* spp.)	–	–	6.21
Blue pine forest (*Pinus wallichiana*)	9,230.85	–	–
Kharsu oak forest (*Quercus semecarpifolia*)	2,814.66	–	–
Temperate pastures	5,404.14	–	3,257.64
Upper oak–fir forest	3,086.64	–	–
Birch–fir forest (*Betula utilis*)	1,066.59	–	1,278.72
Sub-alpine high level fir forest (*Abies* spp.)	–	–	652.41
Birch-Rhododendron scrub	218.43	–	0.9
Alpine pastures	17,269.02	4,267.89	18,101.97
Dry alpine scrub	–	275.94	–
Juniper scrub	–	17.73	–
Salix–Myricaria–Hippophae scrub	–	4.14	–
Agriculture/orchards	808.38	63.09	1,096.83
Habitation	17.01	–	26.46
Rivers/streams	856.98	502.74	678.96
Bare/rocks	40,798.44	38,010.06	8,816.58
Snow/glacier/clouds	11,341.62	29,468.52	20,341.8

GHNP, Great Himalayan National Park; PVNP, Pin Valley National Park; RBWLS, Rupi Bhabha Wildlife Sanctuary.

Table 4. Accuracy estimate of land and vegetation cover classification of the three protected areas

Protected area	Satellite date of pass	Overall accuracy (%)	Kappa statistics
GHNP	22 October 2011	91.02	0.903
PVNP	7 September 2009	86.72	0.848
RBWLS	12 October 2010	91.02	0.890

structural composition of communities is central to understanding the many ecological processes, including patterns and maintenance of species richness[46] and forest succession[47]. The diversity indices were estimated for different life forms. The temperate and tree line forests in GHNP were found to have the highest diversity of trees, with 11 taxa in *A. pindrow*-dominated forests ($H' = 1.64$, $D = 0.69$) and seven each in *T. wallichiana*-dominated ($H' = 1.43$, $D = 0.7$) and *B. utilis*-dominated forests ($H' = 1.45$, $D = 0.75$; Table 7). Tree diversity in the tree line forest in RBWLS was found to have the lowest values ($H' = 0.11$, $D = 0.05$). The diversity of shrubs was highest in the *A. pindrow*-dominated forest ($H' = 1.61$, $D = 0.65$), with the highest density of *Jasminum humile*. This was followed by *T. wallichiana*-dominated forest ($H' = 1.41$, $D = 0.7$). The diversity of herbs was higher in the alpine meadows (Table 7).

The tree growth is dependent and influenced by soil and topographic factors[48–50]. The soils of high altitudes with their large carbon stock and potential sensitivity to climate change play a significant role in the global terrestrial carbon cycle[51,52]. The average values for pH are greater in the soils of cold desert ecosystems of PVNP (6.53–7.36) and are lower for tree line and alpine meadow ecosystems (4.5–6.4; Table 8). Total carbon content also follows a similar trend for the ecosystems under study (Table 8). The diversity of herbs showed a positive trend with increasing carbon and nitrogen concentrations in the soils. The correlation is not significant at $P < 0.05$, and this could be due to insufficient data and needs to be validated from more PMPs in future.

Discussion and conclusions

Mahar *et al.*[53] assessed patterns of species diversity and endemism using 15×15 sq. m grid cells and identified potential areas for conservation in the Indian Himalayan Region. The proposed sites fall under those grids with maximum species richness and endemic richness of the analysed dominant families. The monitoring of these PAs is important due to their geographical uniqueness and the presence of good populations of threatened species of plants and animals. Thompson[54] also suggested that choosing key habitats for rare species is important in a

Table 5. Density of selected species (per ha) as observed in different 1 ha plots

Plot	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Trees										
Abies pindrow	135	–	–	–	–	80	–	–	5	–
Acer caesium	5	–	52	–	–	10	–	–	–	–
Betula utilis	–	–	105	–	–	–	–	–	222	–
Cedrus deodara	–	–	–	–	–	5	–	–	–	–
Juglans regia	45	–	–	–	–	–	–	–	–	–
Picea smithiana	–	–	–	–	–	20	–	–	–	–
Prunus cornuta	23	–	75	–	–	–	–	–	–	–
Quercus semecarpifolia	–	–	–	–	–	120	–	–	–	–
Rhododendron arboreum	–	–	–	–	–	30	–	–	–	–
Taxus wallichiana	2	–	–	–	–	225	–	–	–	–
Shrubs										
Berberis spp.	67	–	–	–	–	–	–	–	40	–
Caragana jubata	–	–	–	–	–	–	227	160	–	–
Jasminum humile	813	–	–	–	–	–	–	–	–	–
Ephedra gerardiana	–	–	–	–	–	–	880	14	–	–
Lonicera spp.	13	–	–	–	–	360	253	–	–	–
Rhododendron anthopogon	–	–	–	–	–	–	–	–	40	–
Rhododendron campanulatum	–	–	–	–	–	–	–	–	320	–
Rosa spp.	40	–	–	760	–	40	–	1627	–	–
Temperate Bamboo species	–	–	–	–	–	640	–	–	–	–
Viburnum foetens	–	–	–	360	–	–	–	–	–	–
Herbs										
Arnebia euchroma	–	–	–	–	–	–	0.5	0.03	–	–
Bupleurum longicaule	–	–	–	–	–	–	0.1	–	–	–
Chenopodium album	–	–	–	–	–	–	–	–	–	0.4
Fragaria indica	–	–	1.2	–	–	–	–	–	–	–
Geranium himalayense	–	–	–	2.8	7.13	–	–	–	–	–
Geum elatum	–	–	–	3.2	0.9	–	–	–	–	0.03
Hedychium spicatum	–	–	–	1.43	–	–	–	–	–	–
Heracleum candicans	–	–	–	3.87	0.07	–	–	–	–	–
Iris ensata	–	–	–	–	2.2	–	–	–	–	–
Jurinea dolomaea	–	–	–	–	3.2	–	–	–	–	–
Meconopsis sp.	–	–	–	–	0.07	–	–	–	–	–
Mentha longifolia	–	–	–	–	–	–	–	–	–	0.03
Morina coulteriana	–	–	–	–	0.07	–	–	–	–	1.3
Origanum vulgare	–	–	–	3.63	–	–	–	–	–	1.4
Pedicularis pectinata	–	5.8	0.07	2.3	0.6	–	–	–	–	–
Plantago depressa	–	–	–	–	–	–	–	–	–	0.07
Pleurospermum sp.	–	–	–	–	–	–	0.23	–	–	–
Potentilla atrosanguinea	–	28	–	5.73	7.6	–	–	–	–	4.2
Rhodiola hetrodonta	–	–	–	–	–	–	–	–	–	–
Rumex nepalensis	–	0.47	–	3.6	–	–	–	–	–	–
Selinum candollii	–	–	–	0.23	10.8	–	–	0.1	–	–
Strobilanthes atropurpureans	5.9	–	–	–	–	–	–	–	–	–
Thymus linearis	–	–	–	–	–	–	–	–	–	0.5
Valeriana hardwickii	0.33	–	–	–	–	–	–	–	–	–
Rosularia alpestris	–	–	–	–	–	–	–	–	–	2.9

Details of PMPs are as given in Table 2. For the herbs, densities are given per sq. m.

monitoring programme. Further, positioning of permanent plots in transects perpendicular to abiotic gradients would provide detailed information on changes in vegetation patterns and individual species in relatively smaller areas[2]. The detailed design of PMPs has been worked out after a careful consideration of monitoring programmes across the globe (Table 1). The VPs laid in homogenous forest areas and MWPs laid as transects on either side across ecotones provided suitable observations for studying the effect of climate change[39]. The world review of PMPs revealed the consistency of plot selection criteria with that of most of other programmes across the globe, which can possibly be used for data comparison in the future. In India, PMPs have been established only in the southern region of the Western and Eastern Ghats[55,56].

Table 6. Stand features of the four PMPs in forest ecosystems

Plot	Number of stumps	Mean DBH (cm)	BA (m^2 ha^{-1})	Main species
#1 (Marour, Sainj, GHNP)	135	43.89	40.00	*Abies pindrow* (93%)
	45	50.04	8.04	*Juglans regia* (60%)
#3 (Naina Thach, GHNP)	64	47.93	23.79	*Betula utilis* (100%)
	42	21.89	3.48	*Prunus cornuta* (93%)
	23	29.49	3.80	*Acer caesium* (93%)
	225	36.94	63.81	*Taxus wallichiana* (100%)
#8 (Shilt, GHNP)	120	45.10	22.29	*Quercus semecarpifolia* (100%)
	80	61.61	24.26	*Abies pindrow* (83%)
#9 (Mulling, Bhabha Valley, RBWLS)	222	24.33	11.29	*Betula utilis* (93%)
	5	12.98	0.12	*Abies pindrow* (20%)

BA, Basal area; DBH, Diameter at breast height. Only trees with DBH > 10 cm were considered. The frequencies of tree species are given after their names.

Table 7. Diversity indices for different life forms

	Trees			Shrubs			Herbs		
Plot ID	No. of species	*H′*	*D*	No. of species	*H′*	*D*	No. of species	*H′*	*D*
1	11	1.64	0.69	18	1.61	0.65	20	2.34	0.82
2	–	–	–	–	–	–	6	1.06	0.59
3	7	1.45	0.75	3	0.83	0.35	14	1.29	0.47
4	–	–	–	4	1.07	0.49	29	2.95	0.93
5	–	–	–	–	–	–	42	2.79	0.92
6	–	–	–	5	1.23	0.72	16	2.39	0.85
7	–	–	–	8	1.09	0.48	14	1.69	0.75
8	7	1.43	0.7	7	1.41	0.7	15	2.5	0.84
9	2	0.11	0.05	3	0.64	0.34	NS	–	–
10	–	–	–	–	–	–	32	3.02	0.81

H′, Shannon's diversity index; *D*, Simpson's diversity index (calculated as $1 - \sum p_i^2$).

Table 8. Chemical characteristics for top layer of soils sampled from 1 ha plots. Average values with their standard deviations are given

Plot	pH	Electrical conductivity (mmhos/cm)	Sand (%)	Silt (%)	Clay (%)	Available nitrogen (%)	Total nitrogen (%)	Total carbon (%)
# 1	6.33 ± 0.33	0.38 ± 0.24	56.45 ± 7.57	35.17 ± 5.42	8.33 ± 3.35	0.028 ± 0.01	0.094 ± 0.06	13.25 ± 6.025
# 3	4.55 ± 0.41	0.85 ± 0.25	83.35 ± 0.91	8.15 ± 3.04	8.5 ± 2.12	0.023 ± 0.007	0.99 ± 0.39	13.37 ± 8.20
# 4	5.65 ± 0.19	0.27 ± 0.19	87.23 ± 2.80	4.1 ± 2.01	8.67 ± 1.53	0.022 ± 0.01	1.14 ± 0.361	13.14 ± 5.13
# 5	5.53 ± 0.20	0.228 ± 0.09	87.03 ± 1.52	6.63 ± 1.53	6.33 ± 0.577	0.02 ± 0.00	0.55 ± 0.10	0.08 ± 0.01
# 6	5.12 ± 0.34	0.08 ± 0.01	81 ± 5	7.67 ± 4.51	11.33 ± 0.58	0.013 ± 0.005	0.43 ± 0.08	4.83 ± 0.77
# 7	7.36 ± 1.18	0.182 ± 0.17	86.9 ± 1.85	2.77 ± 1.08	10.33 ± 2.31	0.01 ± 0.00	0.31 ± 0.102	1.35 ± 1.17
# 8	6.53 ± 0.47	0.08 ± 0.04	82.7 ± 1	7.97 ± 1.16	9.33 ± 0.58	0.038 ± 0.00	0.29 ± 0.02	1.08 ± 0.13
# 9	5.52 ± 0.3	0.39 ± 0.41	87.57 ± 0.51	3.77 ± 1.66	8.67 ± 1.53	0.02 ± 0.01	0.72 ± 0.44	8.01 ± 7.60
# 10	6.40 ± 0.57	0.24 ± 0.09	86 ± 1.73	4.67 ± 2.08	9.33 ± 0.58	0.02 ± 0.00	0.78 ± 0.14	7.18 ± 2.11

Species richness studied over a period of 10 years in ten 1 sq. m quadrats in a protected alpine area of central Himalaya showed significant increase in species richness[57]. Species inhabiting the upper mountain limits, particularly those restricted to alpine regions (> 3500 m amsl), are particularly vulnerable to erosion, thus indicating that alpine species and alpine ecosystems are most vulnerable to climate change. Alpine species under rising temperature conditions cannot migrate upwards and hence they have been befittingly called 'heading towards heaven'[58]. The western Himalaya has as much as 380 plant species restricted to a narrow alpine range (between 3000 and 5500 m amsl)[59]. It is expected that these species are sensitive to changes in climate. Out of these 380 recorded species, more than 50 species are confined to altitudes above 4000 m amsl, and hence are most vulnerable. However, species plasticity and their interactive behaviour would characterize the adaptive and highly vulnerable species. There is evidence that alpine populations of the Himalayan ecotypes of *Oxyria digyna* vary in their response compared to their arctic ecotypes[60]. Thus, only a few species may be able to colonize these bare habitats, but the majority will be at risk as moraines and glacier debris limit plant growth. These reports necessitate a long-term programme for monitoring the ecology of the Himalayan region. The current programme is an appropriate and timely step in this direction. In the initial five years, PMPs would be set up in the targeted PAs to give a representation of forest types as detailed in Figure 1 *a*, and baseline data on community structure, function and environment would be assessed in different seasons which would be monitored after every five years. A network of weather stations across the Himachal Pradesh and across elevations would provide higher resolution dataset to be utilized for climate modelling studies and studying their effect on the ecosystems. Integration of field ecological data with remote sensing satellite imagery would provide a spatio-temporal dimension and help in building comprehensive ecological models.

Changes in environmental variables would also result in changes in species distributional impetus and affect their spatial relocation. In relation to altitude, upward migration of alpine[61] and sub-alpine mountain shrubs[58] is an important indicator of climate change triggered by warming of the globe. Research in Alps during the last few decades has shown that grassland species from the lower slopes have crept up as much as 4 m/decade – an apparent response to a 0.7°C regional warming[62], with a consequent increase in species richness at the mountain tops[7,63]. In Europe, upward shift of 171 plant species at a rate of 29 m/decade has been reported during 1905 and 2005 (ref. 64). Upward tree limit shifts have also been recorded in other European countries like Sweden[65] and Bulgaria[66]. In the Himalayan context, range shift patterns have also been reported for *Talicada nyseus* in the sub-Himalayan tracts[67].

The alpine meadows and high altitude forest ecosystems in western Himalaya that harbour important threatened and medicinal plant species, are particularly susceptible to adverse effects of climate change and need to be conserved. The existing natural resource conservation and development policies and programmes need to be oriented to incorporate climate change impacts, vulnerability and adaptation. There is also a realization on the need to explore and promote synergy between mitigation and adaptation while addressing changing climates[68]. For example, in the forest sector, mitigation approaches such as biodiversity conservation, PA management and sustainable forestry, while reducing vulnerability also promote adaptation. Under the National Action Plan on Climate Change, a National Mission for Sustaining the Himalayan Ecosystem has been launched to address the issues of melting of the Himalayan glaciers, biodiversity and wildlife conservation and sustainable livelihoods. The mission also proposes a coordinated effort in the identification and strengthening of institutes already engaged in the conservation and management of the natural resources in the Indian Himalayan Region. Through scrutiny of the recent literature and to the best of our knowledge, it was found that a comprehensive ecological monitoring programme in the Himalaya is still lacking. The present initiative is in this direction and more organizations could also initiate such a programme in other regions of the Himalaya.

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