Long-term ecological monitoring and observation: a review in the context of Indian Himalaya

Vikram S. Negi*, Suresh K. Rana*, Bhawana Dangwal, Shinny Thakur, K. Chandra Sekar and I. D. Bhatt

G.B. Pant National Institute of Himalayan Environment (GBP-NIHE), Almora 263 643, India

Long-term experiments are essential in understanding the ecological consequences of global land use and climate change. Further, it is well established that long-term data sets are prerequisites for effective management of forest resources and biodiversity conservation. In view of this, the present study attempts to contribute to major global long-term ecological monitoring (LTEM) networks and the status of LTEM studies in India with a special focus on Indian Himalayan Region. Over the last 40 years, around 103 countries from the America, Europe, Africa, Asia and Australia have been engaged in LTEM studies on various aspects of biodiversity, monitoring and predicting climate change impacts in a range of ecosystems, including the mountains. The temporal distribution of past studies on the subject shows a gradual increasing pattern (3 papers in 1992) with a peak during 2021 (105 papers). The established LTEM networks across the globe provide a significant empirical basis for understanding ecosystem structure and dynamics. Literature indicates plenty of permanent monitoring plots from India, mostly from southern India, and their significant contribution to ecosystem understanding. Himalayan regions are important sites for monitoring biological and socio-ecological responses to environmental perturbations, including climate change. LTEM studies are lacking in the IHR; only a few sites have been established, mostly in alpine ecosystems. This review identifies research gaps, opportunities with respect to LTEM studies, and the possibilities for strengthening long-term research and observation in India in general and the Himalaya in particular.

Keywords: Alpine ecosystem, biodiversity conservation, forest management, Himalaya, long-term ecological monitoring, long-term observations.

LONG-TERM studies are essential in understanding the ecological consequences of global land use and climate change[1,2]. Long-term ecological monitoring (LTEM), focusing on forest and alpine ecosystems, is globally contributing in understanding the impacts of land use and climate change on biodiversity[3–5]. LTEM generally refers to monitoring a particular system, i.e. forests, alpine vegetation, and oceans, for over 10 years. Establishing permanent monitoring plots (PMPs) is a robust approach of LTEM for observing changes in plant species richness and population parameters such as growth, biomass, recruitment, mortality, etc.[6,7]. Further, LTEM not only improves our understanding of the relationship between vegetation and the environment, but also helps in understanding the ecosystem responses to global climate change[8,9]. PMPs established in forests provide baseline data, trends and processes of vegetation change and engender hypotheses on its pace and causes[10]. In addition, long-term studies provide essential information for forest ecological research, adaptation and conservation planning across the globe[11–13].

Globally, long-term monitoring and research have led to developing networks to share and collect data, and foster collaboration among researchers and institutions. The National Ecological Observatory Network (NEON), DIVERSITAS (an international programme of biodiversity science), South African Environmental Observation Network (SAEON), Terrestrial Ecosystem Research Network (TERN), Long-term Ecological Research Network (LTERN), LTER-Europe, Tropical Ecology Assessment and Monitoring (TEAM), Chinese Terrestrial Ecosystem Observation and Experiment Network (CEOBEX), National Center for Ecological Analysis and Synthesis (NCEAS), the Global Observation Research Initiative in Alpine Environments (GLORIA), Chinese Ecosystem Research Network (CERN), the Center for Tropical Forest Science-Forest Global Earth Observatory (CTFSForest GEO) are such network examples[14–16]. Among others, RAINFOR in tropical forests of Amazonia, Hubbard Brook Experiment in the US and Biodiversity Exploratories in Germany are reported as the most recognized and globally accepted LTEM networks. Literature indicates around 45 countries engaged in LTEM studies on various aspects of biodiversity and environmental monitoring[4,5,17]. India is also part of a few LTEM networks and significantly contributing to understanding forest dynamics and ecological processes[18,19]. Most information on long-term monitoring in India is available from Mudumalai, southern India[18,20–24]. The available records show that there are 309 preservation

*For correspondence. (e-mail: vikramsnegii@gmail.com; envsuresh09@gmail.com)

plots in the country, of which 187 are located in natural forests and 122 in plantations covering a total area of approximately 8500 ha (ref. 18). It was reported that LTEM studies were carried out in many parts/regions of India such as Uttar Pradesh, Tamil Nadu, Andhra Pradesh, Assam, Maharashtra, Bihar, Kerala, West Bengal, however, published information in the form of research papers is mostly available from Mudumalai.

In India, Himalayan biodiversity is well reported to be highly sensitive to global warming due to its unique vertical gradient, and in turn, this would define the future of forest ecosystems and local people in the region[25,26]. The Himalayan region, with only 18% of land area of country, houses 81.4% of gymnosperms, 47% of angiosperms, 59.5% of lichens, 58.7% of pteridophytes, 43.9% of bryophytes and 53.07% of fungi found in India[27]. The Intergovernmental Panel for Climate Change[28] described the Himalayan region as ‘data-deficient in observing climate change impacts on ecosystem and biodiversity’. The main reasons for this are a limited number of long-term research stations, automatic weather stations, systematic collection of information/data set, and mechanism to share data/information among existing institutions and stakeholders[11,29]. Only a few LTEM plots/sites in the forest and alpine ecosystems of the Indian Himalayan states, i.e. Himachal Pradesh and Uttarakhand, have been established[8,11]. Therefore, there is an urgent need to synthesize and compile the status of long-term monitoring and research to find gaps and scope for their establishments in India, particularly in the IHR. In view of this, the present study is an attempt to (i) highlight the contribution of global long-term monitoring and research networks and (ii) to synthesize the status and information on LTEM in India with a special focus on the IHR.

Methods

A systematic approach for synthesizing information through a step-wise process was applied for extracting the relevant peer-reviewed literature. The peer-reviewed articles were searched using Boolean operators with a combination of the following keywords (long-term AND ecological AND monitoring AND plants) on the Scopus database (www.scopus.com). In addition, general search keywords were used to review the relevant research using the keywords long-term ecological monitoring and research on forest and alpine vegetation on Google Scholar (http://scholar.google.com). All publications in the English language, irrespective of the number of citations, were selected for further systematic review. From each publication, information on the publication year, name of the journal/publisher, name of the author/s, country of the author/s, subject area of the publication etc. was compiled for the spatial and temporal trend analysis in this research field. In this article, LTEM refers to monitoring vegetation and forest ecosystems for more than 10 years.

Results and discussion

Importance of global long-term ecological research networks

The review of literature provides a total of 1561 studies on long-term monitoring and research across the globe (Figure 1). The temporal distribution of LTEM shows a gradual increasing pattern over the years, with a peak in 2021. The maximum number of studies on LTEM are reported from the United States (332), followed by China (123) and the United Kingdom (92) (Figure 2). The International Long-Term Ecological Research (ILTER) network is the ‘network of networks’ of 103 countries and currently consists of more than 600 sites worldwide in different types of ecosystems[4,5]. The network has produced over 24,000 papers, theses and books through observing data sets of 40 years[30]. The Amazon Forest Inventory Network was conceived in 1999 with the name RAINFOR to understand the dynamics of tropical forests[29]. RAINFOR plays a critical role in supporting Peru government with their submission to the United Nations Framework on Climate Change (UNFCCC) in 2021 and is officially a ‘nationally determined contribution (NDC)’ to climate change adaptation. The networks have been adapted in Africa (AfriTRON) and Southeast Asia (T-FORCES) and globally supported with ForestPlots.net[31,32].

The LTEM network provides globally distributed long-term research sites for multiple purposes and uses in the fields of ecosystem, biodiversity, critical zone and socio-ecological research[5]. Data from various networks revealed some generalities and long-term trends of change in forests worldwide. The key findings from global LTEM networks include: (i) forests generally, and in particular tropical forests, are highly dynamic[16], (ii) forest composition in terms of species and functional groups has changed in different directions at different sites[33], (iii) environmental variability is the most important factor driving tree population dynamics on decadal time scales[34], (iv) species diversity promotes ecosystem productivity and stability, and that of nutrient supply and herbivory control diversity via changes in composition[35], (v) the inadvertent addition of atmospheric nitrogen by human activities is currently a dominant driver of global grassland productivity[36], (vi) tree species composition and dominance strongly control forest functions[31], (vii) herbivores safeguard plant diversity by reducing variability in dominance[37], (viii) biomass in north-eastern Amazonia is higher than elsewhere due to reduced mortality risk and bigger trees[35], and (ix) intact tropical forests remain major stores of carbon and are key centres of biodiversity[12]. The results of global networks also showed that mature forests of Amazonia have experienced accelerated tree turnover during the past three decades[35]. LTER network helps to understand climate change, loss of biodiversity and changes in patterns of land use. LTER sites enable the detection of both slow, but significant and

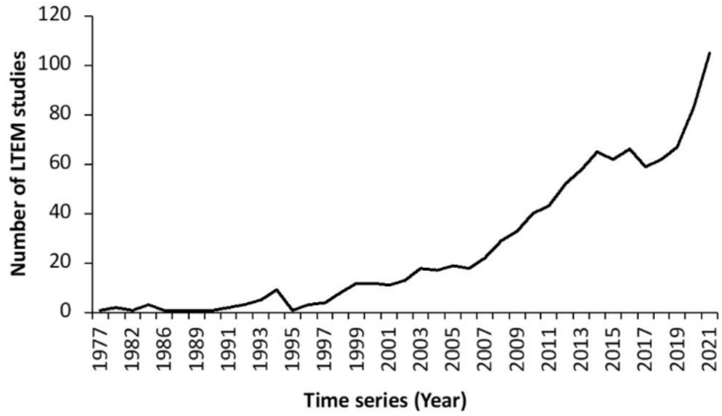

Figure 1. Temporal trend of global LTEM studies.

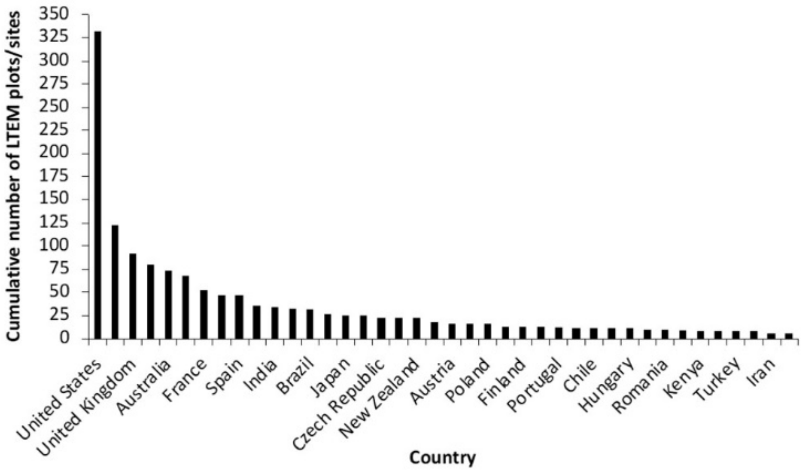

Figure 2. Country-wise distribution of LTEM studies (here we have listed only those countries where number of LTEM plots/sites are higher than five).

extreme changes in ecosystem functioning, responding to the presence, absence and intensity of pressures/drivers[5]. LTEM networks suggest that forest carbon mapping has the potential to reduce uncertainties in the global carbon budget and facilitate effective emissions mitigation strategies[38].

Most of the LTEM network initially focused on monitoring a few parameters, such as growth, richness and biomass in the forest ecosystems. However, with the advancement of technologies, methods, instrumentations and understanding the importance of long-term data sets, LTEM is focusing on additional ecological parameters to understand forest dynamics and the role of environmental perturbations. Monitoring of functional traits, phenology, diameter growth using dendrometer bands, species-level flower and seed production, seedling establishment, growth and survival[16] are examples of some ecological parameters. Camera trapping is used to monitor terrestrial mammals and the phenology of the plants. Recently, short DNA sequences from a standard position within the genome were used to construct phylogenies and distinguish individual species using long-term data sets. The Eddy covariance technique was used to continuously measure CO_2, H_2O and energy exchange between the ecosystem and the atmosphere.

Long-term ecological research in India

The urgency of the LTEM network in India was highlighted in earlier studies[11,39]. Long-term forest research sites in India were often recognized by different terminologies and names like linear tree increment plots, linear increment plots, linear sample plots and permanent preservation plots, which covered diverse plant communities and environmental conditions[18]. India has also initiated the Long-term Ecological Observatories (LTEO) programme through the Ministry of Environment, Forest and Climate Change (MoEF&CC), Government of India (GoI)[40]. Department of Science and Technology (DST), GoI has established INDOFLUX, a coordinated multidisciplinary environmental monitoring network that integrates terrestrial, coastal and oceanic environments[41]. Long-term research programmes on specific taxa have also been operated by different agencies such as the Indian Institute of Science, Dakshin Foundation (marine turtles), Wildlife Institute of India (tigers) and Nature Conservation Foundation (coral reefs). National Forest Inventories (NFIs) are working to manage and effectively plan forests in the country. The Ashoka Trust for Research in Ecology and the Environment (ATREE) was initiated to focus on using forest resources by indigenous groups in the Biligiri-Rangana Hills of southern India[19]. PMPs of India were studied by Mathauda[20] between 1978 and 1993 in collaboration with global partners. Rai[23] has reported a total of 309 PMPs in different forest types of the country. A permanent plot of 50 ha was established in 1988 to understand forest dynamics (i.e. species diversity, density and basal area) in tropical dry deciduous forests of Western Ghats[18,24,42]. The major aim of monitoring sites was to study (i) the pattern of mortality, (ii) the rate of diameter increment and (iii) the rate of diameter and basal area increment. LTEM studies from India have contributed to two-decadal changes in forest structure and tree diversity of tropical dry evergreen forests[18]. Data set on the demography of trees was monitored over 20 years in Uppangala PMPs located within the Pushpagiri Wildlife Sanctuary, Karnataka[43]. It was reported that many PMPs established in India were maintained in good condition up to 1996 and serve as one of the oldest long-term research sites in the world[18]. However, records of the majority of the reported plots are not available[18]. Few studies[42,44,45] from well-managed PMPs indicated the potential of these plots in biodiversity and forest dynamics monitoring in India.

Long-term ecological monitoring in IHR forests

Only a few permanent LTEM plots in the forests of two states, i.e. Himachal Pradesh and Uttarakhand, have been established[8,11] (Table 1, Figure 3). These are the only studies published that provided details of plots/sites and baseline information collected so far. Apart from these, the Himalayan Forest Research Institute, Shimla (Himachal Pradesh), established two forest observational plots. They are (i) the Shimla site established in 2015 and (ii) the Shikari Devi site, started in 2016 (ref. 46). These plots are used for practical demonstration for establishing long-term plots and documentation of information on biodiversity monitoring. In western Himalaya, a total of six LTEM plots were established along an elevation gradient (1000–3800 m above sea level) in the Pithoragarh district of Uttarakhand[11]. Recently, four LTEM plots were established in 2018 by the G.B. Pant National Institute of Himalayan Environment (GBP-NIHE) in Uttarakhand under its in-house project[47] (Table 1, Figure 3). The advantage of these monitoring plots is the support of meteorological observation stations to relate possible changes in plant biodiversity with climate change. One site was also established by the Sikkim Regional Centre of the above institute under the Khangchendzonga Landscape Conservation and Development Initiative (KLCDI) programme to monitor ecological and socio-economic parameters. A permanent plot of 30 ha (600 × 500 m^2) was established for long-term ecological research on biodiversity and forest functioning in a tropical evergreen forest at Varagalaiar, Anamalais, Western Ghats[48]. Lately, the Zoological Survey of India (ZSI) started a biodiversity assessment through long-term monitoring plots in the Indian Himalayan landscape in collaboration with the Botanical Survey of India. The broad focus of these plots is to evaluate the present status and trend of biodiversity in the IHR and to understand local stakeholders' needs for sustainable utilization of bioresources. Notably, many new LTEM plots have been initiated in recent years in various parts of the IHR, although the information and findings are yet to be published.

Long-term ecological monitoring in IHR alpines

High mountain environments are often characterized by low temperatures and short growing seasons, yet they support high plant endemism and biodiversity. However, these ecosystems are considered among the most vulnerable to climatic change[49]. In order to design appropriate policies and strategies to manage such environments in the long-term, data and information are needed. The standardized protocol for long-term ecological observations in alpines was developed as the 'Global Observation Research Initiative in Alpine Environments' (GLORIA). The major focus of GLORIA[47,50] is to monitor the changes in species richness (number of species), patterns of vegetation (changes in per cent cover), species composition (loss or gain of individual species) and soil temperatures of microhabitats[50]. The network found that: (i) changes in plant diversity happened over time in a water-limited and isolated high-mountain range in Sierra Nevada, Spain[51], (ii) climate change affected vegetation differently on siliceous and calcareous summits of the European Alps[52], (iii) despite increase in species richness over time, there was an overall decline in diversity through biotic homogenization across the Australian alpine summits over time[53], (iv) significant diversity changes in higher summits in Mediterranean mountains were related to various aspects[53]. Surprisingly, the Indian Himalaya remained a major gap for monitoring the alpine ecosystems up to 2014. The first GLORIA site was established in 2014 by GBP-NIHE in Chaudans Valley, Uttarakhand, and second in 2015, in Byans Valley of Pithoragarh, Uttarakhand, under Kailash Sacred Landscape Conservation and Development Initiative, and National Mission on Sustaining the Ecosystem (NMSHE) Task Force 3 'Forest Resources and Plant Biodiversity'[54] (Table 2). The observation sites consisted of four summits exposed to the same regional macroclimate along an altitudinal gradient above the natural treeline up to the uppermost vegetation zone. A multi-summit-based long-term measurement network known as

Table 1. Long-term monitoring sites/plots in the forests of Indian Himalayan Region

State	Locality	Altitude (m asl)	Year of establishment/ size of plot	Forest type	Dominant canopy	Frequency of censusing/ sampling	Parameters studied	References
Himachal Pradesh – Institute of Himalayan Bioresource Technology (IHBT), Palampur	Marour, GHNP	2694	2009/1 ha	Birch-fir Forest	*Abies pindrow*	Yearly	Increment in basal area, species richness, plant diversity, population density and chemical characteristics of the soil	8
	Shilt, GHNP	3019	2009/1 ha	Mixed coniferous forest	*Picea smithiana*	Yearly		
	Mulling, Bhabha Valley, RBWLS	3350	2009/1 ha	Birch–Rhodo-dendron scrub	*Betula utilis*, *Rhododendron campanulatum*	Yearly		
	Parkachi, GHNP	3085	2009/1 ha	Temperate parkland	*Rosa scrub*	Yearly		
	Naina Thach, GHNP	3382	2009/1 ha	Birch-fir forest	*Betula utilis*, *Acer* sp.	Yearly		
Uttarakhand (under NMSHE TF 3 co-ordinated by NIHE, Almora)	Kanara, Pithoragarh	900–1000	2015/1 ha	Sub-tropical	*Shorea robusta*, *Pinus roxburghii*	Five yearly	Species richness, composition, increment in basal area, census of seedlings/saplings for regeneration, biomass, nativity, invasion, and chemical characteristics of the soil	11
	Chitgal	1400–1500	2015/1 ha	Sub-tropical	*Pinus roxburghii*	Five yearly		
	Hat-Kalika, Pithoragarh	1600–1700	2015/1 ha	Temperate	*Cedrus deodara*, *Quercus leucotrichophora*	Five yearly		
	Chodyar, Pithoragarh	1800–1900	2015/1 ha	Temperate	*Quercus leucotrichophora*, *Myrica esculenta*	Five yearly		
	Gunji, Pithoragarh	3200–3300	2015/1 ha	Sub-alpine	*Pinus wallichiana*	Five yearly		
	Kuti, Pithoragarh	3800–3900	2015/1 ha	Sub-alpine	*Betula utilis*	Five yearly		
Uttarakhand (under NIHE in-house project)	Gaula catchment, Nainital	679	2017/1 ha	Sal forest	*Shorea robusta*	Yearly	Phenological events of forest communities, species richness and composition, girth increment of trees for biomass productivity, census of seedlings/saplings for regeneration, plant water potential, water vapour flux, CO_2 flux and some phytochemicals, and soil physico-chemical properties	69
	Gaula catchment, Nainital	1450	2017/1 ha	Pine forest	*Pinus roxburghii*	Yearly		
	Gaula catchment, Nainital	1502	2017/1 ha	Mixed broad leaf forest	*Quercus leucotrichophora*	Yearly		
	Gaula catchment, Nainital	1861	2017/1 ha	Oak forest	*Quercus leucotrichophora*	Yearly		
Sikkim (under KLCDI-India by Sikkim Regional Centre, NIHE)	Dzongu, Khangchendzonga Landscape	1100–1225	2016/0.1 ha	Mixed forest	*Symplocos*, *Castanopsis*, *Cinnamomum* spp.	Yearly	Basal area, species richness, tree regeneration pattern, forest structure, biomass, status of invasive species, status of preferred fuel wood species, and status of preferred fodder species	www.icimod.org/initiative/klcdi

GHNP, Great Himalayan National Park; RBWLS, Rupi Bhaba Wildlife Sanctuary.

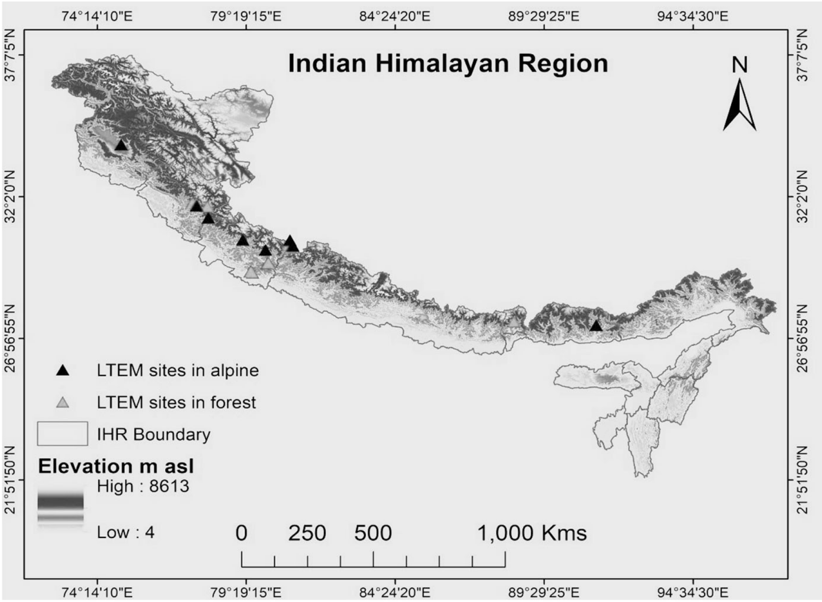

Figure 3. Map showing established LTEM plots/sites in the Indian Himalayan Region.

HIMADRI (Himalayan Alpine Dynamics Research Initiative) has also been conceptualized for understanding long-term alpine vegetation dynamics in the IHR states coordinated by Space Applications Centre, ISRO, Ahmedabad. A total of 20 summits with more than 1000 quadrats have been established along an elevation gradient (3200–4200 m) in the alpine ecosystem under the network[54–60] (Table 2).

Contributions of long-term ecological monitoring in India

There can be uncertainties regarding the consequences of various drivers of change due to lack of long-term data, sporadic and scattered research, limited access, unreliability and incomparability of existing data[29,39]. The long-term forest plots have been extremely successful in achieving the primary aim of improving our knowledge of forest ecology. In India, forest plots cover diverse forest types and environmental conditions. Presently, some PMPs and LTEM sites are functional, some are disturbed, and many have almost been lost[18]. The data/information generated from LTEM plots in India is becoming increasingly important in the context of environmental modelling and climate change. Mathauda[20] studied patterns of mortality and diameter increment through LTEM, while Rai[23] investigated the diameter and basal area growth of 95 species from tropical rain forests of Karnataka. The studies commonly concluded that: (i) the pioneer species showed higher rates of basal area increment, (ii) moving away from protected area boundaries enhanced conservation practice in the larger landscape, (iii) long-term scientific data is key to influencing the right decisions in management and conservation and (iv) the knowledge of basal area increment of a species or forest community is of paramount importance in forest management. These studies contributed to classifying trees into three crown classes and four social classes[18]. These studies were also intended to observe the effect of silvicultural treatments on the rate of growth of studied species. These studies further contributed to forest management and conservation.

The Mudumalai forests in Tamil Nadu (eastern foothills of the Western Ghats of southern India) are well known for LTEM studies in India and have significantly contributed to the understanding of forest dynamics. These plots were established by the Centre for Ecological Sciences of the Indian Institute of Science, Bengaluru. The LTEM plots in Mudumalai are surveyed every year for recruitment and mortality. Sukumar *et al.*[24] investigated the relationship of various environmental drivers with diameter and growth of the basal area. The observation of the plots revealed that leaves were shed by January–February; new leaves emerged by the end of April, and the majority of the tree species produced leaves and flowers simultaneously[61]. The relationship between annual rainfall and tree mortality in a tropical dry forest was assessed based on a 19-year LTEM study at Mudumalai[46]. These studies play an important role in understanding the impact of fire and elephants on forest regeneration and dynamics[18]. The influence of climatic variability on tree phenology in the tropical dry forests of Mudumalai was assessed based on the long-term data sets[62]. Condit *et al.*[63–65], using the data from Mudumalai plots, explained the importance of demographic niches to tree diversity and species–area and species–individual relationships for tropical trees using PMPs. Growth models developed from LTEM studies are used for projecting and generating reasonable scenarios at landscape level[18].

Table 2. Long-term monitoring sites in alpine ecosystem of Indian Himalayan Region

State (Co-ordinating institute)	Locations	Altitude range (m asl)	Characterized vegetation	LTER network/ protocol	Frequency of censusing/sampling	References
Uttarakhand (NIHE, Kosi-Katarmal, Almora)	Chaudas, Pithoragarh	3773–4266	*Danthonia cachemyriana*, *Kobresia* spp., *Jurinea* spp., *Geranium* spp., *Trachydium* spp., *Potentilla* spp., *Geum* spp., etc.	GLORIA	Five yearly	54
Uttarakhand (NIHE, Kosi-Katarmal, Almora)	Byans, Pithoragarh	3999–4154	*Danthonia cachemyriana*, *Kobresia* spp., *Potentilla* spp., *Juniperus indica*, etc.	GLORIA	Five yearly	54
Uttarakhand (HAPPRC, HNBGU, Srinagar Garhwal)	Tungnath, Chamoli	3200–3500	*Trachydium roylei*, *Carex inanis*, *Danthonia cachemyriana*, *Gentiana pedicellata*, *Taraxacum officinale*, *Rhododendron anthopogon*, etc.	HIMADRI	Five yearly	55, 70
Uttarakhand (NIHE, Kosi-Katarmal, Almora)	Pakhwa region, Bageshwar	3251–3807	*Danthonia cachemyriana*, *Trachydium roylei*, *Geum elatum*, *Viola biflora*, *Taraxacum officinale*, *Fragaria nubicola*, *Geranium nepalense*, *Saxifraga roylei*, etc.	HIMADRI	Five yearly	56
Himachal Pradesh (CSIR-IHBT, Palampur)	Raktisar, Teerath, GHNP, Mulling, Bhabha Valley, RBWLS	3780–3738	*Poa alpina*, *Carex* spp., *Kobresia* spp., *Potentilla* spp., *Thymus* spp., *Morina* spp., *Jurinea* spp., *Pedicularis* spp., etc.	Followed a specific protocol developed by the institute	Five yearly	8
Himachal Pradesh (CSIR-IHBT, Palampur)	Chansal, Shimla	3600–3900	*Potentilla* spp., *Geranium* spp., *Anaphalis* spp., *Aquilegia* spp., *Thalictrum* spp., *Stellaria* spp., *Pedicularis* spp., *Primula* spp., *Gentiana* spp., etc.	HIMADRI	Five yearly	57
Jammu and Kashmir (Kashmir University, Srinagar)	Pir Panjal Range, Gulmarg	3598–3671	*Juniperus squamata*, *Sibbaldia cuneata*, *Phlomis bracteosa*, *Polygonum affine*, *Anaphalis royleana*, *Rhododendron anthopogon*, etc.	HIMADRI	Five yearly	58
Arunachal Pradesh (DST, Regional Division)	Tawang district	3657–4179	*Fragaria nubicola*, *Anaphalis busua*, *Cyperus rotundus*, *Senecio diversifolius*, *Primula prolifera*, *Rhododendron anthopogon*, *Juniperus indica*, etc.	HIMADRI	Five yearly	59

HAPPRC, High Altitude Plant Physiology Research Centre; CSIR-IHBT, CSIR-Institute of Himalayan Bioresource Technology.

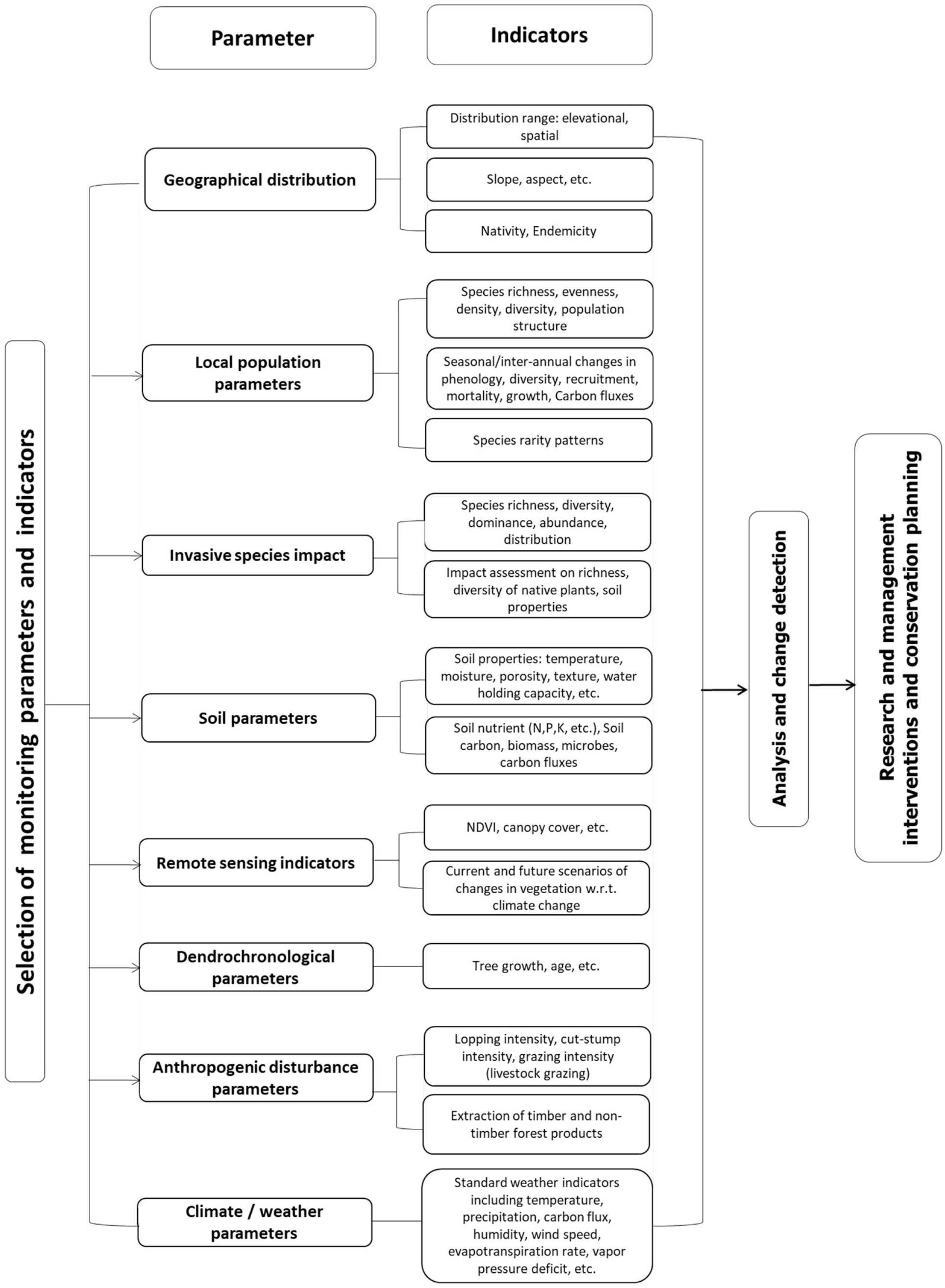

Figure 4. Suggested parameters and indicators for long-term ecological monitoring.

Research gaps and recommendations

Literature indicates a wide network of PMPs in India; however, they were not considered very suitable for long-term ecological monitoring and planning because of: (i) their relatively small size, (ii) limited representation of ecosystem diversity, (iii) dominant economic tree species, (iv) existence of high anthropogenic pressure, (v) poor management, (vi) availability of data sets generated for only few plots and (vi) paucity of funds. This kind of situation calls for urgent attention of researchers towards generating robust data sets by following globally compatible protocols. Lack of collaborations with global networks and issues of data sharing creates a wide gap in understanding long-term dynamics in the Indian and South Asian regions[19]. De Lima *et al.*[66] suggested solutions for the data sharing issues. Setting priorities, criteria and indicators has been suggested as the first step for establishing LTEM plots/sites in any region, which would provide a tool for assessing changes in given forestry situations[11]. The present study identified the criteria and indicators used globally for LTEM studies based on the literature (Figure 4).

Table 3. Approach and indicators used in long-term ecological monitoring studies in the Indian Himalayan Region

LTER approaches/plot size	Parameter/indicator studies	Name of the project and location	Advantage	Limitations	References
Global Observation Research Initiative in Alpine Environments (GLORIA)/HIMADRI	• Species composition • Species richness • Plant diversity	• Kailash Scared Landscape Conservation and Developmental Initiative, Uttarakhand • National Mission for Sustaining the Himalayan Ecosystem, Uttarakhand	• Strong global network • Wide spectrum of research with long-term data • High-quality research with increasing network members • Scope for trends and projections through modelling	• Soil analysis is missing • No data on anthropogenic pressure • Limited to alpine ecosystem	54–57, 59, 60
Quadrat method (1 ha permanent plot)	• Basal area (growth) • Species richness and diversity • Invasion (number of species along density) • Soil analysis	• National Mission for Sustaining the Himalayan Ecosystem, Uttarakhand	• Detailed vegetation analysis, i.e. vegetation structure and composition Status of soil nutrients • Biomass and productivity • Plots represent elevation gradient • Linkage with climate data (soil logger established)	• Socioeconomic parameters not used, i.e. anthropogenic pressure • Comparability of research from site to site is limited • Effect of forest fire on tree diversity and regeneration potential • Anthropogenic pressure was not analysed	20, 69
Quadrat method (1 ha permanent plot)	• Basal area (growth) • Vegetation structure and composition • Soil analysis	• Council of Scientific and Industrial Research network programme on LTEM, IHBT Himanchal Pradesh	• Detailed vegetation analysis • Species richness and diversity • Status of soil nutrients • Elevation gradients	• Socio-economic parameters not used, i.e. anthropogenic pressure • Comparability of research from site to site is limited • Linkage with climate data is missing	8
Quadrat method (0.1 ha permanent plot)	• Basal area, species richness, tree regeneration pattern, forest structure, biomass • Status of invasive species • Status of preferred fuel wood and fodder species	• The International Centre for Integrated Mountain Development (ICIMOD), Nepal	• Detailed vegetation analysis, i.e. vegetation structure and composition • Socio-economic parameters used, i.e. anthropogenic pressure • Biomass and regeneration status	• Soil analysis is missing	www.icimod.org/initiative/klcdi

The dimensions of LTEM plots are another important factors to consider in understanding the relationship between biodiversity and climate change. In addition, the sample size (number of plots) depends on the area of forest proposed for monitoring and the standard protocol to be followed[35]. In pure or homogenous forests, fewer plots can represent the ecosystem; however, in mixed forests, a significantly higher number of plots is important for representing the ecosystem. For example, the size of plots used for monitoring were 20 × 20 m, 50 × 50 m and 100 × 100 m in some of the earlier studies. Further, logistics is also an important factor to consider while selecting the plots in a particular forest. Thus, the sampling size of the plot should be of standard unit or measure following global monitoring protocols. For example, the plot size was taken as one hectare (100 × 100 m) for permanent monitoring[14,11] in a few studies, while a few other studies[8,24,63,64] used 20 × 20 m and 50 × 50 m PMPs. Also, trade-offs related to the choice of plot size, shape, orientation, etc. have been well-studied[38,67,68]. Most of the studies suggested for collecting climatic data to support the LTEM studies to trace the impacts of climate change. It is also recommended that all the LTEM plots/sites should be supported with an automatic weather station for monitoring basic environmental parameters, i.e. temperature, rainfall, humidity, carbon flux, etc. The size of the plots should be according to the objectives of the study and the feasibility or accessibility of the sites. A skilled workforce is needed to maintain the LTEM plots and data recording.

The merits and limitations of long-term studies carried out in IHR are provided in Table 3. The frequency of observation, i.e. 10, 20 and >20 years, is recommended in many studies; however, PMPs should be monitored yearly for predicting change in herb composition, i.e. change in native/endemic and threatened species, invasion by alien invasive species, etc.[11]. Further, data management is especially critical for long-term monitoring as there is likely to be a turnover of working staff, i.e. researchers, scientists[1,3]. Therefore, the organization/institute working on LTEM should update the information/findings through their web portal. Considering the larger extents of IHR, knowledge gaps on LTEM still exist in the region.

Funding for long-term research and monitoring in India is becoming increasingly difficult to obtain[19]. In India, most funding agencies provide funds for three or five years; however, initial two or three years are spent to establish just the LTEM plots. Even when donors are attracted to the long-term presence of researchers in a landscape, the money is targeted at short-term action and impact. This makes the maintenance of existing data and extensions of the monitoring schemes challenging. Thus, the maintenance of the LTEM plots and documentation of the observations have become tough. In the case of IHR, it becomes further difficult to establish LTEM plots due to tough terrain and requiring a higher and more skilled workforce. Among other things, this often involves submitting a set of published papers to appraise the new team on the work done on the site over the years. Getting permission for long-term monitoring (above five years) from the state forest administration is difficult in India. This has affected work and produced gaps in research when we have had to wait for permission. Strengthening partnerships among organizations, including the state forest department is required for biodiversity monitoring and knowledge networking.

Conclusion

Global interest in LTEM is increasing for a better understanding of the fate of biodiversity to various drivers and threats, including global warming. These studies provide key insight into forest management and biodiversity conservation across the globe. However, the literature indicates that the local climate data are inadequate, as the instrumentation is not sufficiently standardized in India, particularly in IHR. Thus, there is a strong need to strengthen automatic weather stations to establish the impacts of climate change on biodiversity. Few scientific institutions have started the establishment of LTEM plots in forests and alpine ecosystems in the IHR; however, continuous monitoring of these plots requires a lot of funds and support. The assessment methods in the LTEM are usually not uniform; thus, there is a need to develop or follow existing global protocols and parameters to make studies comparable across diverse regions. The information generated by LTEM not only helps frame national environmental policies but also plays an increasingly relevant role for international conventions and the broader scientific community.

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