Tewari et al. Forest Ecosystems (2017) 4:13
DOI 10.1186/s40663-017-0100-4

Forest Ecosystems

REVIEW Open Access

Climate change effects in the Western Himalayan ecosystems of India: evidence and strategies

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Abstract

Background: The fragile landscapes of the Himalayan region are highly susceptible to natural hazards, and there is ongoing concern about current and potential climate change impacts. This study provides background information on India's Western Himalayas and reviews evidence of warming as well as variability in precipitation and extreme events.

Methods: Understanding and anticipating the impacts of climate change on Himalayan forest ecosystems and the services they provide to people are critical. Efforts to develop and implement effective policies and management strategies for climate change mitigation and adaptation requires particular new research initiatives. The various studies initiated and conducted in the region are compiled here.

Results: Several new initiatives taken by the Himalayan Forest Research Institute in Shimla are described. This includes new permanent observational field studies, some with mapped trees, in high altitude transitional zones for continuous monitoring of vegetation response. We have also presented new strategies for mitigating potential climate change effects in Himalayan forest ecosystems.

Conclusions: Assessment of the ecological and genetic diversity of the Himalayan conifers is required to evaluate potential responses to changing climatic conditions. Conservation strategies for the important temperate medicinal plants need to be developed. The impact of climate change on insects and pathogens in the Himalayas also need to be assessed. Coordinated efforts are necessary to develop effective strategies for adaptation and mitigation.

Keywords: Himalayan ecosystem, Climate change, New strategies, High altitude, New observational studies

Background

The Indian Himalayan region is home to about 51 million people, many of whom practice hill agriculture in fragile and diverse ecosystems, including species-rich forests. The region has a considerable hydropower potential and feeds numerous perennial rivers which depend upon the sustainable existence of glaciers (GoI 2010, DST 2012). Due to its high biological and socio-cultural diversity, the region has been identified as one of 34 "biological hotspots" by Gautam et al. (2013). The fragile landscapes of the Himalayan region are highly susceptible to natural hazards, and there is ongoing concern about current and potential climate change impacts which may include abnormal floods, droughts and landslides (Barnett et al. 2005; Cruz et al. 2007), loss of biodiversity and threats to food security (Xu et al. 2009). In order to fulfil India's vision of sustainable development in the context of climate change, a National Action Plan on Climate Change was launched in June 2008. This National Action Plan includes eight specific objectives, including a "National Mission for Sustaining the Himalayan Eco-systems" and a "National Mission on Strategic Knowledge for Climate Change".

Mountain ecosystems are important for economic growth and human well-being. They provide numerous public goods and services including fresh water, food, lifesaving medicinal products, energy, Bio-diversity and associated traditional knowledge. However, these services have received comparatively little recognition in

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national economic decision-making (Pandey 2012). Mountains are among the most fragile environments and are most vulnerable to catastrophic events. If mountains become degraded, or fail to provide essential services, the costs may be severe. Therefore, Chapter 13 of the United Nations Agenda 21 specifically recognizes the value of mountain systems. Yet these recommendations are not sufficiently reflected in national, regional, and international policies and priorities (Pandey 2012).

In India's Western Himalayas, changes in altitude are dramatic producing a very specific pattern of vegetation types that include alluvial grasslands, subtropical forests, conifer mountain forests and alpine meadows. The plant species that inhabit the mountains have already started to migrate to higher altitudes due to warming (Padma 2014), and some are in danger of being lost before anyone has even recorded their existence. The melting glaciers are often the principal concern of climate change in the Himalayas. However, the region is also home to one-tenth of the world's known higher-altitude plant and animal species, and half of India's native plant species (Padma 2014). Particularly rich in biodiversity are the Western Himalayas that include the Indian states of Himachal Pradesh, Jammu and Kashmir, Uttarakhand and Sikkim, where elevations vary from 300 m to more than 6000 m and where the mountains thus act as a natural barrier to species migration (Padma 2014).

Evidence of warming

Global evidence

The State of the Climate report of the US National Oceanic and Atmospheric Administration (NOAA 2009), presents overwhelming evidence that the Earth is warming. The evidence is based on 10 indicators. Seven of these are increasing (air temperature in the troposphere; specific humidity; Ocean heat content; rising sea level; sea-surface temperature; temperature over oceans; temperature over land) while three indicators are decreasing (extent of snow cover; volume of glaciers and sea ice).

According to IPCC (2014) climate and non-climate stressors are projected to have a direct effect on forest ecosystems during the twenty-first century, which will cause large-scale forest die-back, biodiversity loss and reduced ecosystem services. Fischlin (2007) reports that 20%–30% of the plant and animal species would face a high risk of extinction if the global average temperature increase would exceed 2–3 °C above the pre-industrial level.

Local evidence

Several studies evaluating the impact of climate change on forest ecosystems in India have been published recently (for example, Chaturvedi et al. 2011; Gopalakrishnan et al. 2011). However, most of these studies lack an assessment of expected development at the local level (Upgupta et al. 2015). Evidence collected at local climate stations in the Himalayas overwhelmingly show a warming trend, albeit at different rates and in different periods depending on specific regional and seasonal circumstances (Gautam et al. 2013).

Local warming

Analyses of temperature trends in the Himalayan region have shown that temperature increases are greater at the higher altitudes than in the lowlands (Shrestha et al. 1999). In a regional study using a reconstructed temperature dataset of the Climate Research Unit, Brohan et al. (2006) and Diodato et al. (2012) concluded that during the last few decades the Himalayan and Tibetan Plateau regions have been warming at a rate higher than the rates observed during the past century. They show a 0.5 °C increase in the average maximum temperature ($T_{\max}$) during the period 1971–2005 when compared to the period 1901–1960. Dash et al. (2007) reported that in the western Indian Himalayas a 0.9 °C average increase was observed during the 102-year period 1901–2003. They found that much of this observed trend is due to increasing temperatures after 1972. Dimri and Dash (2012) also found a warming trend over the western Indian Himalayas, with the greatest observed increase in $T_{\max}$ between 1.1 °C and 2.5 °C. In the north-western Indian Himalayan region, Bhutiyani et al. (2007) found an increase of 0.16 °C per decade during the past century. Singh et al. (2008) also observed increasing trends in the seasonal average of the daily maximum temperature for all seasons, except during monsoon, over the lower Indus basin in the north-western Indian Himalayas. Shekhar et al. (2010) presented analyses at different ranges of the western Himalayas which show significant variations in temperature and snowfall during the past few decades. These various findings from the region are summarised in Table 1.

Table 1 Summary of the various findings about the rise of the temperature in Western Himalayas

Brohan et al. (2006), Diodato et al. (2012)	Dash et al. (2007)	Dimri and Dash (2012)	Bhutiyani et al. (2007)
0.5 °C increase in the average maximum temperature ($T_{\max}$) during 1971–2005 compared to 1901–1960	Average increase of 0.9 °C in temperature during 1901–2003	Increase in maximum temperature between 1.1 and 2.5 °C	Increase of temperature 0.16 °C per decade during the century

Local variability in precipitation and extreme events

Based on observations at three weather stations, Bhutiyani et al. (2010) reported a statistically significant downward trend (at 5% significance level) in monsoon and average annual rainfall in the north-western Indian Himalayas during the period 1866–2006. A similar trend was observed for the period 1960–2006 in the western Indian Himalaya region (Sontakke et al. 2009), without mentioning statistical significance. The literature also presents evidence of intra-regional differences in winter rainfall trends over the Western Indian Himalayas. Dimri and Dash (2012) noted significantly decreasing winter precipitations between December and February in the region during the period 1975–2006 amid lack of spatially coherent phases among stations. An increase in pre-monsoon (March–May) precipitation was observed in the western Indian Himalayas during 1901–2003 (Guhathakurta and Rajeevan 2008).

Dimri and Dash (2012) reported for the western Indian Himalayas an increasing number of warm days and a decreasing number of cold days during the period 1975–2006. They also found a rising trend in maximum number of consecutive dry days (< 1 mm water equivalent of snowfall) in winter (December–February) at eight stations across the western Indian Himalayas during the period 1975–2006. At the same time, the maximum number of consecutive wet days (days with 90th percentile of events with >1 mm water equivalent of snowfall) were observed at most of these stations (Dimri and Dash 2012). Table 2 summarizes the various findings from the western Indian Himalayan region regarding the main features of climate warming of the region.

The seasonal and annual rainfall variation in the State of Himachal Pradesh was observed by the Indian Meteorological Department during 2004–2012 (IMD 2004; 2005; 2006; 2007; 2008; 2009; 2010; 2011; 2012). Table 3 presents the arithmetic means of the data recorded at 36 stations covering all the districts of the State. The numbers given in the Table show the positive or negative relative deviations of rainfall when compared with the normal mean seasonal and annual rainfall in the State of Himachal Pradesh. The normal mean rainfall in winter, pre-monsoon, monsoon and post-monsoon season in Himachal Pradesh are 377.5, 285.2, 1723.0 and 526.2 mm, respectively while the mean total annual rainfall is 1251.0 mm, all during 2004–2012.

The observations presented in Table 3 show that, except in the winter of 2005, in all other years and seasons, the rainfall was much less compared to the mean annual and seasonal rainfall.

Climate change studies in Himalayan forest ecosystems

Understanding and anticipating the impacts of climate change on the Himalayan forest ecosystems and the services they provide to people are critical to the efforts to develop and implement effective policies and management strategies for mitigation and adaptation. To anticipate possible impacts of climate change on the structure and functions of these unique ecosystems, and to evaluate their socio-ecological sustainability, long-term monitoring and modelling of forest structure and dynamics are indispensable.

The Himalayan region is severely data-deficient in terms of observations of climate change impacts on ecosystem and biodiversity (IPCC 2007). There is a serious lack of systematic studies and empirical observations about species-level impacts of climate change in the Himalayas (Gautam et al. 2013). The few available research reports deal with assumed climate sensitivities. One example is a recent study which reports a decline in apple yields in some parts of Himachal Pradesh because the chilling requirements which are essential for proper flowering and fruiting, are no longer being observed (Raina 2009).

National Forest Research in India is primarily coordinated by the Indian Council of Forest Research and Education. The head office which reports to the Ministry of Environment, Forests and Climate Change is located in Dehradun and deals with policy issues regarding the development of forest research, education and extension in India. To this purpose, the Indian Council of Forest Research and Education carries out applied research dealing with specific issues regarding forest ecosystems, including potential effects of climate change, conservation of biodiversity, combating desertification and sustainable management of forest resources. Figure 1 shows the location of the nine

Table 2 Summary of the various findings about the changes in monsoon and rainfall due to climate warming in Western Himalayas

Bhutiyani et al. (2010)	Sontakke et al. (2009)	Dimri and Dash (2012)	Guhathakurta and Rajeevan (2008)
Downward trend in monsoon and average rainfall during 1866–2006	Decreasing trend in monsoon and average rainfall during 1960–2006	Decreasing winter precipitation during December–February, increase in number of warm days, decrease in number of cold days, and rising trend in number of consecutive dry days in winter during 1975–2006	Increase in pre-monsoon precipitation during 1901–2003

Table 3 Percent seasonal and annual departure of rainfall in Himachal Pradesh during 2004–2012 based on IMD annual climate summaries (IMD 2004; 2005; 2006; 2007; 2008; 2009; 2010; 2011; 2012)

Year	Relative change in total annual rainfall (% departure)				
	Winter	Pre-monsoon	Monsoon	Post-monsoon	Total annual
2004					
2005	2	−44	−8	−99	−21.0
2006	−48	−41	−24	−45	−32.0
2007	−38	−11	−36	−77	−34.8
2008	−20	−59	−5	−51	−20.8
2009	−51	−46	−34	−36	−39.0
2010	−46	−36	13	−18	−8.0
2011	−32	−32	−11	−83	−23.0
2012	−9	−51	−16	−62	−25.0

regional research institutes of the Indian Council of Forest Research and Education.

One of the nine regional research institutes of the Indian Council of Forestry Research and Education is the Himalayan Forest Research Institute in Shimla, which is responsible for forest research on Western Himalayan ecosystems, including the extensive Cold Desert areas in Jammu and Kashmir and Himachal Pradesh.

New observational studies

Long-term forest observational studies provide the empirical basis for forest policies and for developing models of forest dynamics. Observational studies provide information at various scales, ranging from specific sites where management actions have been or will be implemented to large geographical regions or an entire nation (Tewari et al. 2014; Tewari 2015). A *Forest Observational Studies* (FOS) network would ensure effective monitoring and analysis of forest ecosystems covering a range of topics, including changes in ecosystem structure and diversity, response to natural disturbances, as well as tree mortality and regeneration. Data from Forest Observational Studies that are collected over long periods of time can effectively complement the observations of a *National Forest Inventory* (Gadow et al. 2016).

Forest Observational Studies, locally known as "Linear Tree Increment plots", "Linear Sample plots" and "Permanent Preservation Plots" (Tewari et al. 2014) have a long tradition in India. An extensive network of forest plots covers diverse forest types and environmental conditions. Numerous long term observational studies were initiated at the beginning of the twentieth century. Some of these sites are still in good condition, some have been neglected and many have been lost. There is an urgent need to re-establish and maintain these sites, which are invaluable for providing essential information about forest structure and dynamics. Detailed monitoring of forest ecosystem processes including growth and mortality and the relationship between density, biodiversity and production are important areas of forest research. Because of the issues related to climate change effects, new Observational Studies on natural

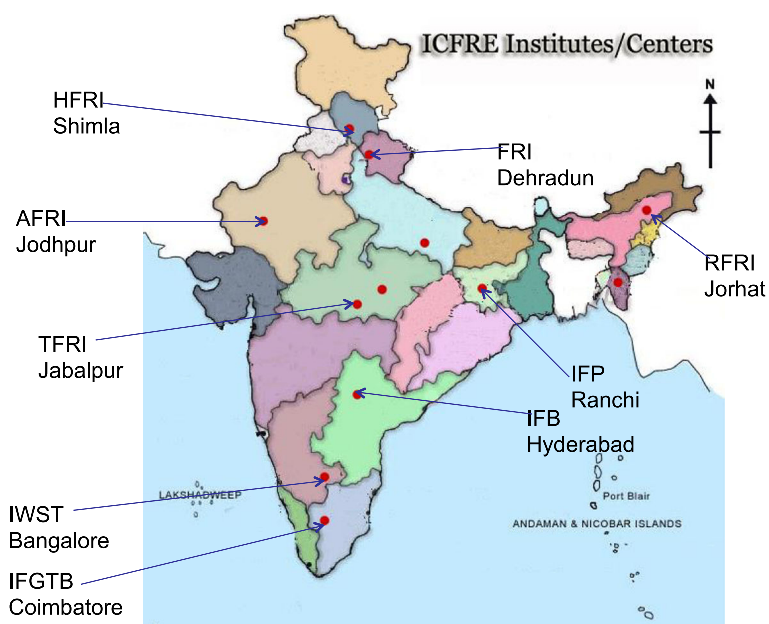

Fig. 1 Location of the nine regional research institutes of the Indian Council of Forestry Research and Education

regeneration of conifers and oak forests of the Himalayas are urgently needed.

Permanent Forest Observational Studies (PFOS) have been established in many countries as a "Green Infrastructure" which provides essential information for forest ecological research. PFOS installations are used to collect observations without manipulating the ecosystem. They represent an increasingly important complement to a National Forest Inventory. Skilful and continuous observation is necessary for describing complex forest structures, understanding ecosystem processes and evaluating the potential of forests to provide a range of essential products and services. The main objective of a PFOS network is to ensure continuity of re-measurements, using standardized plot designs and field assessment protocols. The value of any PFOS network will increase with each additional re-measurement, because observations collected over long periods of time will increasingly reveal basic ecosystem responses to climate change and other influencing factors. This requires a strong national commitment to continuity, a firm decision to ensure that all forest observational plots are protected, for example by assigning a special status to all PFOS' by Act or Regulation through Parliament. To achieve this objective, the Food and Agricultural Organisations of the United Nations is currently supporting a project which aims at integrating long-term observational field plots into the existing National Forest Inventory in India.

New observational studies at high altitudes

Five new permanent observational studies were established by the Himalayan Forest Research Institute between August 2012 and October 2012 at altitudes above 3500 m in the Sutlej, Beas and Ravi river catchments. The objective of these initiatives was to monitor long-term effects of climate change on vegetation communities at high altitudes. A brief summary of the five study sites is presented in Table 4.

These long-term observational studies are used to assess the effects of global warming in the High Altitude Transition Zones in Himachal Pradesh. These zones, where the snow is trapped for a long period, play an important role in the Himalayan ecology.

The Chakah Kanda (Kinnaur) study area features an observational plot on a slope along Kalpa Kanda, about 6 km from Kalpa in sub-alpine scrub with thickets of *Salix* sp. (50%) and *Juniper* sp. (20%) and scattered young *Abies specatabilis* and *Pinus wallichiana* trees at the well-defined tree-line. The area was found suitable for long-term floristic studies. A permanent plot of 4 ha area was established ranging between 3630 m and 3730

Table 4 Some details of the five high altitude study sites established by the Himalayan Forest Research Institute

No.	Name of the site	Altitude (m)	Latitude (N)	Longitude (E)	Area (ha)	Photo
1	Chakah Kanda (Kalpa, Kinnaur)	3650	31°32'31.1"	78°13'44.8"	4	
2	Kinner Kailash (Kinnaur)	3700	31°31'41.1"	78°18'49.2"	3	
3	Naradu Khud (Chitkul, Kinnaur)	3740	31°20'27.8"	78°26'16.2"	5	
4	Tarakkad (Sach Pass, Chamba)	3700	32°59'32.5"	76°12'40.2"	3	
5	Dhel Thatch (GHNP, Kullu)	3538	31°45'22.7"	77°27'55.4"	10	

m asl. Plot boundaries were marked with yellow paint and the GPS coordinates were recorded. The major floristic composition of the site was also recorded.

The Kinner Kailash study site (Kinnaur) is located near the 'Ashiqui Park' camping site en route to Kinner Kailash at about 3600 m asl and about 12 km from the nearest road. The site includes the tree line species *Betula utilis*, *Abies spectabilis* and *Pinus wallichiana* and a permanent plot of 3 ha area was established. The plot boundaries were marked and a botanical profile was also established.

The Naradu Khud study site (Kinnaur) is located about 6 km from the village Chitkul across the Baspa Khud at an elevation of about 3650 m asl. The floristic composition at this site includes forest vegetation with *Pinus wallichiana*, *Betula utilis* and *Abies spectabilis* and alpine scrub with stunted *Betula utilis* and shrubs of *Rhododendron campanulatum*, *Rhododendron anthopogon*, *Salix* spp., *Lonicera* spp., *Rosa macrophylla*, *Juniperus indica* and *Juniperus communis*. Dominant herb species recorded from the site include *Podophyllum hexandrum*, *Bergenia stracheyi*, *Fritillaria roylei*, *Anemone tetraphylla*, *Viola biflora*, *Ranunculus* spp., *Geranium* sp., *Potentella* spp., *Polygonatum oppositifolium* and *Polygonatum cirrhifolium*. A five hectare plot was established at this site to adequately cover the treeline, alpine scrub and alpine pasture.

The Tarakkad study site (Sach Pass, Chamba): A **s**urvey of the tree-line vegetation around Satrundi (3515 m asl) revealed two dominant woody plant species, the *Betula utilis-Quercus semicarpifolia* and *Rhododendron campanulatum*. A permanent observational study was initiated in October 2012 to monitor the impact of warming on the vegetation. A rectangular plot of 3 ha area was found suitable to lay permanent plot for monitoring the impact of global warming and plot was laid out at Tarakkad.

The Dhel Thatch (GHNP, Kullu) study site, covering an area of 10 ha, is located at 3560 m asl along the left bank of the Sainj rivulet about 26 km from the nearest Niharni road. The site presents a typical tree line scrub community and alpine meadow. *Abies spectabilis* and *Quercus semicarpifolia* are dominant at the tree-line with scattered *Sorbus microphylla*, *Prunus cornuta* and *Betula utilis*. The main shrub species is *Rhododendron campanulatum* with sporadic occurrence of *Ribes* sp., *Lonicera* sp., and *Rosa macrophylla*, and regeneration of *Quercus semicarpifolia*, *Quercus semicarpifolia*, *Angelica glauca* and *Polygonatum* sp. The main alpine meadow species include *Potentilla* sp., *Anemone* sp., *Geranium* sp., *Bulpeurum* sp., *Cynanthus* sp., *Anaphalis* sp., *Jurinea macrocephala*, *Doctylorhiza hatageria* and *Gymnadenia* sp. The site is protected by Wildlife protection act.

The High Altitude Transition Zones in Himachal Pradesh contribute especially to recharge the aquifers in addition to preventing soil erosion. They are home to a rich and rare flora and fauna, with many species being recognized as 'endangered'. In addition to the threats to the biosphere, the particular region is also experiencing a significant impact of rising temperatures that could affect the Himalayan glaciers that are the source of many perennial rivers in the country. Recent studies on the receding glaciers and changes in plant phenologies have focused on the timberline (Bertin 2008; Ali et al. 2015). The tree species of this zone are likely to respond rapidly to any change in ambient temperatures and associated shifts in ecosystem boundaries**.**

Data loggers were installed in these locations and data are collected regularly. The data collected during the past 5 years show a slight increase in the mean air temperature and decreasing precipitation. The regeneration status of junipers has improved. More specific and reliable results will be available after monitoring for longer periods of time. The reports indicate that during last decade the average maximum temperature increased by about 1.8 °C (from 19.8 °C to 21.6 °C) while minimum temperature increased from 0.5 °C to 1.2 °C in the dry temperate zone of Kinnaur. The average snowfall decreased from 441.8 to 398.4 cm during the period. Also, the total area under snow decreased to by about 14% in the state.

In the state of Himachal Pradesh, transition zones occur in the Kinnaur, Kullu and Chamba districts and, hence, observational study sites were established in the transition zones of these districts. These particular study sites are rich in flora and fauna and include rare and endangered species. The species of these transition zones are likely to show responses to climatic variations and, therefore, the study sites are interlinked with each other.

New forest observational study sites

Two new forest observational studies were established recently by the Himalayan Forest Research Institute in Shimla. One of these, known as the Shimla site was established in 2015. The other, known as the Shikari Devi site, was started in 2016. Both observational studies are used as practical examples to demonstrate plot establishment, tree measurements and tagging of trees.

Field plots with mapped trees are essential for analysing competition effects and spatially explicit structure and diversity and forest dynamics (Tewari et al. 2014).

They provide the essential empirical basis for understanding ecosystem structure and dynamics. Observations collected over long time periods may provide useful information about the effects of climate change on tree growth and mortality.

The HFRI Arboretum at Potter's Hill

The objective of maintaining an arboretum, herbal garden or a special nursery in a specific agro-climatic zone is to preserve particular germ-plasms and to provide suitable planting material. The Himalayan Forest Research Institute maintains an Arboretum at Potter's Hill, near Shimla for the ex situ conservation of the temperate Himalayan native tree flora including endemic and endangered species. So far, a total of 106 tree-, 10 herb- and 22 shrub species native to the Western Himalayas were planted in the arboretum.

The arboretum is of significant interest for ecotourism and environmental education, addressing the needs of students and nature lovers and serves as an example for implementing similar conservation programmes in the region involving native tree species.

Conclusions

Human pressures on the natural ecosystems of the Western Himalayas are intensifying, and this requires new research efforts and management strategies.

Seed orchards and breeding programmes

There is a need to assess the ecological and genetic diversity of the Himalayan conifers to evaluate potential responses to changing climatic conditions. Preservation of certain genotypes in clonal orchards will help not only to conserve the genotype but also for screening clones to be used in future planting programmes. Identification of stress resistant strains and clones of important Himalayan tree species that are potentially suitable for large-scale reforestation programmes is also required.

Development and identification of superior clones/strains of major tree species are essential for ensuring future survival and productivity of the Himalayan forest communities. The reproductive biology of the conifer species, especially in view of the observed irregular seed production, is not well understood. Hence, inter-institutional linkages for genetic improvement of conifers, including improved breeding programmes, are needed. This includes development of nurseries and planting techniques involving shrub and wild fruit species native to the Himalayan region as a prerequisite for initiating large-scale planting programmes aimed at generating additional sources of income for the rural populations.

Due to over-exploitation and un-scientific destructive harvesting, many important medicinal plants have almost become extinct. Detailed assessment of the medicinal and aromatic plant wealth in the region is, therefore, needed and appropriate conservation strategies need to be developed. In addition, cultivation, management and sustainable harvesting practices should also be implemented to improve the livelihood security of rural people. In the absence of the natural predators, the local monkey (*Macaca mulatta*) is causing extensive damage to agricultural crops. Better methods of controlling the monkey populations are required, and new approaches should be developed to reduce the damage.

Invasive insects and pathogens

There is an urgent need to study the impact of climate change on insects and pathogens in the Himalayas. Assessment of the status and impact of invasive insects on forest health are needed in the north-western Himalayas, especially in view of the expected climate change. The beetle *Pityogenus scitus*, has been causing extensive damage in *Pinus wallichiana* forests in the states of Himachal Pradesh and Jammu and Kashmir during 2000–2001. The Lepidoptera species *Lymantria obfuscata*, is causing mortality in several tree species, including *Quercus leucotrichophora*, *Q. dialatata*, *Alnus nitida*, *Salix alba*, *Falix fragilis* and several Poplar species. Affected host tree species of the sap sucking aphid *Tuberolachnus salignus* are *Salix alba*, *Salix correalua* and *Salix babilonica.*

The rate of change as well as the number and severity of extreme climatic events is likely to affect the magnitude of these impacts and the ability to cope with them. Predictions of outbreak frequencies are hard to make without proper understanding of the population dynamics and the prevailing natural conditions. The distribution ranges of pathogens and pests are likely to extend to new areas, but prediction is difficult. Thus, improved knowledge about the anticipated effects of the changing climate on these biotic threats is desirable.

Evaluating current resource management practices

Studies on fuel wood and fodder consumption patterns in different regions of the Western Himalayas are needed to evaluate the effectiveness or wastefulness of existing agricultural and agroforestry practices. Rural people depend on the forests to collect fuel wood for their daily needs, but sustainable wood harvesting studies are not available for the region. Most of the highland pastures are in the state of severe degradation due to heavy livestock pressure, and studies are also needed to determine the carrying capacities of grasslands and alpine pastures of the Himalayas, to regulate grazing and improve sustainable production.

Several government departments and numerous private agencies are doing research on medicinal plants but there is a serious lack of coordination between the different institutions. The production of economically valuable medicinal plants, e.g. through enrichment planting in the temperate Himalayas, requires effective coordination among various organizations and the sharing of knowledge and available technology to improve the use of available resources.

The biodiversity of the protected and unprotected areas across the Indian Himalayan Region needs to be assessed and monitored for understanding the status and development patterns. Data on the biodiversity status of native, endemic and threatened species are lacking. For example, the invasive shrub *Lantana camara*, which occurs at the lower and mid Himalayan regions, has taken over vast forest areas thus reducing biodiversity. Studies should be initiated to determine the effectiveness of bamboo plantations and other measures in combating Lantana.

The environmental impacts of hydroelectric projects, which have recently been established in the region, need to be assessed due to growing concern about their negative effects. Studies on existing micro-watersheds of Himalayas are also required for proposing strategies for their management under changing climatic conditions. These initiatives may be more successful within international cooperation networks and an effective capacity building program.

There is a need to strengthen climate data collection in the western Himalayan region. Local climate data are scarce, assessment methods are usually not uniform and the instrumentation is not sufficiently standardized (Negi et al. 2012). The vulnerable mountain ecosystems are likely to face greater risk of climate change impacts than other ecosystems. Coordinated efforts are therefore required to develop effective strategies for adaptation and mitigation.

The Global Forest Biodiversity Initiative (GFBI) is a new global research network focused on the use of "big data" to share information about biodiversity loss and climate change. Until now, the required large-scale understanding of forest ecosystems has been based on remote sensing data. GFBI can supplement this information with massive ground-sourced inventory data, which will greatly enhance our understanding of forest dynamics in a global context (Liang et al. 2016). Linking these local efforts with international initiatives is likely to produce greater transparency and more effective global cooperation in responding to regional environmental threats in the Western Himalayas.

Authors' contributions

VPT drafted the manuscript and was involved in establishment of Shimla observational plot, RKV helped in establishment of observational plots and field data collection, and KVG did analysis and editing of manuscript. All the authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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Received: 18 March 2017 Accepted: 27 July 2017
Published online: 10 August 2017

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