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REVIEW ARTICLE

Vulnerability of forests in the Himalayan region to climate change impacts and anthropogenic disturbances: a systematic review

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Abstract

The Himalayan region is not only threatened by rapid changes in anthropogenic activities but also by global climate change. Given the uncertainties of magnitude and characteristics of climate change, prior knowledge of long-term changing distribution pattern of forests is of crucial importance. Owing to the heterogeneity of the Himalayan mountain system, knowledge on potential impacts on forests makes it a paramount concern in this region. Therefore, to understand vulnerability as a prerequisite for forest management, we systematically review and synthesize peer-reviewed literature on climate change impacts of the Himalayan forests ($n = 118$). Of the reviewed articles, 91.5% were published after 2009. Our findings emphasize that due to a wide variety of disciplinary domains, the conceptual, methodological, and subsequent findings (observed and predicted) vary greatly given the complexity of the theme of the review. Most assessments addressing climate change vulnerability of forests and forest-dependent people fail to acknowledge the importance of scalar and temporal aspects of vulnerability. In addition, despite the brevity of the phenomena, much lesser is known about adaptation potentials, planning and policy initiatives, and coordinated multi-disciplinary decision making for managing forest resources and dependent livelihood options under different climate change scenarios. This insufficiency of knowledge requires identification of more prioritized focused research efforts. Given the substantial debate surrounding research management and policy-making, we highlight the urgent need to deal with ecological and societal implications of climate change impacts on the Himalayan forests.

Keywords Himalayan forests · Climate change impacts · Vulnerability · Adaptation · Systematic review methodology

Introduction

Globally, forest-dominated mountainous landscapes provide a wide range of ecosystem services for people residing in the mountains as well as for people residing in lower hills and plains (Grêt-Regamey et al. 2013). Forests to some extent are resilient and many species have adapted historically to changing climatic conditions (Keenan 2015). However, future

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changes of high magnitude could potentially be beyond the natural capacity of forests species to adapt in mountainous regions (Gottfried et al. 2012; Corlett and Westcott 2013; Gómez et al. 2015).

In this context, the Himalayan forests are vulnerable to climate change impacts as well as are subjected to severe ecological deterioration due to anthropogenic pressures (Ma et al. 2012). Despite previous research on the Himalayan forests, there is lack of knowledge on the uncertainties associated with climate change impacts and adaptive capacity of forests to those impacts in the future (Negi et al. 2012). We do not know whether the adaptive capacity of the Himalayan forests varies between the forest types and/or among different regions, and to what extent the Himalayan forests can continue to provide multiple ecosystem services to the human population, without depleting the forest structure and composition, forest cover area, and native biodiversity. The Himalayan forests' capacity to adapt may be linked to inherent vulnerability of forest ecosystems to climate change (Upgupta et al. 2015); however, till date, attempts to study the same have not been carried out extensively. Few studies have attempted to investigate the potential impacts of climate change on vegetation composition and shifts in the Himalayan forests, but no comprehensive review has been evaluated to find implications of such changes on ecosystem services and communities dependent on forests and forest-based resources. The knowledge on vulnerability of forests and social systems to climate change impacts and ways to increase their adaptive capacities is almost negligible in the Himalayan region. Knowledge gaps exist in terms of information supporting potential and theoretical observations, and practical ground realities. This warrants a better understanding on climate change impacts in the Himalayan region by reviewing the state of the art for developing climate adaptive strategies for forest management as well as to earmark the areas of future research.

The forests in the Himalayan region are known to be multi-functional as they provide a range of ecosystem services for supporting livelihood options of local communities (Rasul 2014). They are legacies of human-nature interactions that have been going on for a long time, creating cultural landscapes and traditional systems of forest resource management in many regions. However, the balance between human and nature has been waning, and degradation of forests due to anthropogenic disturbances is increasing because of population growth, poverty, and limitations of alternative livelihood options (Arya et al. 2012). This strong existing relationship between sustenance of larger number of population in the Himalayan region and forest resources makes it inseparable to manage forests without considering the importance of social, economic, and ecological aspects of forest management to the well-being of local people (Baland et al. 2010). Therefore, the Himalayan forests and the communities depending on forests should be seen as a part of an evolving social-ecological system, while assessing the impacts of climate change and anthropogenic pressures in the era of Anthropocene.

With that background, this literature review was aimed to address three broad aspects of understanding the knowledge on climate change impacts and its consequences on the Himalayan forests. First, we addressed the evidences supporting climate change vulnerability of the Himalayan forests. We discussed what constitutes vulnerability to climate change impacts among different forest species' and/or ecosystems. Second, we explained interaction of communities with forests and how climate change influences forest ecosystem services. Third, we inferred how adaptive capacities of forests to climate change impacts would vary with human disturbances. In addition, we evaluated the scope of community-based forest management in increasing the adaptive capacities of forests to climate change impacts. In the end, we synthesized the principle research areas for increasing the adaptive capacity, and mitigating climate change and anthropogenic impacts on the Himalayan forests. Finally, based on the review, we briefly pointed out the need for policy reforms in the Himalayan region.

Conceptualizing vulnerability: to what and to whom?

Various frameworks have been adapted for assessing vulnerability of natural resources which usually involves identification of climate change impacts, vulnerability assessments of different species or ecosystems, development of climate change adaptation and mitigation strategies, and incorporation of these strategies for different on-going conservation and management initiatives. It is crucial to note that the concept of "vulnerability" can be theorized differently by the research community based on various disciplines (Lwasa 2015). While measurement and classification of vulnerability is highly debatable, it largely depends on the rationale of identifying patterns of vulnerability based on the system in concern (Kok et al. 2016).

For this review, we adopted the latest Intergovernmental Panel on Climate Change (IPCC) framework to suit the specificities of our review, where climate change vulnerability can be defined as a function of system's exposure, sensitivity, and adaptive capacity (IPCC 2014). In this case, forest ecosystem as a natural resource is considered vulnerable if it is susceptible to changes in species structure and composition (such as phenology or migration/altitudinal shifts or local extinction), or reduction in the health and productivity of the forests (such as changes in vegetation indices or biomass); thereby, altering their fundamental identity (Allen et al. 2015). The direct and indirect effects of climate change in an area, such as changes in temperature, precipitation, extreme weather conditions, and increased fire frequencies, can be categorized as *exposure* and the extent to which forest species or ecosystems respond to such alterations can be defined as their *sensitivity*. Together, *exposure* and *sensitivity* have been combined as *impacts* on the system. Therefore, in this paper, we define *impacts* as the immediate or potential direct and indirect consequences (either positive or negative) of climate change. On the other hand, the theory behind the concept of *adaptive capacity* among natural resource managers may vary widely, subjected to the context of the study region (Nicotra et al. 2015). In this paper, we consider two aspects of *adaptive capacity*: (i) the ability of any forest species or ecosystem to accommodate or cope with potential climate change impacts with minimal disruption (Keenan 2015), and (ii) organizational capacity such as social or economic factors in the assessment of adaptive capacity among societies (Johnston and Hesseln 2012). We address the issue of vulnerability by understanding climate change impacts on forests and people, and the possible human interventions to increase adaptive capacities of forests and social systems by decreasing their sensitivities to climate change. Both ecological and social characteristics should be factored to discourse the inter-connectedness of dynamism of socio-ecological system viz., relationship between human and nature in order to capture vulnerability of forests to climate change in the Himalayan region. Therefore, we compiled current knowledge under two broad dimensions, *impacts* and *adaptive capacity* of forests to climate change vulnerability.

Methodology

Characteristics of study area

The review was focused on the Hindu-Kush Himalayan region of Asia. This region extends in an arc of about 3500 km in length and covers approximately an area of about 3,441,719 km^2 extending over all or parts of eight countries including, extending from northern Afghanistan and Pakistan, north western and north eastern states of India, Nepal, Bhutan, northern hills of Bangladesh, and parts of China and Myanmar (Shrestha et al. 2012). Figure 1 shows distribution of the Hindu-Kush Himalayan boundary and its geographical distribution among different countries. The Himalayan range extends from 27° N to 38° N latitude and stretches over a distance of about 3000 km from West to East, and the altitude varies considerably from about 300 m to more than 8000 m, which in turn creates diverse temperature and rainfall regimes across the region (Singh and Singh 1992). As a result, the Himalaya supports tropical moist forests, temperate forests to alpine forests, and harbors rich floral and faunal diversity.

Systematic literature search

For this review, we followed a systematic approach for synthesizing information through a dedicated step-wise process for selecting available peer-reviewed literature sources. Systematically reviewing selected literature is relatively more or less new in the field of climate science criteria, but is often considered advantageous over the generic standard review methods. One of the reasons is because they provide both quantitative and qualitative analysis of trends in the literature (Berrang-Ford et al. 2015). Therefore, given the complexity of the theme, we based our review centered on a clear set of criteria for the review.

We searched for peer-reviewed articles of climate change impacts on the Himalayan forests using the ISI Web of Science and Scopus-indexed publications. These search engines were selected as they provide a comprehensive all-encompassing database for various interdisciplinary domains, including disciplines such as social and environmental sciences (Kilroy 2015; Landauer et al. 2015; Räsänen et al. 2016). The review focused on peer-reviewed literature documenting climate change impacts published over the time interval from the years 1975 to 2016. We used factorial combinations of the following keywords in the searches: ("climate change" and "forest*") and ("Himalaya*" or "mountain*" or "hill*"). From the search conducted in these two databases, the selection terms were examined from the title, abstract, and keywords of the articles. The results included 2898 hits from ISI Web of Knowledge and 2515 hits from Scopus on December 25, 2016. After removing gray literature (reports, conference proceedings, and notes) from the lists of searches, we selected articles based on the scope of the study region which led to 74 articles through ISI Web of Knowledge and 94 through Scopus. With removal of duplicates and an initial review of abstracts from both searches, a final total of 118 studies were selected to be reviewed (see supplementary material for complete list of references (SI-1)). The inclusion and exclusion criteria applied to the selected documents are presented in the supplementary material (SI-2). The first two authors carried out the literature review and analysis of the findings jointly. A series of meetings and discussions summarizing the referred articles were carried out by all the authors. Finally, the fourth author critically looked into the findings and provided semantics in the presentation of the review. We preferred to do a systematic review over a meta-analysis because most of the studies did not fulfill the criteria of meta-analysis (e.g., control vs. experimental treatment, randomized design, availability of parameters such as standard deviation of mean, etc.) as suggested by Vetter et al. (2013). However, it is important to point out that in order to cover extensive scientific studies conducted throughout the vast Himalayan mountain belt, the literature search was not limited to these specific keywords, especially in outlining impacts of

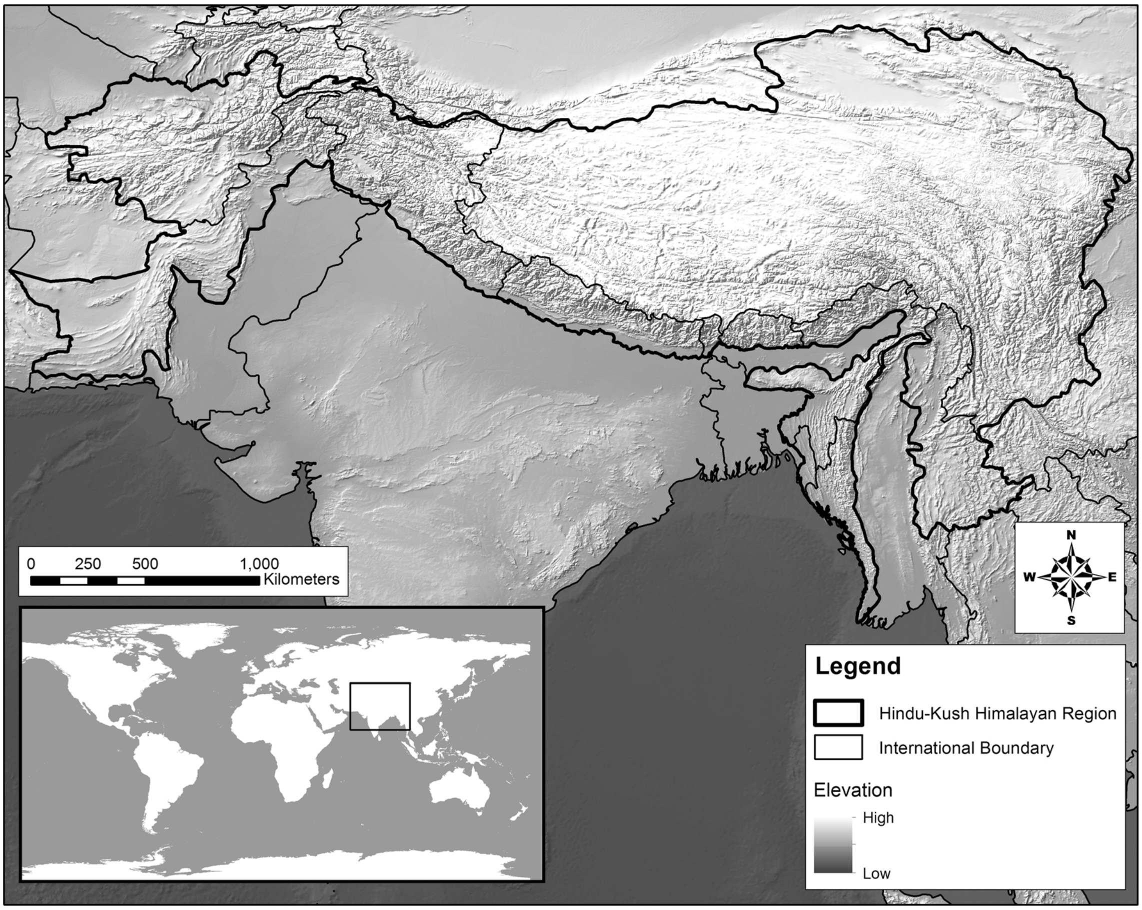

Fig. 1 Study area showing the geographical distribution of the Himalaya-Kush Himalayan (HKH) region

anthropogenic disturbances and underlying knowledge gaps on vulnerability of the Himalayan forests in the discussion and conclusion. As the present study primarily focused on documenting the climate change impacts on the Himalayan forests only, the review process restricted and focused only on peer-reviewed scientific literature. However, given the much important knowledge presented by the gray literature carried out by national, sub-national, or local governments across the Himalayan region, we have tried utilizing them in developing the discussion and conclusion of the review paper.

Results

General trend of literature

A total of 118 articles were examined for this review. The review shows that there has been a significant increase in the number of studies that encompass impacts of climate change on forests (in general or otherwise) over the past few years (Fig. 2a). We searched for peer-reviewed articles since 1975; however, it was not until 1996 when studies were specifically focusing on climate change impacts on forest ecosystems in the Himalayan region. Almost 91.5% of the total number of papers has been published between 2009 and 2016. The number of publications increased after 2009, with a peak of publications being 28 (23.7%) in 2015, followed by 24 (20.3%) in 2016. This recent growth in the number of studies suggests the enhanced interest in understanding vulnerability of forests and related systems due to climate change over the recent years.

In geographical terms, the majority of the studies were in India (66.1%), with peak number of publications up to 78 articles. This was followed by Nepal (18.6%) with 22 articles (Fig. 2b). Very few peer-reviewed articles were located in Bhutan (4.2%), China (4.2%), and Pakistan (1.7%). On the other hand, countries such as Afghanistan, Bangladesh, and Myanmar, no such studies on the theme of the review were found. The most likely reason could be the geographical area coverage of the Himalayan mountain range. Regional studies were also conducted in the study region, with one study covering countries, Nepal and China (0.8%), and the other study covering the entire Hindu-Kush Himalayan (HKH) region (0.8%). There were four articles which discussed the impacts of climate change on forests in general (3.4%), mostly as a suggestive discussion (from management perspective) or review (from previous studies).

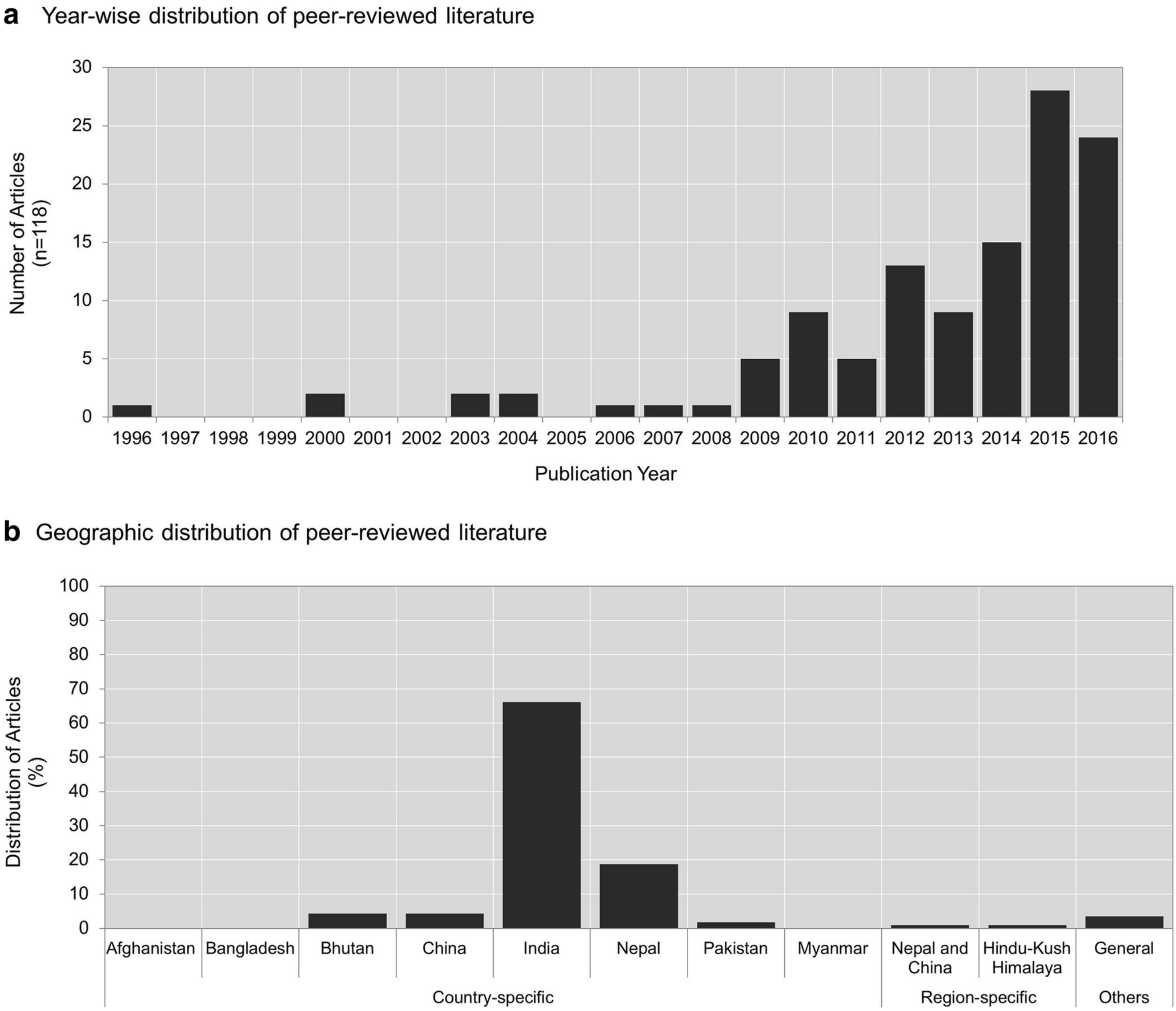

Fig. 2 Distribution of peer-reviewed articles based on **a** year-wise distribution and **b** geographical distribution, in the Himalayan region (data till 25th December, 2016)

Perspective on evidence of impacts

Various disciplines and contrasting diverse suite of methodologies have been explored to study the impacts of climate change on forests. For instance, few studies indirectly assess changes in vegetation through palynological studies (Demske et al. 2016) or through increasing number of invasive species (Mandal and Joshi 2015) in the Himalayan region. In other instances, studies explore direct impacts focusing on identifying changes in the forest structure and composition (Pandey et al. 2016; Müller et al. 2016), or changes in seasonality (Shrestha et al. 2012), or shifts in geographic location of vulnerable species (Chitale et al. 2014; Chakraborty et al. 2016). In addition, many theoretical papers (discussion articles or review papers) focus on climate change impacts affecting the Himalayan ecosystem in general; thereby, implicating need to proactively manage forests in a changing climate scenario in the future. To emphasize on the evidences of impacts in the Himalayan region, we categorize the type of impact on forests through different perspectives of the reviewed articles (Fig. 3a). We identify ten perspectives on which we categorized the peer-reviewed papers where the studies focused on (i) changes in structure and composition of forests, (ii) changes in vegetation productivity, (iii) changes in seasonality (physiology and phenology), (iv) biomass (above and below ground) and soil carbon estimates, (v) climate change indicators (climate variables or forest species) or local observations, (vi) tree-ring chronologies or palynogical/paleo-ecological/paleo-dendrological studies, (vii) migration of species (either at the ecosystem level or species-level, or changes in treeline

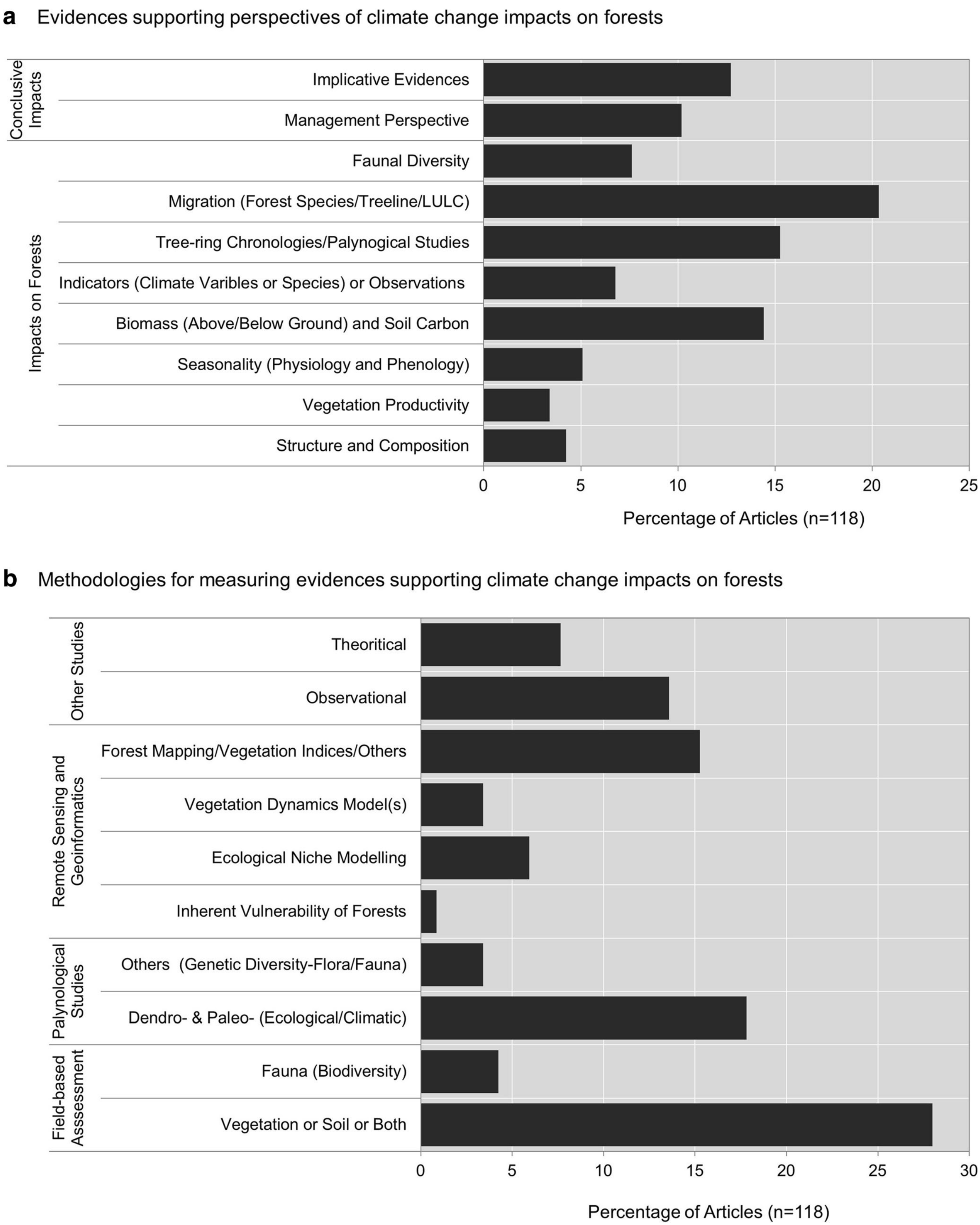

Fig. 3 Distribution of peer-reviewed articles based on **a** evidences supporting perspectives on climate change impacts on forests and **b** methodologies for measuring evidences supporting climate change impacts on forests

or other land-use land-cover (LULC) changes), (viii) changes in faunal diversity, and, in few cases, other conclusive impacts discussing climate change impacts on forests through (ix) forest management perspective, and (x) implicative evidences of impacts through discussion of related studies (mostly theoretical papers). The maximum number of articles focused on changes in forest cover area (migration or otherwise), with publication number up to 24 articles. This was followed by studies assessing changes in vegetation through mostly tree-ring analysis or palynological studies (18 articles), and biomass and carbon estimation studies (17 articles).

While we recognize there is a gradient of perspective available categorizing the different evidences suggesting impacts on forests, there also exist differences in the type of methodologies of the studies conducted, given the vast scope of scientific disciplines. We, therefore, categorize the different methods available to assess vulnerability of forests (or related systems) to climate change impacts (Fig. 3b). We identified ten broad groups of methodologies used to conclude impacts of climate change on forests in the Himalayan region. These include (i) field-based vegetation and soil assessments; (ii) field-based faunal biodiversity assessments; (iii) palynogical studies such as dendro-climatic or paleo-ecological analysis; (iv) other palynogical studies focusing on changes in genetic diversity of both flora and fauna; (v) inherent vulnerability of forests; (vi) ecological niche modeling of forests; (vii) vegetation dynamics models such as integrated biosphere simulator (IBIS) model; (viii) other remote sensing and GIS-based studies, which includes mapping of forests, changes in vegetation indices, and other LULC changes; (ix) observational studies on climate change impacts on forests; and (x) theoretical papers discussing the same. While maximum studies are based on field-based observations of vegetation and soil (28%), this was followed by evidences of changes in vegetation and climate through palynological studies (17.8%) and remote sensing and GIS-based methods (15.3%). Few participatory studies were also prevalent in this region through social surveys (13.6%). It is important to note that modeling studies such niche modeling (5.9%) and vegetation dynamics models (3.4%) are not explored as extensively as expected. The likely reason could be paucity of available data on species, climate observations, and in some cases, inaccessibility of remote areas to validate such modeling studies.

Climate change impacts on the Himalayan forests

Developing the understanding on vulnerability of forests to climate change in the Himalayan mountain region is very complex, as current and potential changes not only stress adaptive capacities of forests but also challenge the mountain communities (Ma et al. 2012; Briner et al. 2013). The vulnerability would depend on both ecological and social resilience in the face of any disturbance, such as climate change. In addition to this, vulnerability assessments to climate change impacts will vary across different hierarchical levels of an ecosystem and spatial scales of measurements. More than often, understanding vulnerability of forest ecosystems becomes challenging as the mechanisms determining vulnerability cannot be observed directly (Polsky et al. 2007). In such cases, we resort to the use of proxy indicators (either climate variables such as temperature and precipitation, or indicator species, or forest conditions such as biological richness or degradation/disturbance index) that capture causal processes determining the "inherent" vulnerability of forests (Sharma et al. 2013; Upgupta et al. 2015). Therefore, it becomes crucial to explicitly specify the context and framework of vulnerability studies by capturing multi-dimensionality in both space and time.

Much of the literature in the Himalayan region comes to an understanding that climate is an important driver which could influence forests in this region. This could include changes in vegetation structure and composition to past climate data (Biswas et al. 2016; Demske et al. 2016; Gaire et al. 2017), or changes in vegetation productivity including changes in biomass (Zhang et al. 2013; Alekhya et al. 2015), changes in phenology (Shrestha et al. 2012; Singh et al. 2015; Bajpai et al. 2016; Tewari et al. 2016), or shifts in different forest-cover types to future climate data (Joshi et al. 2012; Telwala et al. 2013; Wani et al. 2013; Chitale et al. 2014; Rashid et al. 2015; Chakraborty et al. 2016). However, formulating any forest management policy is extremely difficult as most of these assessments vary based on their geographic (in terms of ecological hierarchy) and temporal (past and/or future) scale of assessment (see supplementary material (SI-3)). The changes in vegetation patterns, however, are not only due to climate change (Rawat et al. 2012; Schickhoff et al. 2014); they have been accelerated by anthropogenic disturbances such as human encroachment to primary forest areas (Rawat et al. 2012; Brandt et al. 2013), fire (Gupta 1978), cutting (Awasthi et al. 2003), over-grazing (Nautiyal et al. 2004), deforestation (Kumar and Ram 2005), intensive agriculture (Semwal et al. 2004), shifting-cultivation (Zonunsanga et al. 2014), and other land-use practices, which further challenge the coupled human-natural systems in Himalaya.

Impacts on forests

Warming in the Himalayan region varies along the mountain belt, with warmer conditions over western and central Himalaya and cooler conditions over eastern Himalaya (Polanski et al. 2014). Average annual mean temperature has increased by 1.5 °C with an average increase of 0.06 °C per year, while average annual precipitation has increased by 163 and 6.52 mm per year between 1982 and 2006 (Shrestha et al. 2012). There has been significant variation in the precipitation patterns as well as increase in number of cloudy days with the increase in temperature over time (Banerji and Basu 2010).

Pronounced warming trends over the Tibetan Plateau in recent decades have led to high intensity rainfall events in western Himalayan region (Madhura et al. 2014). Regional climate models also capture sudden high rainfall events over the Himalayan region (Menon et al. 2013). Incidences of heavy rainfall events and seasonal variability, accompanied with irregularity of monsoon rainfall, are predicted in the entire Himalayan region (Bhutiyani et al. 2010; Cook et al. 2010; Turner and Annamalai 2012). With general increasing trend of temperature combined with regional changes in precipitation patterns, drastic decrease in discharge of water resources (up to 94%) with retreating glacier coverage have been reported (Akhtar et al. 2008). Most of the glaciers in Himalaya are losing mass by melting and calving, except for indications of stability and mass gain in the Karakoram belt (Inman 2010; Bolch et al. 2012). Studies indicate quality and abundance of water in the Himalayan region with the presence of Oak forests (Sheikh and Kumar 2010), while decrease in water holding capacities linked with Pine forests (Singh and Singh 1987). Therefore, depletion of water resources can not only be associated with retreating glacier coverage but also with distribution patterns of different forest-types; thus, showing a complex relationship in the Himalayan region with interlinkages between hydrology and climate, which affects phenology and growth of many species in this region.

Based on satellite-derived normalized difference vegetation index (NDVI), decrease in vegetation productivity during average growing seasons has been reported (Shrestha et al. 2012; Zhang et al. 2013). In addition to this, field-based vegetation studies show significant changes in the leaf emergence, flower initiation, and growing seasons of many forest species (Xu et al. 2009; Negi et al. 2012; Singh et al. 2015; Bajpai et al. 2016; Tewari et al. 2016). Despite knowing the vulnerability to climate change in this region, there is a dearth of landscape level phenological observations. Changes in timberline due to climate change have been reported in the central Himalaya (Panigrahy et al. 2010); however, such studies have been highly criticized for their selection of inappropriate methodologies and inaccuracies in interpreting vegetation classes (Bharti et al. 2011), and also in using terminologies such as "timberline" and "treeline" in the alpine ecosystem (Negi 2012). Often palynological studies are used as a better reference for understanding changes in the structure and composition of treeline in the Himalayan region (Liang et al. 2014; Tiwari et al. 2017). Many medicinal plant species are particularly susceptible to changing climatic variables (Gairola et al. 2008; Chawla et al. 2012; Negi et al. 2012). Upward shifts of Himalayan pine have been observed (19 m per 10 years on south and 14 m per 10 years on north slope) which reflect high sensitivity to climatic warming (Dubey et al. 2003). Literature indicates reduced distribution pattern of *Quercus* spp. and *Pinus* spp. with changes in temperature and precipitation variables (Saran et al. 2010; Chakraborty et al. 2016). Rhododendron species are predicted to show significant changes in its extent of spatial distribution to potential changes in climate variables (Kumar 2012). In many regions, increased occurrences of forest fires are associated with warming in the Himalayan region, especially between altitudes ranging from 600 to 2650 m (Negi et al. 2012). While the treeline in the Himalayan region is the most sensitive and vulnerable region to climate change impacts (Telwala et al. 2013), the Alpine meadows show decrease in its cover due to increased shrub encroachments augmented by anthropogenic influences (Brandt et al. 2013; Schickhoff et al. 2014). Changing climate is likely to support the niche of Himalayan birch (*Betula utilis*) as there is potential for this species to grow in the sub-alpine region in the absence of other stimuli influencing its growth (Singh et al. 2013). Other ecosystem-related studies show changes in different ecological hierarchies, based on climate change as the major factor influencing vegetation (Chakraborty et al. 2013).

Most of these studies are based on a time-scale, which is hard to be interpreted as only a climate change impact. The major hurdle of interpreting such results of any potentiality lies in the uncertainty of future climate predictions (Rosenzweig et al. 2014). We lack baseline data for vegetation studies and permanent monitoring plots (PMPs) have seldom been used for long-term ecological monitoring across the Himalayan region (Chawla et al. 2012). Therefore, in order to accurately monitor climate change impacts on forests, inventories on long-term vegetation data are required in the Himalayan mountain range.

Impacts on forest goods and services

With the realization of the ecological importance of forests in the Himalayan region and their significance in the life-support system of local communities, several studies have been conducted to evaluate goods and services provided by the Himalayan forests (Awasthi et al. 2003; Rijal et al. 2011). The relationship between forest and local communities plays a key role in maintaining economy as well as ecology of the Himalayan region (Rao et al. 2003; Negi et al. 2011; Rayamajhi et al. 2012). With probable impacts of predicted climate change, maintaining a continuous supply forest ecosystem services for mountain communities would be a challenging task (Awasthi et al. 2003). In addition to direct and indirect impacts of climate change on forests, changes in climate variables are likely to affect the local population who are either dependent on forests and/or forest-based resources, or are mainly agrarian and pastoral communities (Singh et al. 2011; Mishra et al. 2012; Pandey and Jha 2012).

Fodder is one of the major products derived from Himalayan forests, Oak foliage being the main preference (Awasthi et al. 2003). Fuel wood is also extracted in this region (Kala 2000) as it meets the energy consumption need for cooking, heating, and lighting. Although large-scale felling of trees is prohibited to prevent further degradation of the Himalayan mountain system (Kala 2000), timber might still be illegally extracted in some areas. Non-timber forest products (NTFPs) are commercially important ecosystem services derived in this region. These include products derived from forest such as fruits, seeds, nuts, resin, latex, mushrooms, honey, and medicinal and aromatic plants (Saha and Sundriyal 2012). Literature indicates assessments of carbon sequestration potential in the Himalayan forests (Mandal and Laake 2005) as it is crucial in managing atmospheric carbon concentration. The net primary productivity (NPP) shows possibility of an increase in values with modeled potential climate change scenarios (Chaturvedi et al. 2011; Gopalakrishnan et al. 2011); however, these predictions involve many limitations.

With changes predicted in distribution pattern of forests as a response to climate change, benefits derived from forests would be invariably altered in predicted climate change scenario. Scientific research elsewhere across the globe quantify the consequences of climate change affecting forest-based goods and services and other forest activities (Haines-Young et al. 2012; Briner et al. 2013). However, most of the previous studies in the Himalayan region focus on only quantifying goods and services from the Himalayan forests, while not dwelling in the concept of changing climate (Ma et al. 2012; Rayamajhi et al. 2012). This indicates the lack of empirical studies quantifying change in ecosystem goods and services, while considering climate change impacts on forests in the Himalayan region. The ecosystem services from forests vary with region-specific species composition, which in turn are influenced by management regime applied in the forests. The continual generation of periodic data on quantification of goods and services is almost non-existent in this region. For instance, we could not integrate harvesting NTFPs throughout Himalaya in any plausible climate change scenario, although it guarantees livelihood improvement (Negi et al. 2011; Rijal et al. 2011). With the current and potential climate change scenario, inclusion of NTFPs can prove to be a viable option that could be exploited in the coming future. This increases the incentive to retain forest resources, instead of direct the conversion of forest land to be used for agriculture or livestock. Even degraded forests in Himalaya are now considered as a management option for mitigating carbon sinks (Murthy et al. 2012). A summary of the sensitivity of forest goods and services to climate change impacts in the Himalayan region is provided in the supplementary material (SI-4). It is crucial to note that more research efforts are required on changes in forest goods and services for long-term planning to suffice for the deficiency in knowledge. By comprehensively understanding forest dynamics and its driving factors, either climate change and/or human-induced pressure on forests, forest management strategies should be developed, which necessitates ample scope for further research in this regard.

Although climate change as a driver affecting geographic distribution of ecosystems has been well-established (Seidl and Lexer 2013; Lindner et al. 2014; Allen et al. 2015), it should be noted that climate change and its impacts on the Himalayan forests is ongoing. With uncertainty and paucity of available data and scientific literature, it is difficult to demonstrate the amount of regional vulnerabilities of forests in the Himalayan region. With wide ecological variability and geologically unstable topography (Singh and Singh 1987), more exploration and assessments are required to understand regional vulnerabilities, including risks and possible opportunities in potential climate change scenarios.

Adaptive capacity of the Himalayan forests

The adaptive capacity of the forests is related to the resistance, recovery, and resilience of forests to climate change-induced disturbances such as extreme heat or cold events, changes in seasonality and intensity of precipitation patterns, and landslides, among others (Morin et al. 2015; Reyer et al. 2015). Resistance of the forest can be defined as the capacity of forest ecosystems at community or species level to withstand the stress created by the disturbances. Recovery ensures a forest to regenerate and grow after the disturbance, which is often a trigger event such as succession. Resilience is the return to pre-disturbance level in forest structure and composition. Under the long-term evolutionary context, novel ecosystem emerged through this dynamic process, which is characteristic of complex and adaptive biological systems (Messier et al. 2013). In this section, we will present how adaptive the Himalayan forests are to the impacts of climate change as described in earlier section.

Current stressors: exploitation of forest resources

The Himalayan forests have evolved and have been exposed to extensive human-manipulated changes over the past few hundred years. Therefore, climate change alone cannot be held responsible for affecting forests in the Himalayan region. The influence of anthropogenic disturbances has had substantial implications on the forests as well (Arunachalam et al. 2004; Kumar and Ram 2005; Bawa et al. 2007). The rapidly changing land use patterns attributed by increased urbanization and population dynamics has immensely contributed in shaping current distribution pattern of forests in the Himalayan landscape (Singh 2006). This consequently leads to sediment and nutrient losses, thereby creating disturbed and degraded forest ecosystems (Sharma et al. 2007). Overgrazing by livestock, illegal encroachment, and trading are the biggest threats to regeneration of vegetation in all the forested areas

(Balooni et al. 2007; Baland et al. 2010). Overexploitation and conversion of forests into pasture lands and other practices, such as horticulture, have substantially decreased the forest cover in the Himalayan mountain range (Semwal et al. 2004). The major human activities related to forests that have influenced the Himalayan landscape over the past few hundred years are provided in the supplementary material (SI-5). Such changes, heightened by uncertainties of climate change impacts, can lead to irreversible damage of Himalayan forests. Therefore, large-scale conservation efforts, including forest protection and reforestation, are urgently required to avoid and possibly reduce the impending losses in the Himalayan region. A clear understanding of the preceding forest management practices will provide a baseline for implementing restoration and conservation strategies in favor of adapting to climate change impacts of the Himalayan forests.

Adaptation processes and long-term consequences

While conceptual management theories involving communities to continuously adapt to changing forest systems has been discussed (Kerry et al. 2012), much gaps still exists within planned and implemented policy measures to increase adaptive capacities of forests and social systems (Seidl and Lexer 2013). The forests can have life cycles ranging from decades to centuries depending on the forest types (Spittlehouse and Stewart 2004). Forests which are already well-managed can significantly reduce their vulnerabilities to climate change impacts. The societies directly or indirectly dependent on such forest types are usually able to find ways to adapt to both current and future climate risks, as the forests are able to provide wider range of ecosystem goods and services in various stressed scenarios (Locatelli et al. 2011).

The Himalayan forests require actions at the present in order to avoid long-term impacts of climate change. Documented cases involving adaptive capacities of these forests are almost negligible. Even though disturbances have played a crucial role in determining changes in forest structure, composition, and functions (Arya et al. 2012), the continuous exposure of forests to changing climate scenarios, and increasing dependence along with overexploitation of forest resources have drastically deteriorated the ecosystem in this region. This increases potential risks to forests, and challenges, in certain cases, decreases their adaptive capacities. In the case of very high periodic and chronic disturbances induced by human activities, some regions in Himalaya have witnessed conversion of oak forests into *Pinus roxburghii* forests or open scrubs (Upreti et al. 1985). Mostly, in such cases, disturbed *P. roxburghii* forests are associated with low levels of biological diversity and little understory vegetation (Sinha 2002; Kumar and Ram 2005). Local forest management practices, like annual burning of forest floor, in order to have fresh grass cover for grazing, significantly influences shifts in different forest types in the Himalayan region (Thadani and Ashton 1995). In certain pockets, commercial logging has led to loss of natural forest patches, where the choice of species for plantation is based on high timber value, following slash, and burning on clear-cut forest lands (Shankar et al. 1998). Such a scenario dramatically alters the landscapes, majorly interrupts the ecosystem recovery, and causes considerable loss of species. Despite the evidences suggesting changes in forests in the Himalayan region, in most cases, the changes in forests are more likely due to anthropogenic causes rather than direct impacts of climate change. Few experimental evidences support model predictions of loss of species due to climate change, as indirect effects on species richness causing major decline in plant species diversity in the Himalayan highlands (Klein et al. 2004). Even short-term experimental warming using the open top chamber (OTC) method alters structural and functional leaf traits, and enhances photosynthetic capacity of treeline birch, *Betula utilis*, saplings (Xu et al. 2011). This study corresponds to the study by Singh et al. (2013), which concludes favorable growth of this species under future warmer scenario. However, till date, only a few authors have studied the independent and combined effects of experimental warming and anthropogenic disturbances on forests in the Himalayan region, which is highly vulnerable to both ongoing climate and land use changes.

Studies indicate involvement of local communities in deciding future possibilities under the stresses of changing climate variables (Kelkar et al. 2008; Meenawat and Sovacool 2011; Aase et al. 2013; Aryal et al. 2014). Several adaptation options include community-level awareness, controlling forest fires, creation of protected areas to conserve the forests, and sustainable newer livelihood options (Banerji and Basu 2010). However, proper implementation of adaptation strategies in response to changing climatic conditions is still not well-developed (Pandey and Jha 2012; Wani et al. 2013). The communities in this region are already facing a range of challenges varying from social, economic, political, and environmental factors; vulnerability from these factors has, however, intensified due to climate change (Barua et al. 2014). Immediate attention is required in this domain since climate change effects are increasingly being recognized all-throughout the Himalayan region.

Discussion

The review highlights a significant increase in the number of studies that encompasses vulnerability of forests to climate change impacts in the Himalayan region, and a rapid increase in publications since 2009. The findings report a recent growth in the number of publications suggesting the

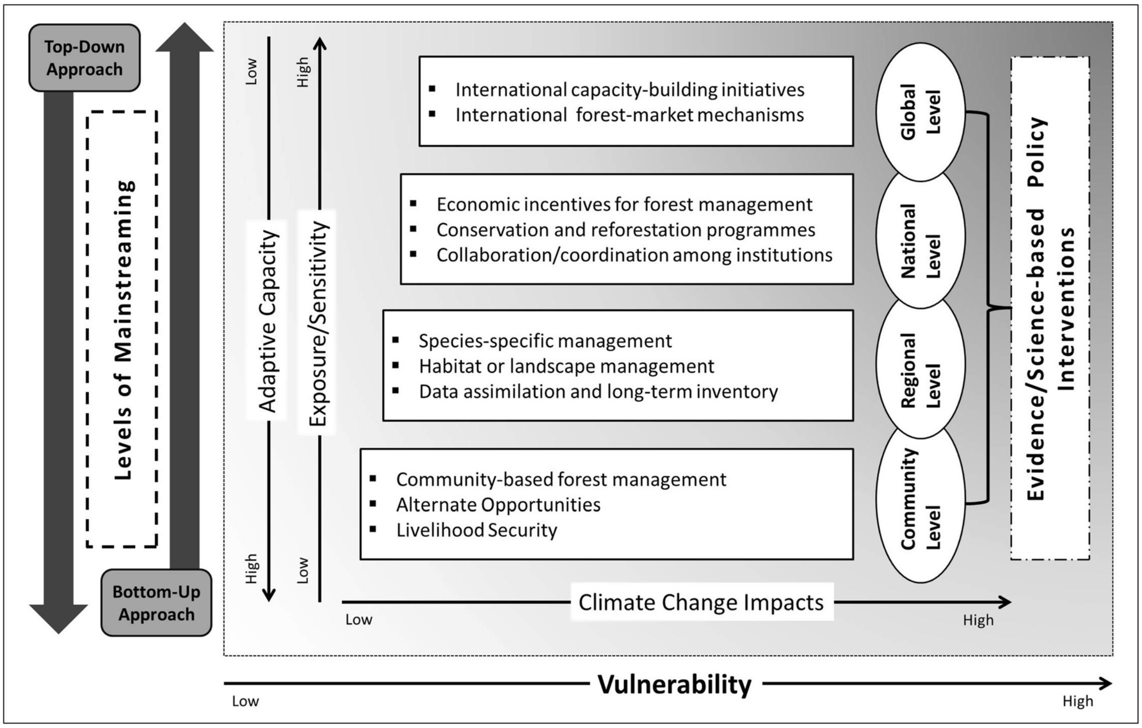

Fig. 4 Framework for managing and conserving forest ecosystems in the Himalayan region based on relative intensity of vulnerability to climate change impacts

enhanced interests in studying and understanding the vulnerability of forests and related systems due to climate change over the recent years. The studies report a wide range of perspectives on collection of evidences of the impacts on the Himalayan forests, and these results in shaping and interpreting their adaptive capacity. While we acknowledge the importance of the research carried out, this review brings out two important aspects related to vulnerability of the Himalayan forests: one, the scope of forest management initiatives, and the other, importance of community-based forest management. We uncover these based on the reviewed literature and other information collected through grey literature. We assume the utility of these findings in reporting outcomes of future research, and also, in influencing the policy and practices related to the Himalayan forests and its vulnerability to climate change impacts.

Scope of forest management in the Himalayan region

In order to develop proper strategies for adapting forests to climate change, the first and foremost step would involve strengthening ecological databases in this region, as it lacks continuous surveying and monitoring (Rawal et al. 2003; Gopalakrishnan et al. 2011; Singh and Thadani 2015). The next step is to have information regarding vulnerability of forests, forest-based communities (Upgupta et al. 2015), and societies depending on resources from forests (Negi et al. 2012), including dependent lowland and downstream communities. Vulnerability to climate change impacts has not been fully studied in the entire Himalayan region; as a response, many critical endemic species have not yet been explored (Gopalakrishnan et al. 2011; Negi et al. 2012). Identification of vulnerable hotspots is required so as to determine the areas for intervention in the Himalaya to adapt to climate-related risks (Banerji and Basu 2010). The identification of driving factors other than climate variables such as bio-physical and socio-economic parameters of climate change can also be used as an area of adaptation measure for managing communities and their extraction of forest-based resources depending on current or possible future vulnerability of the Himalayan forests (Barua et al. 2014; Schickhoff et al. 2015).

Short-term adaptive planning strategies, such as thinning highly dense forest stands to promote recovery, resilience, and resistance of trees to disturbance events, like drought (Sohn et al. 2016), forest fire (Stephens et al. 2013), flooding (Horner et al. 2010), and frost (Bremer and Jongejans 2009); or by reducing plant competition, have never been tested in the Himalayan region. The implementation of similar strategies in the Himalayan region could be particularly important for maintaining the forest cover, where management goal is to provide forest-based products including timber, fuelwood, and fodder to mountain communities in a resourceful yet sustainable manner. In many parts of Himalaya, oak-dominated broadleaved forests were converted to pine forests in the past, mostly by human activities (Singh et al. 1984; Upreti et al.

1985). Such pure pine stands could be more vulnerable to climate change impacts, and there is a need to develop strategies for converting such pine forests to mixed forests. In the long-run adaptive planning, human interventions to change the forest composition are a question of the vulnerability of forest tree species to extinction under the rapidly changing climate (Chakraborty et al. 2016). Elsewhere in the world, forest managers are converting climatically vulnerable forests to diverse forest by gradual species replacement to increase the ecological complexity of the forests (Lindner 2000). Such conversion of the forest eventually increases the adaptive capacity of the forest. However, basic research on the vulnerability to extinction assessment of the Himalayan flora under climate change is lacking, which puts forward significant challenges among forest managers to opt for long-term adaptation measure, such as forest conversion. This warrants long-term monitoring of Himalayan vegetation to create baseline data on autecology, synecology, ecophysiology, and future distribution shifts of the Himalayan forest species by installing permanent monitoring plots (PMPs) (Singh and Thadani 2015). Strong evidence-based scientific understanding on the response of forest species to climate change is seriously lacking in the Himalayan region (Negi et al. 2012). Therefore, traditional knowledge of local communities for developing climate change adaptation strategies, as well as to reduce impact of climate change on forest ecosystems, should be encouraged in this region (Singh et al. 2011). With that context, community-based forest management can play an important role to manage forest sustainably under the scenario of climate change.

Community-based forest management in the Himalayan region

Many communities living in the Himalayan region have subsistence living, and are therefore mostly dependent on forests and forest-based resources for their livelihoods (Singh and Singh 1987). This has evolved to an intricate relationship among people and forests in this region, which in turn implicates that the Himalayan forests are being and will be influenced by the impacts of climate change as well as by the communities residing in this region. With the agenda of conserving forests along with uncertainties of climate change, understanding traditional knowledge and encouraging people participation in forest resource management is crucial. In this section, we highlight how community-based forest management can be used for reducing vulnerability of the Himalayan forests under ongoing and future climate change.

Many forest areas conserved by local community are not recognized and well-understood, and in many cases, not documented as well (Kothari 2006; Axford et al. 2008), leaving it in jeopardy of lacking political and financial support, which in turn subsequently increases their vulnerability to external threats. In certain instances, community-based forest participation has led to conservation of endangered flora and fauna (Shahabuddin and Rao 2010; Anthwal et al. 2010; Baral et al. 2014). In other cases, local institutions of community-based forest governance show examples for forest management practices, which include sustainable resource uses of fuelwood, fodder, timber, medicinal and aromatic forest products, among others (Agrawal and Chhatre 2006; Saha and Bisht 2007; Chettri et al. 2015). Forest conservation policies including local communities often empower them by providing enormous opportunities to utilize forests and forest-based resources under different land management scenarios. This in turn allows them to actively play a major role in community-based forest management practices, carbon sequestration initiatives, and other community forest user groups (CFUGs) activities such as REDD+ initiatives (Poudel et al. 2014; Sharma et al. 2015). Such cases of community participation for protecting forests in the Himalayan region would help forests to cope up with indefinite climate change impacts, as it conserves organisms which are already critically endangered or are facing threats due to other anthropogenic factors. Such forest conservation efforts would also increase the ecological complexity (i.e., species diversity, structural diversity, functional diversity, and genetic diversity) of the forests, thereby enhancing the adaptive capacity of the forests. And finally, active contributions of communities to sustainably manage forest resources ensures better planning of natural resources, checks for indiscriminate and unscientific destruction of forest resources, along with alleviating poverty of many marginalized mountain communities. These initiatives will ultimately allow opportunities to reduce vulnerability of forests to climate change-induced disturbance events in a human-dominated landscape, such as the Himalayan region (Singh et al. 2011).

Conclusions

In summary, this paper reviews impacts of climate change and anthropogenic disturbances on the Himalayan forests in order to capture the vulnerability of this region. We find that despite advances in climate change research on forests in the Himalayan region, much lesser is known about regional vulnerabilities. In terms of forest management perspective, while considering climate change vulnerabilities of forests, most planning initiatives and policy frameworks are based on gross macro-level systems-based vulnerability assessments (Wellstead et al. 2014). The failure of such approaches are often associated with lack of integration of ecosystem services of local planning in the adaptation processes on account of which several policy decisions are convened (Lemieux et al. 2014). In order to effectively deal with such discrepancies, forest policy initiatives should be inconclusive at the national, sub-national, and local level sectoral plans, while encompassing ecological and social dimensions of the forest ecosystem. Adopting flexible adaptation policies, with adjustment from different stakeholders, is imperative to continuously benefit from goods and services provided by the Himalayan forests. Figure 4 illustrates the framework for managing and conserving the forests in Himalaya based on the relative intensity of vulnerability of forests with social structure being an integral part of the system. Institutional arrangements with support from regional bodies and local communities would guarantee judicious and sustainable forest resource management.

Our review focused on climate change impacts on forests in the Himalayan region. Although, there has been progress in terms of various assessments attempted over the last few years, but their number remains very limited. There exists a clear gap in conceptualizing climate change vulnerability of forests as understood by a wide variety of research conducted in the Himalayan region. The findings from the present study highlight the limited number of studies, which represent this region as rather void in terms of scientific research on vulnerability in social-ecological landscapes, especially with respect to the global climate change phenomena. Given the data scarcity in this region, all the Himalayan stakeholders should attempt collective research to comprehensively synergize to maximize utility of various available information, knowledge, and datasets developed in the Himalayan region. With the amalgamation of newer scientific approaches based on empirical evidences, along with traditional knowledge from different communities, an integrated multi-disciplinary and multi-sector approach should be initiated. This will ultimately allow us to better inform and execute conservation and adaptation planning throughout the mountain belt. The outcomes of government efforts should trickle down to the local levels in each country. Such an effort will help the decision makers to strategically plan and delegate adaptation and mitigation measures for managing forest resources and dependent livelihood options across the Himalayan region under different climate change scenarios.

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References

Aase TH, Chapagain PS, Tiwari PC (2013) Innovation as an expression of adaptive capacity to change in Himalayan farming. Mt Res Dev 33:4–10. https://doi.org/10.1659/MRD-JOURNAL-D-12-00025.1

Agrawal A, Chhatre A (2006) Explaining success on the commons: community forest governance in the Indian Himalaya. World Dev 34: 149–166. https://doi.org/10.1016/j.worlddev.2005.07.013

Akhtar M, Ahmad N, Booij MJ (2008) The impact of climate change on the water resources of Hindukush-Karakorum-Himalaya region under different glacier coverage scenarios. J Hydrol 355:148–163. https://doi.org/10.1016/j.jhydrol.2008.03.015

Alekhya VVL, Pujar GS, Jha CS, Dadhwal VK (2015) Simulation of vegetation dynamics in Himalaya using dynamic global vegetation model. Trop Ecol 56:219–231

Allen CD, Breshears DD, McDowell NG (2015) On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Ecosphere 6:1–55. https://doi.org/10.1890/ES15-00203.1

Anthwal A, Gupta N, Sharma A, Anthwal S, Kim KH (2010) Conserving biodiversity through traditional beliefs in sacred groves in Uttarakhand Himalaya, India. Resour Conserv Recycl 54:962–971. https://doi.org/10.1016/j.resconrec.2010.02.003

Arunachalam A, Sarmah R, Adhikari D, Majumder M, Khan ML (2004) Anthropogenic threats and biodiversity conservation in Namdapha nature reserve in the Indian Eastern Himalayas. Curr Sci 87:447–454

Arya N, Tewari B, Ram J (2012) The effect of natural and anthropogenic disturbance in forest canopy and its effect on species richness in forests of Uttarakhand Himalaya, India. Russ J Ecol 43:117–121. https://doi.org/10.1134/S1067413612020099

Aryal S, Cockfield G, Maraseni TN (2014) Vulnerability of Himalayan transhumant communities to climate change. Clim Chang 125:193–208. https://doi.org/10.1007/s10584-014-1157-5

Awasthi A, Uniyal SK, Rawat GS, Rajvanshi A (2003) Forest resource availabilty and its use by the migratory villages of Uttrarkashi, Garhwal Himalayas (India). For Ecol Manag 174:13–24. https://doi.org/10.1016/S0378-1127(02)00026-9

Axford JC, Hockings MT, Carter RW (2008) What constitutes success in Pacific Island community conserved areas. Ecol Soc 13:45

Bajpai O, Pandey J, Chaudhary LB (2016) Periodicity of different phenophases in selected trees from Himalayan Terai of India. Agrofor Syst 91:1–12. https://doi.org/10.1007/s10457-016-9936-9

Baland JM, Bardhan P, Das S, Mookherjee D (2010) Forests to the people: decentralization and forest degradation in the Indian Himalayas. World Dev 38:1642–1656. https://doi.org/10.1016/j.worlddev.2010.03.007

Balooni K, Ballabh V, Inoue M (2007) Declining instituted collective management practices and forest quality in the central Himalayas. Econ Polit Wkly:1443–1452

Banerji G, Basu S (2010) Adapting to climate change in Himalayan cold deserts. International Journal of Climate Change Strategies and Management 2:426–448. https://doi.org/10.1108/17568691011089945

Baral HS, Sahgal B, Mohsanin S, Namgay K, Khan AA (2014) Species and habitat conservation through small locally recognised and community managed special conservation sites. J Threat Taxa 6:5677–5685 https://doi.org/10.11609/JoTT.o3792.5677-85

Barua A, Katyaini S, Mili B, Gooch P (2014) Climate change and poverty: building resilience of rural mountain communities in South Sikkim, eastern Himalaya, India. Reg Environ Chang 14:267–280. https://doi.org/10.1007/s10113-013-0471-1

Bawa KS, Joseph G, Setty S (2007) Poverty, biodiversity and institutions in forest-agriculture ecotones in the western Ghats and eastern

Himalaya ranges of India. Agric Ecosyst Environ 121:287–295. https://doi.org/10.1016/j.agee.2006.12.023

Berrang-Ford L, Pearce T, Ford JD (2015) Systematic review approaches for climate change adaptation research. Reg Environ Chang 15:755–769. https://doi.org/10.1007/s10113-014-0708-7

Bharti RR, Rai ID, Adhikari B, Rawat G (2011) Timberline change detection using topographic map and satellite imagery: a critique. Trop Ecol 52:133–137

Bhutiyani MR, Kale VS, Pawar NJ (2010) Climate change and the precipitation variations in the northwestern Himalaya: 1866–2006. Int J Climatol 30:535–548. https://doi.org/10.1002/joc.1920

Biswas O, Ghosh R, Paruya DK, Mukherjee B, Thapa KK, Bera S (2016) Can grass phytoliths and indices be relied on during vegetation and climate interpretations in the eastern Himalayas? Studies from Darjeeling and Arunachal Pradesh, India. Quat Sci Rev 134:114–132. https://doi.org/10.1016/j.quascirev.2016.01.003

Bolch T, Kulkarni A, Kääb A, Huggel C, Paul F, Cogley JG, Frey H, Karg JS, Fujita K, Scheel M, Bajracharya S, Stoffel M (2012) The state and fate of Himalayan glaciers. Science 336:310–314. https://doi.org/10.1126/science.1215828

Brandt JS, Haynes MA, Kuemmerle T, Waller DM, Radeloff VC (2013) Regime shift on the roof of the world: alpine meadows converting to shrublands in the southern Himalayas. Biol Conserv 158:116–127. https://doi.org/10.1016/j.biocon.2012.07.026

Bremer P, Jongejans E (2009) Frost and forest stand effects on the population dynamics of Asplenium Scolopendrium. Popul Ecol 52:211–222. https://doi.org/10.1007/s10144-009-0143-7

Briner S, Elkin C, Huber R (2013) Evaluating the relative impact of climate and economic changes on forest and agricultural ecosystem services in mountain regions. J Environ Manag 129:414–422. https://doi.org/10.1016/j.jenvman.2013.07.018

Chakraborty A, Joshi PK, Ghosh A, Areendran G (2013) Assessing biome boundary shifts under climate change scenarios in India. Ecol Indic 34:536–547. https://doi.org/10.1016/j.ecolind.2013.06.013

Chakraborty A, Joshi PK, Sachdeva K (2016) Predicting distribution of major forest tree species to potential impacts of climate change in the central Himalayan region. Ecol Eng 97:593–609. https://doi.org/10.1016/j.ecoleng.2016.10.006

Chaturvedi RK, Gopalakrishnan R, Jayaraman M, Bala G, Joshi NV, Sukumar R, Ravindranath NH (2011) Impact of climate change on Indian forests: a dynamic vegetation modeling approach. Mitig Adapt Strateg Glob Chang 16:119–142. https://doi.org/10.1007/s11027-010-9257-7

Chawla A, Yadav PK, Uniyal SK, Kumar A, Vats SK, Kumar S, Ahuja PS (2012) Long-term ecological and biodiversity monitoring in the western Himalaya using satellite remote sensing. Curr Sci 102:1143–1156

Chettri S, Krishna AP, Singh KK (2015) Community forest management in Sikkim Himalaya towards sustainable development. International Journal of Environment and Sustainable Development 14(1):89–104

Chitale VS, Behera MD, Roy PS (2014) Future of endemic flora of biodiversity hotspots in India. PLoS One 9:e115264. https://doi.org/10.1371/journal.pone.0115264

Cook ER, Anchukaitis KJ, Buckley BM, D'Arrigo RD, Jacoby GC, Wright WE (2010) Asian monsoon failure and megadrought during the last millennium. Science 328:486–489. https://doi.org/10.1126/science.1185188

Corlett RT, Westcott DA (2013) Will plant movements keep up with climate change? Trends Ecol Evol 28:482–488. https://doi.org/10.1016/j.tree.2013.04.003

Demske D, Tarasov PE, Leipe C, Kotlia BS, Joshi LM, Long T (2016) Record of vegetation, climate change, human impact and retting of hemp in Garhwal Himalaya (India) during the past 4600 years. The Holocene 26:1661–1675

Dubey B, Yadav RR, Singh J, Chaturvedi R (2003) Upward shift of Himalayan pine in western Himalaya, India. Curr Sci 85:1135–1136

Gaire NP, Koirala M, Bhuju DR, Carrer M (2017) Site- and species-specific treeline responses to climatic variability in eastern Nepal Himalaya. Dendrochronologia 41:44–56. https://doi.org/10.1016/j.dendro.2016.03.001

Gairola S, Rawal RS, Todaria NP (2008) Forest vegetation patterns along an altitudinal gradient in sub-alpine zone of west Himalaya, India. African J Plant Sci 2:42–48

Gómez JM, González-Megías A, Lorite J, Abdelaziz M, Perfectti F (2015) The silent extinction: climate change and the potential hybridization-mediated extinction of endemic high-mountain plants. Biodivers Conserv 24:1843–1857. https://doi.org/10.1007/s10531-015-0909-5

Gopalakrishnan R, Jayaraman M, Bala G, Ravindranath NH (2011) Climate change and Indian forests. Curr Sci 101:348–355

Gottfried M, Pauli H, Futschik A, Futschik A, Akhalkatsi M, Barančok P, Alonso JLB, Coldea G, Dick J, Erschbamer B, Calzado MRF, Kazakis G, Krajči J, Larsson P, Mallaun M, Michelsen O, Moiseev D, Moiseev P, Molau U, Merzouki A, Nagy L, Nakhutsrishvili G, Pedersen B, Pelino G, Puscas M, Rossi G, Stanisci A, Theurillat JP, Tomaselli M, Villar L, Vittoz P, Vogiatzakis I, Grabherr G (2012) Continent-wide response of mountain vegetation to climate change. Nature Clim Change 2:111–115. https://doi.org/10.1038/nclimate1329

Grêt-Regamey A, Brunner SH, Kienast F (2013) Mountain ecosystem services: who cares? Mt Res Dev 32:S23–S34. https://doi.org/10.1659/MRD-JOURNAL-D-10-00115.S1

Gupta RK (1978) Impact of human influences on the vegetation of the western Himalaya. Vegetatio 37:111–118

Haines-Young R, Potschin M, Kienast F (2012) Indicators of ecosystem service potential at European scales: mapping marginal changes and trade-offs. Ecol Indic 21:39–53. https://doi.org/10.1016/j.ecolind.2011.09.004

Horner GJ, Baker PJ, Nally RM, Cunningham SC, Thomson JR, Hamilton F (2010) Forest structure, habitat and carbon benefits from thinning floodplain forests: managing early stand density makes a difference. For Ecol Manag 259:286–293. https://doi.org/10.1016/j.foreco.2009.10.015

Inman M (2010) Settling the science on Himalayan glaciers. Nature Reports Climate Change:28–30. https://doi.org/10.1038/climate.2010.19

IPCC (2014) Summary for Policymakers. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, Whit LL (eds) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, pp 1–32

Johnston M, Hesseln H (2012) Climate change adaptive capacity of the Canadian forest sector. Forest Policy Econ 24:29–34. https://doi.org/10.1016/j.forpol.2012.06.001

Joshi PK, Rawat A, Narula S, Sinha V (2012) Assessing impact of climate change on forest cover type shifts in western Himalayan eco-region. J For Res 23:75–80. https://doi.org/10.1007/s11676-012-0235-7

Kala CP (2000) Status and conservation of rare and endangered medicinal plants in the Indian trans-Himalaya. Biol Conserv 93:371–379. https://doi.org/10.1016/S0006-3207(99)00128-7

Keenan RJ (2015) Climate change impacts and adaptation in forest management: a review. Ann For Sci 72:1–23. https://doi.org/10.1007/s13595-014-0446-5

Kelkar U, Narula KK, Sharma VP, Chandna U (2008) Vulnerability and adaptation to climate variability and water stress in Uttarakhand state, India. Glob Environ Chang 18:564–574. https://doi.org/10.1016/j.gloenvcha.2008.09.003

Kerry J, Pruneau D, Blain S, Langis J, Barbier PY, Mallet MA, Vichnevetski E, Therrien J, Deguire P, Freiman V, Lang M, Laroche AM (2012) Human competences that facilitate adaptation to climate change: a research in progress. International Journal of Climate Change Strategies and Management 4:246–259. https://doi.org/10.1108/17568691211248711

Kilroy G (2015) A review of the biophysical impacts of climate change in three hotspot regions in Africa and Asia. Reg Environ Chang 15:771–782. https://doi.org/10.1007/s10113-014-0709-6

Klein JA, Harte J, Zhao X-Q (2004) Experimental warming causes large and rapid species loss, dampened by simulated grazing, on the Tibetan plateau. Ecol Lett 7:1170–1179. https://doi.org/10.1111/j.1461-0248.2004.00677.x

Kok M, Lüdeke M, Lucas P, Sterzel T, Walther C, Jansses P, Sietz D, de Soysa I (2016) A new method for analysing socio-ecological patterns of vulnerability. Reg Environ Chang 16:229–243. https://doi.org/10.1007/s10113-014-0746-1

Kothari A (2006) Community conserved areas: towards ecological and livelihood security. Parks 16:3–13

Kumar A, Ram J (2005) Anthropogenic disturbances and plant biodiversity in forests of Uttaranchal, central Himalaya. Biodivers Conserv 14:309–331

Kumar P (2012) Assessment of impact of climate change on rhododendrons in Sikkim Himalayas using Maxent modelling: limitations and challenges. Biodivers Conserv 21:1251–1266. https://doi.org/10.1007/s10531-012-0279-1

Landauer M, Juhola S, Söderholm M (2015) Inter-relationships between adaptation and mitigation: a systematic literature review. Clim Chang 131:505–517. https://doi.org/10.1007/s10584-015-1395-1

Lemieux CJ, Gray PA, Douglas AG, Nielsen G, Pearson D (2014) From science to policy: the making of a watershed-scale climate change adaptation strategy. Environ Sci Pol 42:123–137. https://doi.org/10.1016/j.envsci.2014.06.004

Liang E, Dawadi B, Pederson N, Eckstein D (2014) Is the growth of birch at the upper timberline in the Himalayas limited by moisture or by temperature? Ecology 95:2453–2465. https://doi.org/10.1890/13-1904.1

Lindner M (2000) Developing adaptive forest management strategies to cope with climate change. Tree Physiol 20:299–307

Lindner M, Fitzgerald JB, Zimmermann NE, Reyer C, Delzon S, van der Maaten E, Schelhaas MJ, Lasch P, Eggers J, van der Maaten-Theunisse M, Suckow F, Psomas A, Poulter B, Hanewinkel M (2014) Climate change and European forests: what do we know, what are the uncertainties, and what are the implications for forest management? J Environ Manag 146:69–83. https://doi.org/10.1016/j.jenvman.2014.07.030

Locatelli B, Evans V, Wardell A, Andrade A, Vignola R (2011) Forests and climate change in Latin America: linking adaptation and mitigation. Forests 2:431–450. https://doi.org/10.3390/f2010431

Lwasa S (2015) A systematic review of research on climate change adaptation policy and practice in Africa and South Asia deltas. Reg Environ Chang 15:815–824. https://doi.org/10.1007/s10113-014-0715-8

Ma M, Singh RB, Hietala R (2012) Human driving forces for ecosystem services in the Himalayan region. Environ Econ 3:53–57

Madhura RK, Krishnan R, Revadekar JV, Mujumdar M, Goswami BN (2014) Changes in western disturbances over the western Himalayas in a warming environment. Clim Dyn 44:1157–1168. https://doi.org/10.1007/s00382-014-2166-9

Mandal G, Joshi SP (2015) Eco-physiology and habitat invasibility of an invasive, tropical shrub (Lantana camara) in western Himalayan forests of India. For Sci Technol 11:182–196. https://doi.org/10.1080/21580103.2014.990062

Mandal RA, Laake PV (2005) Carbon sequestration in community forests: an eligible issue for CDM (a case study of Nainital, India). Banko Janakari 15. https://doi.org/10.3126/banko.v15i2.353

Meenawat H, Sovacool BK (2011) Improving adaptive capacity and resilience in Bhutan. Mitig Adapt Strateg Glob Chang 16:515–533. https://doi.org/10.1007/s11027-010-9277-3

Menon A, Levermann A, Schewe J, Lehmann J, Frieler K (2013) Consistent increase in Indian monsoon rainfall and its variability across CMIP-5 models. Earth System Dynamics 4:287–300. https://doi.org/10.5194/esd-4-287-2013

Messier C, Puettmann KJ, Coates KD (2013) Managing forests as complex adaptive systems: building resilience to the challenge of global change. Routledge, London

Mishra M, Upadhyay DK, Mishra SK (2012) Establishing climate information service system for climate change adaptation in Himalayan region. Curr Sci 103:1417–1422

Morin MB, Kneeshaw D, Doyon F, Goff HL, Bernier P, Yelle V, Blondlot A, Houle D (2015) Climate change and the forest sector: perception of principal impacts and of potential options for adaptation. For Chron 91:395–406

Müller M, Schwab N, Schickhoff U, Bohner J, Scholten T (2016) Soil temperature and soil moisture patterns in a Himalayan alpine Treeline ecotone. Arct Antarct Alp Res 48:501–521

Murthy I, Alipuria AK, Ravindranath N (2012) Potential for increasing carbon sink in Himachal Pradesh, India. Trop Ecol 53:357–369

Nautiyal MC, Nautiyal BP, Prakash V (2004) Effect of grazing and climatic changes on alpine vegetation of Tungnath, Garhwal Himalaya, India. Environmentalist 24:125–134

Negi GCS, Samal PK, Kuniyal JC, Kothyari BP, Sharma RK, Dhyani PP (2012) Impact of climate change on the western Himalayan mountain ecosystems: an overview. Trop Ecol 53:345–356

Negi P (2012) Climate change, alpine treeline dynamics and associated terminology: focus on northwestern Indian Himalaya. Trop Ecol 53:371–374

Negi VS, Maikhuri RK, Rawat LS (2011) Non-timber forest products (NTFPs): a viable option for biodiversity conservation and livelihood enhancement in central Himalaya. Biodivers Conserv 20:545–559. https://doi.org/10.1007/s10531-010-9966-y

Nicotra AB, Beever EA, Robertson AL, Hofmann GE, O'Leary J (2015) Assessing the components of adaptive capacity to improve conservation and management efforts under global change. Conserv Biol 29:1268–1278. https://doi.org/10.1111/cobi.12522

Pandey KP, Adhikari YP, Weber M (2016) Structure, composition and diversity of forest along the altitudinal gradient in the Himalayas, Nepal. Appl Ecol Environ Res 14:235–251. https://doi.org/10.15666/aeer/1402_235251

Pandey R, Jha S (2012) Climate vulnerability index-measure of climate change vulnerability to communities: a case of rural lower Himalaya, India. Mitig Adapt Strateg Glob Chang 17:487–506. https://doi.org/10.1007/s11027-011-9338-2

Panigrahy S, Anitha D, Kimothi M, Singh S (2010) Timberline change detection using topographic map and satellite imagery. Trop Ecol 51:87–91

Polanski S, Fallah B, Befort DJ, Prasad S, Cubasch U (2014) Regional moisture change over India during the past millennium: a comparison of multi-proxy reconstructions and climate model simulations. Glob Planet Chang 122:176–185. https://doi.org/10.1016/j.gloplacha.2014.08.016

Polsky C, Neff R, Yarnal B (2007) Building comparable global change vulnerability assessments: the vulnerability scoping diagram. Glob Environ Chang 17:472–485. https://doi.org/10.1016/j.gloenvcha.2007.01.005

Poudel M, Thwaites R, Race D, Dahal GR (2014) REDD+ and community forestry: implications for local communities and forest management—a case study from Nepal. Int For Rev 16:39–54. https://doi.org/10.1505/146554814811031251

Rao KS, Semwal RL, Maikhuri RK, Nautiyal S, Sen KK, Singh K, Chandrasekhar K, Saxena KG (2003) Indigenous ecological knowledge, biodiversity and sustainable development in the central Himalayas. Trop Ecol 44:93–111

Räsänen A, Juhola S, Nygren A, Nygren A, Kakonen M, Kallio M, Monge AM, Kanninen M (2016) Climate change, multiple stressors and human vulnerability: a systematic review. Reg Environ Chang 16:2291–2302. https://doi.org/10.1007/s10113-016-0974-7

Rashid I, Romshoo SA, Chaturvedi RK, Ravindranath NH, Sukumar R, Jayaraman M, Lakshmi TV, Sharma J (2015) Projected climate change impacts on vegetation distribution over Kashmir Himalayas. Clim Chang 132:1–13. https://doi.org/10.1007/s10584-015-1456-5

Rasul G (2014) Food, water, and energy security in South Asia: a nexus perspective from the Hindu Kush Himalayan region. Environ Sci Pol 39:35–48. https://doi.org/10.1016/j.envsci.2014.01.010

Rawal RS, Pandey B, Dhar U (2003) Himalayan forest database—thinking beyond dominants. Curr Sci 84:990–994

Rawat PK, Tiwari PC, Pant CC (2012) Climate change accelerating land use dynamic and its environmental and socio-economic risks in the Himalayas. International Journal of Climate Change Strategies and Management 4:452–471. https://doi.org/10.1108/17568691211277764

Rayamajhi S, Smith-Hall C, Helles F (2012) Empirical evidence of the economic importance of central Himalayan forests to rural households. Forest Policy Econ 20:25–35. https://doi.org/10.1016/j.forpol.2012.02.007

Reyer CPO, Bugmann H, Nabuurs G-J, Hanewinkel M (2015) Models for adaptive forest management. Reg Environ Chang 15(8):1483–1487. https://doi.org/10.1007/s10113-015-0861-7

Rijal A, Smith-Hall C, Helles F (2011) Non-timber forest product dependency in the central Himalayan foot hills. Environ Dev Sustain 13:121–140. https://doi.org/10.1007/s10668-010-9252-x

Rosenzweig C, Elliott J, Deryng D, Ruanea AV, Müllere C, Arneth A, Boote KJ, Folberth C, Glotter M, Khabarov N, Neumannk K, Piontek F, Pugh TAM, Schmid E, Stehfest E, Yang H, Jones JW (2014) Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. PNAS 111:3268–3273. https://doi.org/10.1073/pnas.1222463110

Saha D, Sundriyal RC (2012) Utilization of non-timber forest products in humid tropics: implications for management and livelihood. Forest Policy Econ 14:28–40. https://doi.org/10.1016/j.forpol.2011.07.008

Saha S, Bisht NS (2007) Role of traditional ecological knowledge in natural resource management among Monpas of North-western Arunachal Pradesh. Indian Forester 133:155–164

Saran S, Joshi R, Sharma S, Padalia H, Dadhwal VK (2010) Geospatial modeling of Brown oak (Quercus semecarpifolia) habitats in the Kumaun Himalaya under climate change scenario. Journal of the Indian Society of Remote Sensing 38:535–547

Schickhoff U, Bobrowski M, Böhner J, Böhner J, Bürzle B, Chaudhary RP, Gerlitz L, Heyken H, Lange J, Müller M, Scholten T, Schwab N, Wedegärtner R (2014) Do Himalayan treelines respond to recent climate change? An evaluation of sensitivity indicators. Earth Syst Dynam Discuss 5:1407–1461. https://doi.org/10.5194/esd-6-245-2015

Seidl R, Lexer MJ (2013) Forest management under climatic and social uncertainty: trade-offs between reducing climate change impacts and fostering adaptive capacity. J Environ Manag 114:461–469. https://doi.org/10.1016/j.jenvman.2012.09.028

Semwal RL, Nautiyal S, Sen KK, Ran U, Maikhuri RK, Rao KS, Saxeana KG (2004) Patterns and ecological implications of agricultural land-use changes: a case study from central Himalaya, India. Agric Ecosyst Environ 102:81–92. https://doi.org/10.1016/S0167-8809(03)00228-7

Shahabuddin G, Rao M (2010) Do community-conserved areas effectively conserve biological diversity? Global insights and the Indian context. Biol Conserv 143:2926–2936. https://doi.org/10.1016/j.biocon.2010.04.040

Shankar U, Lama SD, Bawa KS (1998) Ecosystem reconstruction through 'taungya' plantations following commercial logging of a dry, mixed deciduous forest in Darjeeling Himalaya. For Ecol Manag 102:131–142. https://doi.org/10.1016/S0378-1127(97)00152-7

Sharma E, Bhuchar S, Xing M, Kcithyari BP (2007) Land use change and its impact on hydro-ecological linkages in Himalayan watersheds. Trop Ecol 48:151–161

Sharma J, Chaturvedi RK, Bala G, Ravindranath NH (2013) Challenges in vulnerability assessment of forests under climate change. Carbon Management 4:403–411. https://doi.org/10.4155/cmt.13.35

Sharma SK, Deml K, Dangal S, Rana E, Madigan S (2015) REDD+ framework with integrated measurement, reporting and verification system for community based Forest management systems (CBFMS) in Nepal. Curr Opin Environ Sustain 14:17–27. https://doi.org/10.1016/j.cosust.2015.01.003

Sheikh MA, Kumar M (2010) Nutrient status and economic analysis of soils in oak and pine forests in Garhwal Himalaya. J Am Stud 6:117–122

Shrestha UB, Gautam S, Bawa KS (2012) Widespread climate change in the Himalayas and associated changes in local ecosystems. PLoS One 7:e36741. https://doi.org/10.1371/journal.pone.0036741

Singh JS (2006) Sustainable development of the Indian Himalayan region: linking ecological and economic concerns. Curr Sci 90:784–788

Singh JS, Rawat YS, Chaturvedi OP (1984) Replacement of oak forest with pine in the Himalaya affects the nitrogen cycle. Nature 311:54–56. https://doi.org/10.1038/311054a0

Singh JS, Singh SP (1987) Forest vegetation of the Himalaya. Bot Rev 53:80–192

Singh N, Ram J, Tewari A, Yadav R (2015) Phenological events along the elevation gradient and effect of climate change on Rhododendron arboreum Sm. In Kumaun Himalaya. Curr Sci 108:106–110 https://doi.org/10.18520

Singh PC, Panigrahy S, Parihar JS, Dharaiya N (2013) Modeling environmental niche of Himalayan birch and remote sensing based vicarious validation. Trop Ecol 54:321–329

Singh RK, Bhowmik SN, Pandey CB (2011) Biocultural diversity, climate change and livelihood security of the Adi community: grassroots conservators of eastern Himalaya Arunachal Pradesh. Indian J Tradit Knowl 10:39–56

Singh SP, Singh JS (1992) Forests of the Himalayas: structure, function and impact of man. Gyanodaya Prakashan, Nainital, India

Singh SP, Thadani R (2015) Complexities and controversies in Himalayan research: a call for collaboration and rigor for better data. Mt Res Dev 35(4):401–409

Sinha B (2002) Pines of Himalayas. Energy and. Environment 13:873–881

Sohn JA, Saha S, Bauhus J (2016) Potential of forest thinning to mitigate drought stress: a meta-analysis. For Ecol Manag 380:261–273. https://doi.org/10.1016/j.foreco.2016.07.046

Spittlehouse DL, Stewart RB (2004) Adaptation to climate change in forest management. Journal of Ecosystems and Management 4:2–11

Stephens SL, Agee JK, Fulé PZ, North MP, Romme WH, Swetnam TW, Turner MG (2013) Managing forests and fire in changing climates. Science 342:41–42. https://doi.org/10.1126/science.1240294

Telwala Y, Brook BW, Manish K, Pandit MK (2013) Climate-induced elevational range shifts and increase in plant species richness in a Himalayan biodiversity epicentre. PLoS One 8:e57103. https://doi.org/10.1371/journal.pone.0057103

Tewari A, Bhatt J, Mittal A (2016) Influence of tree water potential in inducing flowering in Rhododendron arboreum in the central Himalayan region. iForest - Biogeosciences and Forestry 9:842–846. https://doi.org/10.3832/ifor1525-008

Thadani R, Ashton PMS (1995) Regeneration of banj oak (Quercus leucotrichophora A. Camus) in the central Himalaya. For Ecol Manag 78:217–224. https://doi.org/10.1016/0378-1127(95)03561-4

Tiwari A, Fan Z-X, Jump AS, Li SF, Zhou ZK (2017) Gradual expansion of moisture sensitive Abies spectabilis forest in the trans-Himalayan zone of central Nepal associated with climate change. Dendrochronologia 41:34–43. https://doi.org/10.1016/j.dendro.2016.01.006

Turner AG, Annamalai H (2012) Climate change and the South Asian summer monsoon. Nature Clim Change 2:587–595. https://doi.org/10.1038/nclimate1495

Upgupta S, Sharma J, Jayaraman M, Kumar V, Ravindranath NH (2015) Climate change impact and vulnerability assessment of forests in the Indian western Himalayan region: a case study of Himachal Pradesh, India. Climate Risk Management 10:63–76. https://doi.org/10.1016/j.crm.2015.08.002

Upreti N, Tewari JC, Singh SP (1985) The oak forests of the Kumaun Himalaya (India): composition, diversity, and regeneration. Mt Res Dev 5:163–174. https://doi.org/10.2307/3673255

Vetter D, Rücker G, Storch I (2013) Meta-analysis: a need for well-defined usage in ecology and conservation biology. Ecosphere 4: 1–24. https://doi.org/10.1890/ES13-00062.1

Wani AM, Raj AJ, Kanwar M (2013) Impact of climate change on forests of eastern Himalayas and adaptation strategies for combating it. International. J Agric For 3:98–104. https://doi.org/10.5923/j.ijaf.20130303.05

Wellstead A, Rayner J, Howlett M (2014) Beyond the black box: Forest sector vulnerability assessments and adaptation to climate change in North America. Environ Sci Pol 35:109–116. https://doi.org/10.1016/j.envsci.2013.04.002

Xu J, Grumbine E, Shrestha A, Eriksson M, Yang X, Want Y, Wilkes A (2009) The melting Himalayas: cascading effects of climate change on water, biodiversity, and livelihoods. Conserv Biol 23:520–530. https://doi.org/10.1111/j.1523-1739.2009.01237

Xu Z, Hu T, Zhang Y (2011) Effects of experimental warming on phenology, growth and gas exchange of treeline birch (*Betula utilis*) saplings, eastern Tibetan plateau, China. Eur J Forest Res 131: 811–819. https://doi.org/10.1007/s10342-011-0554-9

Zhang Y, Gao J, Liu L, Wang Z, Ding M, Yang X (2013) NDVI-based vegetation changes and their responses to climate change from 1982 to 2011: a case study in the Koshi River basin in the middle Himalayas. Glob Planet Chang 108:139–148. https://doi.org/10.1016/j.gloplacha.2013.06.012

Zonunsanga R, Rao CUB, Rinawma P (2014) Degradation of land and forest resources: the story of shifting cultivation and loss of biodiversity in north-East India. In: Singh M, Singh RB, Hassan MI (eds) Climate change and biodiversity. Springer, Japan, pp 259–267. https://doi.org/10.1007/978-4-431-54838-6_20