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Complexities and Controversies in Himalayan Research: A Call for Collaboration and Rigor for Better Data

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The Himalaya range encompasses enormous variation in elevation, precipitation, biodiversity, and patterns of human livelihoods. These mountains modify the regional climate in complex ways; the ecosystem services they provide influence the lives of almost 1 billion people in 8 countries. However, our understanding of these ecosystems remains rudimentary. The 2007 Intergovernmental Panel on Climate Change report that erroneously predicted a date for widespread glacier loss exposed how little was known of Himalayan glaciers. Recent research shows how variably glaciers respond to climate change in different Himalayan regions. Alarmist theories are not new. In the 1980s, the Theory of Himalayan Degradation warned of complete forest loss and devastation of downstream areas, an eventuality that never occurred. More recently, the debate on hydroelectric construction appears driven by passions rather than science. Poor data, hasty conclusions, and bad science plague Himalayan research. Rigorous sampling, involvement of civil society in data collection, and long-term collaborative research involving institutions from across the Himalaya are essential to improve knowledge of this region.

Keywords: *Himalaya; ecosystem services; glaciers; climate change; hydroelectric; collaboration; research agenda, limitations of modeling.*

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Introduction

The Himalayas are the highest mountains of the world. Ecosystem services from these mountains, sometimes called the Water Tower of Asia, are important for the one sixth of humanity that lives in downstream river basins (Schild 2008). High biodiversity and species endemism make these mountains of significant conservation importance (Dhar et al 2000; Xu et al 2009). Forest productivity is high, and the Himalayan forests are important repositories of carbon (Singh and Singh 1992; Singh and Thadani 2013).

In the scientific world, the Himalaya range is often best known for the controversies around research on this region. A few decades ago, debate centered on Himalayan deforestation and its contribution to floods in the adjacent plains (Ives and Messerli 1989). Were a few million people, through reckless cutting of fuelwood, leading to floods that adversely impacted the lives of hundreds of millions of people living downstream? More recently, as the threat of global warming takes center stage in scientific research, the Himalaya range has gained prominence with disputed reports of accelerated rates of glacier melt (Schiermeier 2010). Controversies surrounding the research and politics of glacial melt—complete with images of poor rural women burning cow patties that generate black carbon—led to a disproportionately high number of pages being devoted to the issue in scientific publications. From 2010 to 2015, for example, 13 papers on the Himalaya were published in *Nature*; of these, 9 were on Himalayan glaciers.

The debate on deforestation eventually fizzled out, and the glacier debate now shows signs of doing the same. In both cases in the Himalaya, the cause of controversy was similar—poor-quality science, which was the result of insufficient and, more importantly, poor-quality data (Ives 2006; Cogley 2012).

In this article, we focus on the constraints associated with research in the Himalaya and the limitations of outputs based on fragmented and incomplete data. We also discuss the need to take different approaches so as to enhance both the quality and quantity of data on Himalayan ecosystems.

Sampling issues

While the name Himalaya seems to indicate a uniform entity and terms such as "Himalayan glaciers," "Himalayan people," and "Himalayan forests" appear to allude to homogenous entities, the variability of the region may rival that of Europe.

The Himalaya has an extraordinary altitudinal range, rising from close to sea level to over 100 peaks higher than 7200 m. Equally impressive is the over 2400 km spread along an east-to-west arc, across which forest types, biodiversity levels, and rainfall intensity and patterns vary extensively. Forest types range from tropical to arctic and from very moist to almost xeric. Cherrapunji in the Khasi

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TABLE 1 Variation in environmental, agricultural, and cultural parameters in the Himalaya.

Parameter	Common trends	Source
Annual precipitation	In the east, 3000–4000 mm (Arunachal 3330 mm) In the west, 500–2000 mm (Jammu and Kashmir 902 mm)	Compiled from: Indian Meteorological Department (2015)
Source of precipitation	In much of the outer ranges, Indian monsoon At the eastern boundary, East Asian monsoon In Pamir and interior Tibetan Plateau, westerlies	Yao et al (2012)
Timing of ice accumulation in glaciers	In the east and center, during the Indian monsoon In the west, during winter	Singh et al (2011); Miller et al (2012)
Contribution of glacier melt to river discharge	Yellow River (northeast into China), 1.3% Ganges River (in the center), 9.1% Indus River (in the west), 44.8%	Xu (2005); Rees and Collins (2006); Singh et al (2008)
Tree species diversity	In Arunachal Pradesh (easternmost state of India), 116 species In the western Himalayan states of India, 30–35 species	Derived from data compiled by Indian Institute of Remote Sensing data (IIRS 2002, 2003)
Types of agriculture	In the east, high forest dependence, shifting cultivation dominant in parts with little integration with domestic animals In the center and west, settled agriculture on terraces, integrated with animal husbandry	Anonymous (2010)
Types of livestock grazing	In the east, stall-fed pig raising, few ruminants In the center and west, widespread grazing of cattle, goats, and sheep in forests	Anonymous (2010)
Distribution of broadleaved evergreen trees	In the east, soft-leaved species of Fagaceae (eg *Castanopsis* spp and *Quercus lamellosa*), increased abundance of Lauraceae In the west, largely oaks with sclerophyllous leaves	Singh (2014)
Importance of timber in mountain forests	In the east, due to higher diversity, limited timber extraction In the west, widespread and important timber species including deodar cedar (*Cedrus deodara*), sal (*Shorea robusta*), and chir pine (*Pinus roxburghii*)	IIRS (2002, 2003)
Religion and culture	In the east, primarily (64%–95%) tribal populations that have largely converted to Christianity In the west and center, fewer (3%–10%) tribal populations; Hinduism dominant in the center, and Islam increasingly influential in the far west	Anonymous (2010)

Hills in the eastern Himalaya averages 12,000 mm of rainfall annually, while Leh-Ladakh in Kashmir in the western Himalaya receives about 100 mm. This hundredfold variation is a major reason why the contribution of glacier melt to river discharge varies so widely from one end of the Himalayan arc to the other. Glaciers themselves show great variability in flow velocities and changes in mass balance, with many in the Karakoram and parts of the northwest Himalaya showing accumulation over the past few decades, while in most other parts of the Himalaya, glaciers have been losing mass since the mid-19th century (Bolch et al 2012). Equally varied are Himalayan people and their livelihood regimes, religions, and cultural practices. Table 1 highlights some of the diversity of this region.

Values do not always change linearly along the Himalaya. For example, due to low rainfall, vegetation in some open valleys of Bhutan resembles more that of the western Himalaya than adjoining eastern Himalayan states (Ohsawa 1987).

The steep topography also creates its own conditions. The moist slopes around Nainital town in the central Himalaya receive 80% more rainfall than Almora town, which lies about 30 km to its north (Indian Meteorological Department 2015). Studies in the Nepal Himalaya show similar complex precipitation patterns and high variability over short horizontal distances, with one study reporting a more than 50% decrease in precipitation over a 14 km distance (Immerzeel et al 2014). Northern slopes tend to be moist, with mesic vegetation often dominated

FIGURE 1 Aspect and microsite variation can lead to very different stands in close proximity, such as this patchwork of *Quercus semecarpifolia* (light green, right), *Cedrus deodara* (darker green, left), and *Cupressus torulosa* (deep green, center right, on an old landslip) at 2400 m. (Photo by Vishal Singh)

by oak, while southern slopes tend to be much drier and dominated by pine; the latter also tend to be steeper due to the patterns of folding. The composition and folding patterns of the underlying rock greatly impact drainage and water infiltration, thereby influencing the vegetation. The Himalayan landscape thus has few large, contiguous areas of a single forest type. Instead, it is more a patchwork of stands with contrasting functional attributes occurring within the same climatic regimes (Singh 2014). A relatively pure stand of oak may abruptly give way to a pine-dominated stand. Such variations occur on a scale of a few hectares, often making them hard to capture through satellite imagery (DeFries et al 2007; Danielsen et al 2011; Figure 1).

To capture such diversity, sampling protocols need to be sensitive to the heterogeneity of forest type due to varying aspects, soil depths, soil types, and anthropogenic disturbance—but this is often not the case in the Himalaya. Some areas are invariably highly oversampled, while vast tracts remain unstudied due to the harsh terrain. In forestry research, oversampling of well-protected sites near towns and cities (where universities are situated) has given rise to false notions of regeneration rates and forest health (Thadani and Ashton 1995). Doing field research in Himalaya requires not only a sound brain but also a pair of strong legs.

The controversy surrounding the 2007 Intergovernmental Panel on Climate Change (IPCC) report (Pachauri and Reisinger 2007) helped expose the lack of rigor and insufficient in situ measurements of Himalayan glaciers (Ravindranath 2010; Bolch et al 2012). When the IPCC report was released, no one had measured or published the mass of any Himalayan glacier since the year 2000 (Powell 2012). Several studies since have revealed interesting results. While glaciers in the eastern Himalaya appear to be losing mass (Bolch et al 2011), in the Karakorum range in the western end of the Himalaya, glaciers may actually be gaining mass despite rising temperatures (Powell 2012; Yao et al 2012)—possibly a result of climate-change-induced changes in circulation patterns and higher precipitation in these regions (Hewitt 2005; Yao et al 2012). Thus, while confusion still abounds, just 5 years of intensive research revealed enough to show the beliefs of 2007 to be flawed.

Most recently, the exceptionally high rainfall in Uttarakhand over 2 days in June 2013 highlighted the lack of data and understanding about the region (Figure 2). With thousands dead, mainly pilgrims from across India, and tens of thousands stranded when roads collapsed into rivers, the issue made front-page news for weeks in India. Quoted in news articles and reports, environmentalists blamed unchecked construction, ecologists blamed the loss of forests, and politicians blamed each other. While heavy rains with high levels of damage have begun to be an annual feature in Uttarakhand, studies of vulnerable areas or adaptation to heavy rainfall are absent. The lack

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FIGURE 2 Kedarnath town at the foot of the Kedarnath glacier is an important pilgrimage site; it made international news when thousands of pilgrims died in June 2013 due to floods caused by heavy rain and a lake collapse. (Photo by Vivek Joshi)

of accurate meteorological data and monitoring systems in most watersheds and in particular at higher elevations (Ragettli et al 2015) accentuates the problem.

The limitations of modeling

The 2007 IPCC report (Pachauri and Reisinger 2007) showed the Himalaya as a white spot to emphasize the absence of data. This paucity of local data can lead to a dependence on generalized models, which can be misleading and dangerous. For data-deficient areas such as the Himalaya, modelers may transfer data from other seemingly similar systems (Box 1995; Graham et al 2008). This is not prudent, and it is essential that modelers remain conscious of all assumptions that they make (Vanclay 2014).

For example, the most representative forest types in the Himalaya are broad-leaved evergreen forests, often dominated by oak (*Quercus* spp) and other species of Fagaceae. To make predictions, modelers typically transfer data from seemingly similar temperate oak forests of Europe and America (Zobel and Singh 1997). However, this can be a problem for several reasons:

1. While Himalayan oak forests above 1800 m elevation are often classified as temperate, even at 2500 m, Himalayan forests have characteristics closer to tropical forests in important ecosystem attributes like nutrient turnover time (Zobel and Singh 1997).
2. Oaks in temperate regions are generally deciduous and ring-porous, while Himalayan oaks are evergreen and non-ring-porous varieties (Pearson and Brown 1932: 977–996; Rao and Juneja 1971).
3. Some Himalayan oaks have seeds that are viviparous (germinating while still on the tree) to take full advantage of the wet and warm monsoon period, a trait unheard of in temperate-region trees (Zobel and Singh 1997).
4. Climate change also appears to impact Himalayan forests in different ways. Unlike other alpine forests, where timberlines appear to move uphill as a result of warming, Himalayan timberlines may retreat down-

slope despite warming, as drought may be the main driver of tree growth at upper altitudes in the Himalaya (Liang et al 2014; Qiu 2015).

5. Despite apparently similar genera, the Himalaya ecosystem differs markedly from temperate forests (Singh 2014). The maple (genus *Acer*), for example, is a well-known deciduous tree in Europe and North America, but the Himalaya is home to an evergreen maple (*Acer oblongum*). Similarly, the common alder (*Alnus nepalensis*) and the oaks are mainly evergreen, unlike their deciduous counterparts in temperate forests; rhododendron, which is thought of as a shrub across most temperate forests, grows as a tree (*Rhododendron arboreum*) in the mid-Himalaya. The common chir pine (*Pinus roxburghii*) has needles with barely a 1 year life span, and chir forests turn brown in the spring as old needles senesce before new needles have expanded. In temperate pine forests, in contrast, needles typically have a multi-year life span.
6. Equally importantly, Himalayan forests differ from temperate forests in how they are used. While Himalayan oaks provide poor timber, they are of immense value for biomass products such as fuelwood, fodder, and leaf fertilizer. In contrast, in European and American oak forests, timber values have traditionally driven forest management. The use of fuelwood in the Himalaya has kept per capita carbon dioxide emissions from fossil fuels very low. Himalayan forests may be thought of as carbon forests, rich in ecosystem services.

Projections using dubious data collected from the Himalaya or sound data from unrelated systems with similar species can both be equally inaccurate and create uncertainties (Wiens et al 2009). Furthermore, research papers based on modeled data are typically reviewed primarily from the angle of modeling methods and interpretations of outputs, and the source and quality of data used in the models receive little attention. Consequently, such papers often validate poor-quality data collected without following standard scientific methods. This is a dangerous trend in which unreliable data from suspect sources are published in high-quality journals and thus validated.

Recent trends are, however, more positive, and research, especially on glaciers, does recognize and flag sources of uncertainty. Data are being collected with more rigor than before, and models limit their predictions to limited geographies. For example, Shea et al (2015) modeled the mass balance of glaciers in a narrow geographical area in the Everest region of Nepal. Their calibrated model showed the high sensitivity of glaciers in this region to temperature change and postulated that projected increases in precipitation will be insufficient to offset the increased glacier melt.

The appeal of alarmist opinions

When scholars model mountain conditions and project future scenarios, they often focus on the darker side, as this generates more interest and provides more funding opportunities. Indeed, it is important to warn about threats that the general population is unable to detect. However, doing so based on personal perceptions and without credible data (Ives 2005) not only results in prolonged controversy, but it also damages developmental programs. There is a need to get out of what Ives and Messerli (1989) and Ives (2006) described as a collection of assumptions and misrepresentations in the case of the Himalaya. The dire predictions of forest decline (eg Myers 1986) have not borne out, and Himalayan generalizations have typically proved untrue.

A particularly relevant current example of polarized opinions based on limited science has to do with hydroelectric projects (HEPs). The Hindu Kush–Himalaya has a feasible hydropower potential of around 500 GW (Mukherji et al 2015)—a potential that is now being rapidly tapped by the energy-hungry countries that surround the region. China and India together have plans for over 1000 hydropower projects in the Himalaya (Bawa et al 2010). While power is sorely needed and cannot be denied to the people who live in the region, HEPs also bring with them significant environmental damage and social hardship, which must be mitigated. Environmental impacts tend to be poorly studied using weak methodologies and inadequate ground truthing.

A recent paper by Pandit and Grumbine (2012), for example, estimated the cumulative impact of HEPs on the Indian Himalaya using a model-based approach. It predicted the extinction of 22 angiosperm and 7 vertebrate species and a reduction in tree species richness by 35%, tree density by 42%, and tree basal area by 30% in dense forests. It referred to ground truthing to validate estimates of land-cover types, but it did not indicate sampling frequency. It used data from Nepal (from Grytnes and Vetaas 2002), but these cannot be extrapolated to the eastern or western Himalayas, which have widely divergent species richness (see Table 1). For example, Tehri dam, the largest in the central Himalaya, has extensive species-poor patches of dry deciduous forests with stunted trees and xerophytic euphorbs and *Opuntia* (SP Singh, personal observation). In addition, species extinction may not occur even after 80% loss of forest cover (Carpenter 2005). Furthermore, species–area curves typically overestimate species loss due to habitat loss (He and Hubbell 2011).

Impact analysis studies need to consider the larger picture, look at particular areas, and focus on issues such as downstream flow and impact. Future flow patterns and hydrological regimes need to be estimated, for which good long-term data sets are needed but not always available. A recent model, based on existing information and simulations, projects an increase in runoff until at least 2050 in the major Himalayan river systems, based on an increase in precipitation and accelerated melt (Lutz et al 2014).

Well-designed and well-managed HEPs with equitable distribution of benefits can lead to positive development. For example, hydroelectricity can be used to provide clean cooking energy to mountain people, reduce demand on firewood, and thus be associated with increased carbon sequestration, biodiversity preservation, and improved health indicators due to a reduction in soot and back carbon—which have been thought of as a major cause of glacier melt in the Himalaya (Ramanathan and Carmichael 2008). Forest degradation in much of the Himalaya over the past several decades is primarily the result of biomass extraction for basic needs. Providing alternatives to fuelwood and leaf fodder will greatly help forest recovery.

As for construction of dams on Himalayan rivers, the crucial issue is whether modern engineering can in fact ensure the safety of dams constructed in youthful and fragile mountains, which are susceptible to erosion even without human activity. Blasting of rocks during dam construction fractures already fragile rocks and impacts groundwater flow. This is often a big issue in run-of-the-river dams that have long tunnels bored through mountains to carry water to electricity-generating turbines (Thadani 2006). While environmental impact assessments and environmental management plans are mandatory, their level of accuracy is debatable (Das 2010; Mukherjee 2012), and the impacts of multiple dams on river systems have not been studied (Grumbine and Pandit 2013). Better science and more detailed information are needed to help decide where dams can be constructed and where they must be avoided.

While the Himalayan region is seeing an explosion of HEP building at a rate that is almost certainly unsustainable, not building HEPs is a simplistic and unrealistic solution. Scholars need to address the issue without biases and should identify sustainable numbers and locations and conditions that would minimize environmental damage and social disruption. The merits of small versus big dams need to be better studied. Are numerous small dams better, each with localized and small-scale impacts, or would a few large dams like Tehri, built in areas of low species diversity, be better? While much has been said in praise of small, low-impact dams (Kumar and Katoch 2015), larger dams, which can afford the best-quality engineering support and well-planned and well-monitored rehabilitation plans, may also be an alternative and help restrict environmental and social damage to just a few places while ensuring broad access to basic essentials such as power.

In recent years, great emphasis has been placed on the need for improved cook stoves that reduce biomass use and lower black carbon (Urmee and Gyamfi 2014; Patange et al 2015) emissions compared to traditional cook stoves used across the rural Himalaya. Black carbon is an important contributor to global warming (Ramanathan and Carmichael 2008), and it adversely impacts local health, especially in the form of respiratory diseases (Bruce et al 2000). Many international research groups, and even more local nongovernmental organizations and implementing agencies, have benefited from funding for black carbon mitigation (one of the authors of this paper, Rajesh Thadani, is associated with some such projects). Nonetheless, there is little evidence to indicate that improved biomass cook stoves will achieve widespread use (Anonymous 2014), and the majority of solutions being offered appear to be impractical. While marginal increases in cooking efficiency are being recorded, it is unclear and doubtful if any of the cook-stove programs will lead to either a significant reduction of black carbon or any improvement in health or reduction of forest degradation (Thadani, personal observation; Anonymous 2014). While debate continues (Saleh et al 2014), evidence that black carbon emitted from fossil fuel burning may be twice as likely to cause warming as black carbon from cook stoves (Ramana et al 2010) is rarely discussed while promoting these cook stoves.

The above examples underline the need for more care in shaping research agendas and research policies. In the absence of good baseline data, snippets of incomplete information can, in the hands of the influential, be turned into well-funded research agendas that drive alarmism and spiral into enhanced funding.

Remote sensing can be a powerful technique to measure changes in the vast remote areas of the Himalaya. However, estimates based on satellite measurements vary considerably. For example, a 2010 study based on measurements by the Gravity Recovery and Climate Experiment satellite reported that glaciers in the Himalaya and Tibet Plateau were losing about 50 Gt of ice annually (Matsuo and Heki 2010). Using the same data set, another group estimated only one tenth as much ice loss (Jacob et al 2012), while a third group estimated an intermediate 12 Gt of ice loss a year between 2003 and 2008 in these glaciers (Kääb et al 2012). As the Gravity Recovery and Climate Experiment satellites cannot detect the difference between ice and liquid water, they are likely to have mistaken expanding glacial lakes for increases in glacial mass (Qiu 2012). Furthermore, the satellites' coarse resolving power may be able to effectively study large expanses with homogeneous surfaces such as the Arctic and Antarctic, but not the complex topography of the Himalaya (Mishra et al 2009; Singh et al 2011).

For better generalizations, we need to conduct multisite and long-term research (Knapp et al 2012) across the Himalayan geography—like, for example, BIODEPTH, which investigated the impact of species diversity on ecosystem functioning through experiments in 8 grassland sites in Europe (Hector et al 1997), or the International Tundra Experiment, a collaborative effort by scientists from 11 countries at 26 sites to examine the response of tundra ecosystems to environmental change over 20 years (Henery and Malar 1997; Elmendorf et al 2012). Multisite studies using similar methodologies would be of great utility in providing a broader regional understanding of the Himalaya.

Toward a new research approach

Himalayan systems provide opportunities to understand large-scale patterns and processes related to ecology, environment, and development. Adequate sampling and replication are essential. Meta-analysis, a technique that provides a formal statistical framework to combine and compare the results of a large number of independent studies (Harrison 2011), has been widely used in many scientific disciplines during the past 2 decades (Gurevitch and Hedges 2001). Questions such as whether alpine grasslands in the Himalaya are becoming increasingly woody are particularly suited for meta-analysis. However, when data are scarce, conducting meta-analysis is meaningless (Pachauri and Reisinger 2007).

Remote sensing and modeling methods can help address the challenges imposed by the Himalaya's sheer size, spatial heterogeneity, and microscale variability, provided they are supported by adequate ground truthing and valid data. Participatory research involving local people could help provide the high sampling density that is optimally required to develop generalizations in the Himalaya. This blend of science and local knowledge can lead to the development of "citizen science" as a response to the requirement for massive data collection on issues like climate change (Cooper et al 2007). A few studies have indicated that local communities can take at least a few important steps in measuring forest carbon (Skutsch 2011). While valid concerns have been raised, on issues ranging from data quality and integrity to the possibility of exploitative use of people to collect cheap data, given the growing number of local people, civil society groups, and educational institutions we have encountered that are interested in collecting and contributing such information, we believe that citizen science has tremendous potential. Using such data to support better policy-making and to develop a relationship between local people and their lands could lead to a win–win situation.

There is a need to develop networks, collaborations, and a culture of data sharing among scientists in Himalayan countries. Enhancing the quality of training at Himalayan universities is imperative, and bringing in new talent and ideas and motivating high-quality students to join the ranks of Himalayan scientists are essential. Given the range of ecological and sociological variations that the Himalaya encompasses, the region is particularly suited for conducting what Fraser et al (2013) called "coordinated distributed experiments"—experiments run in parallel by several researchers at many locations using a set of standardized methods to address major research questions. Given environmental flows across political boundaries and as humans are an integral part of virtually all Himalayan ecosystems, there is an urgent need to strengthen integrative approaches. A good start has been made by ICIMOD through its open-access Regional Database Initiative and efforts at long-term monitoring in transboundary landscapes (Chettri et al 2015).

The controversies around glacier melt rate generated by the 2007 IPCC report did provide an impetus for many new studies and collaborations of much higher rigor than ever before. Better monitoring and understanding of Himalayan glaciers have emerged in the past few years as a result of this focus. The same, however, cannot be said for research on forest and riverine systems. Subsurface flows and spring hydrogeology also remain poorly understood despite the increase in boring of mountain tunnels for hydroprojects (Patni et al 2014) and the heavy dependence of mountain people on mountain aquifers for their water security (Tambe et al 2012).

To answer pressing questions regarding the environment and development, better and more rigorous science is needed, along with enhanced collaboration between researchers, and a better balance between modern tools, such as modeling and remote sensing, and old-fashioned physical ground truthing.

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REFERENCES

Anonymous. 2010. *Report of the Task Force—To Look into Problems of Hill States and Hill Areas and to Suggest Ways to Ensure that These States and Areas Do Not Suffer in Any Way Because of Their Peculiarities.* Almora, India: Planning Commission, Government of India and GB Pant Institute of Himalayan Environment and Development. http://gbpihed.gov.in/PDF/Publication/TaskForce.pdf; accessed on 27 September 2015.

Anonymous. 2014. Clean break. *Nature* 509:533–534. http://dx.doi.org/10.1038/509533b.

Bawa KS, **Lian PK**, **Tien ML**, **Liu J**, **Ramakrishnan PS, Yu DW**, **Zhang Y-P**, **Raven PH**. 2010. China, India, and the environment. *Science* 327:1457–1459.

Bolch T, **Kulkarni A**, **Kaab A**, **Huggel C**, **Paul F**, **Cogley JG**, **Frey H**, **Kargel JS**, **Fujita K**, **Scheel M**, **Bajracharya S**, **Stoffel M**. 2012. The state and fate of Himalayan glaciers. *Science* 336:310–314.

Bolch T, Pieczonka T, Benn DI. 2011. Multi-decadal mass loss of glaciers in the Everest area (Nepal Himalaya) derived from stereo imagery. *Cryosphere* 5: 349–358.

Box EO. 1995. Factors determining distribution of tree species and plant functional types. *Vegetatio* 121:101–116.

Bruce N, Perez-Padilla R, Albalak R. 2000. Indoor air pollution in developing countries: A major environmental and public health challenge. *Bulletin of the World Health Organization* 78:1078–1092.

Carpenter C. 2005. The environmental control of plant species density on a Himalayan elevation gradient. *Journal of Biogeography* 32:999–1018.

Chettri N, **Bubb P**, **Kotru R**, **Rawat G**, **Ghate R**, **Murthy MSR**, **Wallrapp C**, **Pauli H**, **Shrestha AB**, **Mool PK**, **Chaudhary D**, **Chaudhary RP**, **Mathur PK**, **Peili S**, **Ning W**, **Sharma E**. 2015. *Long-Term Environmental and Socioecological Monitoring in Transboundary Landscapes: An Interdisciplinary Implementation Framework*. ICIMOD Working Paper 2015/2. Kathmandu, Nepal: ICIMOD.

Cogley JG. 2012. Climate science: Himalayan glaciers in the balance. *Nature* 488:468–469.

Cooper CB, Dickinson J, Phillips T, Bonney R. 2007. Citizen science as a tool for conservation in residential ecosystems. *Ecology and Society* 12(2):11.

Danielsen F, **Skutsch M**, **Burgess N**, **Jensen P**, **Andrianandrasana H**, **Karky B**, **Lewis R**, **Lovett J**, **Massao J**, **Ngaga Y**, **Phartiyal P**, **Poulsen M**, **Singh S**, **Solis S**, **Sørensen M**, **et al.** 2011. At the heart of REDD+: A role for local people in monitoring forests? *Conservation Letters* 4:158–167.

Das S. 2010. The strange valuation of forests in India. *Economic & Political Weekly* 45(9):16–18.

DeFries R, Achard F, Brown M, Herold M, Murdiyarso D, Schlamadinger B, Souza C. 2007. Earth observations for estimating greenhouse gas emissions from deforestation in developing countries. *Environmental Science & Policy* 10: 385–394.

Dhar U, Rawal RS, Upreti J. 2000. Setting priorities for conservation of medicinal plants—A case study of the Indian Himalaya. *Biological Conservation* 95:57–65.

Elmendorf SC, **Henry GH**, **Hollister RD**, **Björk RG**, **Bjorkman AD**, **Callaghan TV**, **Collier LS**, **Cooper EJ**, **Cornelissen JH**, **Day TA**, **Fosaa AM**, **Gould WA**, **Grétarsdóttir J**, **Harte J**, **Hermanutz L**, **et al.** 2012. Global assessment of experimental climate warming on tundra vegetation: Heterogeneity over space and time. *Ecology Letters* 15:164–175.

Fraser LH, **Henry HAL**, **Carlyle CN**, **White SR**, **Beierkuhnlein C**, **Cahill JF**, **Casper BB**, **Cleland E**, **Collins SL**, **Dukes JS**, **Knapp AK**, **Lind E**, **Long R**, **Luo Y**, **Reich PB**, **et al.** 2013. Coordinated distributed experiments: An emerging tool for testing global hypotheses in ecology and environmental science. *Frontiers of Ecology and the Environment* 11:147–155.

Graham CH, Elith J, Hijmans RJ, Guisan A, Peterson AT, Loiselle BA, NCEAS Predicting Species Distributions Working Group. 2008. The influence of spatial errors in species occurrence data used in distribution models. *Journal of Applied Ecology* 45:239–247.

Grumbine RE, Pandit MK. 2013. Threats from India's Himalaya dams. *Science* 339:36–37.

Grytnes JA, Vetaas OR. 2002. Species richness and altitude: A comparison between null models and interpolated plant species richness in the Himalayan altitudinal gradient, Nepal. *American Naturalist* 159:294–304.

Gurevitch J, Hedges LV. 2001. *Meta-analysis: Combining the results of independent experiments*. In: Scheiner SM, Gurevitch J, editors. *Designing and Analysis of Ecological Experiments*. New York, NY: Chapman and Hall, pp 347–369.

Harrison E. 2011. Getting started with meta-analysis. *Methods in Ecology and Evolution* 2:1–10.

He FL, Hubbell SP. 2011. Species area relationships always overestimate extinction rates from habitat loss. *Nature* 473:368–371.

Hector A, **Schmid B**, **Beierkuhnlein C**, **Caldeira MC**, **Diemer M**, **Dimitrakopoulos PG**, **Finn JA**, **Freitas H**, **Giller PS**, **Good J**, **Harris R**, **Högberg P**, **Danell KH**, **Joshi J**, **Jumpponen A**, **Henery GHR**, **Malar V**. 1997. Tundra plants and climate change: The International Tundra Experiment (ITEX). *Global Change Biology* 3:1–9.

Hewitt K. 2005. The Karakoram anomaly? Glacier expansion and the "elevation effect," Karakoram Himalaya. *Mountain Research and Development* 25(4): 332–340.

IIRS [Indian Institute of Remote Sensing]. 2002. *Biodiversity Characterisation at Landscape Level in Western Himalayas, India, Using Satellite, Remote Sensing and Geographic Information Systems*. Dehradun, India: IIRS, Department of Space, Government of India.

IIRS [Indian Institute of Remote Sensing]. 2003. *Biodiversity Characterisation at Landscape Level in Northeast India Using Satellite, Remote Sensing and Geographic Information Systems*. Dehradun, India: IIRS, Department of Space, Government of India.

Immerzeel WW, Petersen L, Ragettli S, Pellicciotti F. 2014. The importance of observed gradients of air temperature and precipitation for modeling runoff from a glacierized watershed in the Nepalese Himalayas. *Water Resources Research* 50(3):2212–2226.

Indian Meteorological Department. 2015. Monthly Rainfall Uttarakhand. Data accessed from Indian Meteorological Department, Hydromet Division, District wise rainfall information, compiled from www.imd.gov.in/section/hydro/distrainfall/uttarakhand.html; accessed 2 October 2015.

Ives JD. 2005. Global warming—A threat to Mount Everest? *Mountain Research and Development* 25(4):391–394.

Ives JD. 2006. Himalayan Perceptions: Environmental Change and the Well-Being of Mountain Peoples. *2nd edition*. Lalitpur, Nepal: Himalayan Association for the Advancement of Science.

Ives JD, Messerli B. 1989. The Himalayan Dilemma. *Reconciling Development and Conservation*. London, United Kingdom, and New York, NY: United Nations University and Routledge.

Jacob T, Wahr J, Pfeffer WT, Swenson S. 2012. Recent contributions of glaciers and ice caps to sea level rise. *Nature* 482:514–518.

Kääb A, Berthier E, Nuth C, Gardelle J, Arnaud Y. 2012. Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. *Nature* 488: 495–498. http://dx.doi.org/10.1038/nature11324.

Knapp AK, **Smith MD**, **Hobbie SE**, **Collins SL**, **Fahey TJ**, **Gretchen JA**, **Hansen DA**, **Kimberly JL**, **Melillo JM**, **Seastedt TR**, **Shaver GR**, **Webster JR**. 2012. Past, present and future roles of long-term experiments in the LTER network. *BioScience* 62(4):377–389.

Kumar D, Katoch S. 2015. Small hydropower development in western Himalayas: Strategy for faster implementation. *Renewable Energy* 77:571–578.

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.

Lutz AF, Immerzeel WW, Shrestha AB, Bierkens MFP. 2014. Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. *Nature Climate Change* 4:587–592.

Matsuo K, Heki K. 2010. The rapidly melting Himalayan glaciers. *Science Letters* 290:30–16.

Miller JD, Immerzeel WW, Rees G. 2012. Climatic change impacts on glacier hydrology and river discharge in the Hindu Kush–Himalayas. *Mountain Research and Development* 32(4):461–467.

Mishra VK, Sharma JK, Singh KK, Thakur NK, Kumar M. 2009. Assessment of different topographic corrections in AWiFS satellite imagery of Himalaya terrain. *Journal of Earth System Science* 118:11–26.

Mukherjee P. 2012. EIA scams: Decaying the EIA legal regime in India. *Journal of Environmental Research and Development* 6:507–513.

Mukherji A, Molden D, Nepal S, Rasul G, Wagnon P. 2015. Himalayan waters at the crossroads: Issues and challenges. *International Journal of Water Resources Development* 31(2):151–160.

Myers, N. 1986. Environmental repercussions of deforestation in the Himalayas. *Journal of World Forest Resource Management* 2:63–72.

Ohsawa M. 1987. Vegetation zones in the Bhutan Himalaya. In: Ohsawa M, editor. *Life Zone Ecology of Bhutan Himalaya*. Chiba, Japan: Chiba University, pp 1–71.

Pachauri RK, Reisinger A, **editors.** 2007. *Fourth Assessment Report to the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: Intergovernmental Panel on Climate Change.

Pandit MK, Grumbine RE. 2012. Potential effects of ongoing and proposed hydropower development on terrestrial biological diversity in the Indian Himalayan. *Conservation Biology* 26:1061–1071.

Patange OS, Ramanathan N, Rehman IH, Tripathi SN, Misra A, Kar A, Graham E, Singh L, Bahadur R, Ramanathan V. 2015. Reductions in indoor black carbon concentrations from improved biomass stoves in rural India. *Environmental Science & Technology* 49(7):4749–4756.

Patni BD, Walvekar AS, Chakraborty A. 2014. *Experience of TBM tunnelling in Himalaya—Prospects and challenges*. In: International Society for Rock Mechanics (ISRM) International Symposium, 8th Asian Rock Mechanics Symposium, 14–16 October, Sapporo, Japan.

Pearson RS, Brown HP. 1932. *Commercial Timbers of India*. Volume II, Fagaceeae, Quercus. Calcutta, , India: Government of India Central Publication Branch.

Powell D. 2012. Himalaya rush. Science News 182:18.

Qiu J. 2012. *Tibetan glaciers shrinking rapidly. Nature News*, 15 July 2012. http://dx.doi.org/10.1038/nature.2012.11010.

Qiu J. 2015. *High-altitude forests in the Himalaya harder hit by droughts. Scientific American*, 27 January 2015. http://dx.doi.org/10.1038/nature.2015.16806.

Ragettli S, Pellicciotti F, Immerzeel WW, Miles ES, Petersen L, Heynen M, Shea JM, Stumm D, Joshi S, Shrestha A. 2015. Unraveling the hydrology of a Himalayan catchment through integration of high resolution in situ data and remote sensing with an advanced simulation model. *Advances in Water Research* 78:94–111.

Ramana MV, Ramanathan V, Feng Y, Yoon SC, Kim SW, Carmichael GR, Schauer JJ. 2010. Warming influenced by the ratio of black carbon to sulphate and the black-carbon source. *Nature Geoscience* 3:542–545.

Ramanathan V, Carmichael G. 2008. Global and regional climate changes due to black carbon. *Nature Geoscience* 1:221–227.

Rao KR, Juneja KBS. 1971. *A Handbook for Field Identification of Fifty Important Timbers of India*. Dehradun, India: Forest Research Institute.

Ravindranath NH. 2010. IPCC: Accomplishments, controversies and challenges. *Current Science* 99(1):26–35.

Rees GH, Collins DN. 2006. Regional differences in response of flow in glacier-fed Himalayan rivers to climate warming. *Hydrological Processes* 20:2157–2167.

Saleh R, ***Robinson ES***, ***Tkacik DS***, ***Ahern AT***, ***Liu S***, ***Aiken AC***, ***Sullivan RC***, ***Presto AA***, ***Dubey MK***, ***Yokelson RJ***, ***Donahue NM***, ***Robinson AL***. 2014. Brownness of organics in aerosols from biomass burning linked to their black carbon content. *Nature Geoscience* 7:647–650.

Schiermeier Q. 2010. Glacier estimate is on thin ice. *Nature* 463:276–277.

Schild A. 2008. ICIMOD's position on climate change and mountain systems. *Mountain Research and Development* 28(3/4):328–331.

Shea JM, Immerzeel WW, Wagnon P, Vincent C, Bajracharya S. 2015. Modelling glacier change in the Everest region, Nepal Himalaya. *Cryosphere* 9: 1105–1128.

Singh JS, Singh SP. 1992. *Forests of Himalaya*. Nainital, India: Gyanodaya Prakashan.

Singh P, Kumar V, Thomas T, Arora M. 2008. Changes in rainfall and relative humidity in river basin in northwest and central India. *Hydrological Processes* 22:2982–2992.

Singh SP. 2014. Attributes of Himalayan forest ecosystems: They are not temperate forests. *Proceedings of the Indian National Science Academy* 80(2): 221–233.

Singh SP, Khadka IB, Karky B, Sharma E. 2011. Climate Change in the Hindu Kush–Himalayan. *The State of Current Knowledge*. Kathmandu, Nepal: International Centre for Integrated Mountain Development.

Singh SP, Thadani R. 2013. *Valuing ecosystem services flowing from the Indian Himalayan states for incorporation into national accounting*. In: Lowman M, Devy S, Ganesh T, editors. *Treetops at Risk: Challenges of Global Canopy Ecology and Conservation*. New York, NY: Springer, pp 423–434.

Skutsch M, ***editor.*** 2011. *Community Forest Monitoring for the Carbon Market: Opportunities under REDD*. London, United Kingdom, and Washington, DC: Earthscan.

Tambe S, Kharel G, Arrawatia ML, Kulkarni H, Mahamuni K, Ganeriwala AK. 2012. Reviving dying springs: Climate change adaptation experiments from the Sikkim Himalaya. *Mountain Research and Development* 32(1):62–72.

Thadani R. 2006. *Incentive-Based Mechanisms in the Hydro Sector: CAT Plans and Beyond*. New Delhi, India, and London, United Kingdom: Winrock International India and International Institute for Environment and Development.

Thadani R, Ashton PMS. 1995. Regeneration of bank oak (*Quercus leucotrichophora* A. Camus) in the central Himalaya. *Forest Ecology and Management* 78:217–224.

Urmee T, Gyamfi S. 2014. A review of improved cookstove technologies and programs. *Renewable and Sustainable Energy Reviews* 33:625–635.

Vanclay JK. 2014. Unsuspected implications arising from assumptions in simulations: Insights from recasting a forest growth model in system dynamics. *Forest Ecosystems* 1:7. http://dx.doi.org/10.1186/2197-5620-1-7.

Wiens JA, Stralberg D, Jongsomjit D, Howell CA, Snyder MA. 2009. Niches, models, and climate change: Assessing the assumptions and uncertainties. *Proceedings of National Academy of Sciences of the United States of America* 106:19729–19736.

Xu J. 2005. The water fluxes of the Yellow River to the sea in the past 50 years in response to climate change and human activities. *Environmental Management* 35:620–631.

Xu J, Grumbine E, Shrestha A, Eriksson M, Yang X, Wang U, Wilkes A. 2009. The melting Himalayas: Cascading effects of climate change on water, biodiversity, and livelihoods. *Conservation Biology* 23(3):520–530. http://dx.doi.org/10.1111/j.1523-1739.2009.01237.x.

Yao T, Thompson L, Yang W, Yu W, Gao Y, Guo X, Yang X, Duan K, Zhao H, Xu B, Pu J, Lu A, Xiang Y, Kattel DB, Joswiak D. 2012. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Climate Change* 2:663–667. http://dx.doi.org/10.1038/NCLIMATE1580.

Zobel DB, Singh SP. 1997. Himalayan forests and ecological generalizations. *BioScience* 47:735–745.