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Rapid warming in the Himalayas: Ecosystem responses and development options

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This article draws attention to the significance of the Himalayas in relation to global climate change, and discusses the likely impact of warming on the Himalayas and ecosystems in both upstream and downstream regions. Scientific evidence suggests that the Himalayas are warming at more than the global average rate. Alpine ecosystems are particularly vulnerable to warming, as species occurring near the mountain tops will have no space for their upward march. Intensification of water stress because of warmer temperatures can adversely affect leaf phenology and the regeneration of many dominant forest species. A suggestion is made that carbon forestry and manure management by local communities could be seen both as mitigation and as adaptation strategies.

Keywords: adaptation; alpine ecosystems; climate change; glacier retreat

1. Introduction

Mountains are known to influence the livelihoods of nearly 40 per cent of people globally. Although populations are small in mountain areas themselves, the river basins below such areas are home to much greater numbers of people. Moreover, mountains represent much of the wilderness where species of lowland regions could potentially migrate to in order to escape warming. Covering about 24 per cent (35.8 million km^2) of the world's land surface, mountains are home to 28 per cent of the planet's closed forests (Iremonger et al., 1997). They are particularly important in tropical regions, being the only source of snow and snow-melt water.

This paper addresses in particular the impacts of climate change in the Himalayan region. Nearly 500 million people live in the adjacent Gangetic plains (Figure 1), where agriculture has been practised for several thousand years using water from these mountains. In the future, global warming may well severely affect the river connections between the Himalayas and the Gangetic plains, and hence the climate regime and food production capacity of the entire region. Yet most of the academic debate on, and public attention to, climate change in the Himalayas has focused on glacier melt (Dyurgerov and Meier, 2005; Ding et al., 2006; Liu et al., 2006). This paper is more concerned with the question of how natural ecosystems and agriculture are going to be affected, issues that have hardly been considered in the scientific literature, in spite of the fact that they have been recognized in the action plan of India's Prime Minister on climate change (Government of India, 2008), which listed these impacts on mountains as being among the priority research areas.

This paper begins with a preliminary account of evidence of climate change in the region, and continues by looking at impacts of this in the areas of water flows and alpine ecosystems. It goes on to

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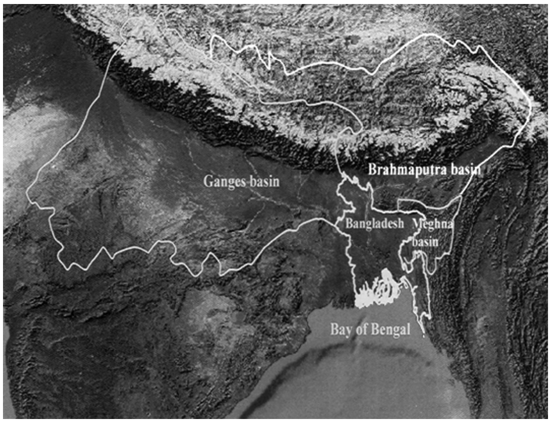

FIGURE 1 Location of the Ganges River basin and Gangetic plains

discuss the role of the Himalayas as a biological refuge in a changing climate, phenological (seasonal) changes that are occurring, tree water relations and the regeneration of dominant species. The paper then turns to the human impacts of climate change in the region, and discusses the spread of disease and impacts on agriculture. The paper concludes by suggesting that adaptation responses could incorporate carbon mitigation strategies, such as community carbon forestry and manure management, which would potentially open up financial flows to support local communities' livelihoods as changes in the climate make it more diffcult to survive in the region.

2. Characteristics of the Himalayas

The Himalayas are a major geo-ecological feature of the planet. Not only is the highest mountain, Everest, found here, but also nine of the world's 14 tallest peaks. The evolution of the monsoon rainfall pattern of the whole of Asia is attributable to the presence of these mountains. The high mountain ranges intercept cold winds from the north and trap moisture from the winds rising from oceans in the south. They have created a maritime climate in a continental location (Singh and Singh, 1992). The adjacent Gangetic plains are more humid and moist than their precipitation values indicate. Vapours emanating from forest cover at 3–4 km altitudes in the Himalayas seem to contribute to the high humidity in the northern India subcontinent (Singh, 2007a, b). Winters are mild, allowing the cultivation of crops throughout the year (Zobel and Singh, 1997).

The young and rising mountains have an immature topography, which is why the slopes are very vulnerable to erosion, causing heavy silt loads in rivers originating in the Himalayas. As measured about 200 km from the ocean in Bangladesh each year, the combined catchment of the Ganges and Brahmaputra rivers transports nearly 1,000 million tonnes of sediment, thereby exacerbating the annual overbank flooding (Wasson, 2003). Precipitation varies widely in the Himalayan ranges. It is extremely high in a few pockets of the eastern Himalayas such as Mawsinram, Meghalaya, where it reaches 11,600 mm annually (Dhar and Nandargi, 2008), whereas in the north of the main Himalayan ranges there are huge rain shadow areas (i.e. dry areas on a mountainside facing away from the direction of the wind). The Himalayan glaciers are generally considered to be the source for most of the major river systems of the Indian subcontinent (though this has been contested, at least for the case of high elevation glaciers feeding into rivers in Nepal, see Armstrong et al., 2009). The glaciers, as noted, have widely been reported to be retreating, even if the rate of this retreat is not yet entirely clear (Dyurgerov and Meier, 2005).

A sizeable area of the region is under alpine meadows (locally called *buggyals*), known for precious medicinal plants and used for grazing sheep and goats. The alpine meadows are rich in soil carbon, particularly where peat lands develop.

3. Observed and expected impacts of climate change in the Himalayas and surrounding areas

How fast are the Himalayas warming? The limited data that are available indicate that the Himalayas seem to be warming several times more than the global average rate (Shrestha et al., 1999; Liu and Chen, 2000), that temperature increases are greater during the winter and autumn than during the summer; and that increases are larger at higher altitudes (Liu and Chen, 2000). For example, the mean annual temperature rise on the Tibetan plateau and surrounding areas from 1961 to 1990 is reported to be 0.11°C between 500 and 1,500 m altitudes, 0.12°C between 1,500 and 2,500 m, 0.19°C between 2,500 and 3,500 m, and 0.25°C above 3,500 m (Liu and Hou, 1998). This study showed that the mean temperature rise across all altitudinal belts was 0.42°C during winter and 0.02°C during summer.

Unfortunately, temperature data over a long period are not available for much of the Himalayan region. An analysis of data collected at a station located in the outer ranges of Kumaon at Nainital (approximately 2,000 m altitude) indicates that the average temperature has increased by 0.6°C over the period 1960–2000 (Sharma, unpublished). An analysis of data collected at the Indian Institute of Tropical Meteorology over the last century shows a decrease in precipitation over 68 per cent of India's area (Kumar et al., 2006) because of cooling of the upper atmosphere and heat intercepted by greenhouse gases in the lower atmosphere, though how much of this change has taken place in the Himalayas was not analysed. However, it is not in doubt that the effects of global warming have major consequences with respect to impacts on all aspects of the environment and human welfare, and many of these impacts are likely to become much more severe as climate change advances.

3.1. Impacts on water flows

Data collected over the period 1966–2005 indicate that snow cover has decreased across the entire northern hemisphere in all months, except November and December (Vergara et al., 2007). The higher Himalayas and the inner Asian ranges together have the largest glaciated areas outside of the polar regions (IPCC, 2007). The Himalayan ranges alone have 35,110 km^2 of glacier and ice cover, with 3,735 km^3 of ice volume. Nearly half of the ice reserve is attributed to glaciers of the Ganges (see Table 1). Glacial melt accounts for 6–45 per cent of average river flows across the Himalayan rivers studied (see Table 2), and in some rivers up to 70 per cent of the flow during summer.

Data from measurements of the lower tips of the Himalayan glaciers indicate that these glaciers are retreating, and the recent controversy, ignited by unrefereed reports quoted by the IPCC, does not in any way contradict this. Rather, it highlights the need for careful studies of the rates at which glacial retreat is occurring, which are likely to be different in different areas. According to one estimate, glaciers in Nepal are retreating at rates between less than 5 and 20 m per year (Fujita et al., 2001), whereas the Indian Himalayan glaciers are in general retreating faster than the world average (Dyurgerov and Meier, 2005) (see Figure 2 and Table 3. Note that the sources from which Figure 2 and Table 3 were drawn, unlike Fujita et al. (2001), were not peer-reviewed journal articles; while they do appear to be credible, there would be value in having such data from a peer-reviewed source).

Ice cores taken from glaciers around the world generally show horizons with raised beta radioactivity associated with atmospheric thermonuclear bomb testing in the 1950s and 1960s. The absence of these marker horizons in the Naimona'nyc Glacier in the Himalayas indicates no net accumulation of ice mass since at least 1950

TABLE 1 Glacier resources in the Himalayas by drainage basins

Drainage basin	No. of glaciers	Total area (km^2)	Total ice volume (km^3)
Ganges river	6,696	16,677	1,971.5
Indus river	6,057	8,926	850.4
Brahmaputra	4,366	6,579	600.4
Sutlej river	1,900	2,861	308.0
Mapam Yamco lake	48	67	4.4
Total	18,067	35,110	3,734.5

Note: The other glacial resources of the central region are KaraKoram (area of 16,600 km^2), Tien Shan (15,417 km^2), Pamir (12,260 km^2), Kulun Shan (12,260 km^2) and Hindu Kush (3,200 km^2).

TABLE 2 Principal river systems of the Himalayan region

River			River basin			
	Annual mean discharge (m 3/5)	Glacial melt in river flow (%)	Area (km^2)	Population (million)	Population density (no./km^2)	Water availability (m^3/person/year)
Yangtze	34,30	18.5	1,722,193	368.5	214	2,909
Ganges	18,691	9.1	10,16,124	407.5	401	1,447
Brahmaputra	19,824	12.3	651,335	118.5	182	5,274
Irrawaddy	13,565	Small	413,710	32.7	79	13,089
Mekong	11,048	6.6	805,604	57.2	71	6,091
Indus	5,533	44.8	1,081,718	178.5	165	978
Tarim	146	40.2	1,152,448	8.1	7	571

Source: Jianchu et al. (2007).

(Kehrwald et al., 2008). However, there appears to be expansion or down-slope redistribution of ice in Karakoram (Hewitt, 2005), possibly because of the change in atmospheric moisture and distribution. The rapid release of meltwater and rainfall has also combined to trigger debris flows and flash floods in higher ranges, including the formation of potentially dangerous lakes (Yamada, 1998). The fear is that these lakes may breach suddenly, resulting in rapid discharge of large volumes of water and debris. According to a United Nations Environmental Programme study, glacial lake floods in the Himalayas increased during the second half of the 20th century (UNEP, 2000).

The river waters have cross-country connections. For example, Nepal contributes 40 per cent of the average annual flow and 70 per cent to the dry season flow in the Ganga basin. Decrease in snow pack size and duration will be crucial factors in water availability at a local

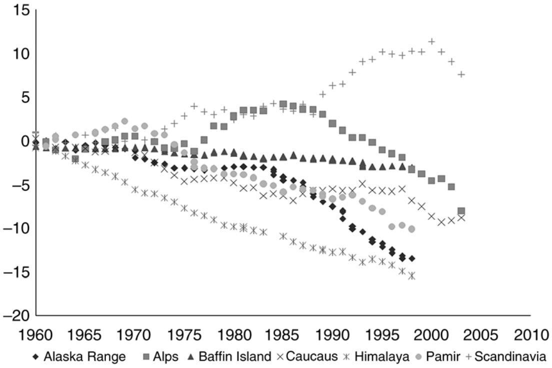

FIGURE 2 Rapid retreat of greater Himalayan glaciers compared with the global average
Source: Dyurgerov and Meier, 2005.

TABLE 3 Rate of glacier retreat in 14 glaciers across different regions of the Himalayas

Region and glacier	Rate of retreat (m/year)
Kashmir and Himachal	
Barashigri, Chandan basin of Eastern Lahul	44
Tajiwas Nar, Sindh basin of Kashmir	5
Stock, Ladak	6
Gangstang, Bhara basin of western Lahul	12
Garhwal	
Trisul, Nanda Devi sanctuary	10
Betharti, Nanda Devi sanctuary	8
East Kamet	5
Gangotari, Bhagirathi Basin	15
Satopanth–Bhagirathi glaciers complex, Alaknanda	12
Kumaun	
Milam, Gouri Ganga basin	13.5
Poting, Gouri Ganga basin	5
Shankalapa, Gouri Ganga basin	23
Sikkim	
Tista Khangse, Tista basin	8
Zemu, Tista basin	8

Source: Mukhophadayay (2006).

scale. With the lack of river flow, pollutants will stay longer in rivers. Water scarcity, pollution and water-borne diseases are already serious problems in the Gangetic plains, where human population densities are around 400 per km^2.

3.2. Impacts on alpine ecosystems

Recent research on alpine vegetation suggests that its response to climate change would be fast and flexible (Cannone et al., 2007), contradicting the earlier notion that alpine plants have inherent inertia to an increase of 1–2°C mean temperature. Because of enhanced hydrological cycles (due to the rapid snow melt and more precipitation) and resultant increased surface instability and disturbance, unexpected changes in vegetation may occur. Alpine areas are particularly vulnerable to hydrological disturbances. Because of low air temperature, runoff is estimated to be 4–5 times greater in this belt than in lower ranges, for a given rainfall. Data based on the use of the tracer technique indicate that the high Himalayas are the main source of sediment output (80 per cent of the total) (Wasson, 2003).

Because the Himalayan mountains are young and still rising, they are unusually vulnerable to topographic instability. The spread of early successional species, including alien invasive species following landslides, may greatly restrict the normal vegetation shifts. The disappearance of snowpack and glaciers will affect species composition and biogeochemistry from local to continental scales, and interfere with other ecological drivers (Singh and Singh, 1992). Many species are able to start their growth with the supply of snow-melt water well before the monsoon begins in June (Negi et al., 1991). These species' growth and life cycles are already being disturbed because of reduced water from snow melt, and they may disappear completely if and when glaciers are gone for good. Warming and resulting desiccation (warming will increase the drying power of the atmosphere) will make grasslands and peatlands prone to fire and depletion of soil carbon accumulated over centuries. Our field observations indicate that already the fire season has advanced by approximately two weeks in the central Himalayas.

Being located near the mountaintops, alpine species are particularly vulnerable to global warming (Beniston, 2003). They would have little scope to march upward as the temperature rises. Species that depend on snow cover for protection would be exposed to frost, and others that require winter chilling for bud-break may not get sufficiently low temperatures over a long enough period to survive. Species typical of windswept areas might increase in extent (Cannone et al., 2007). However, there are records that indicate that some alpine species, such as *Carex curvula*, survived a major climate change about 2,000 years ago (Steinger et al., 1996). Investigation is needed to identify and study the survival strategies of species in the Himalayas.

There are likely to be drastic changes in the lifestyle of many animals living in alpine areas. For example, the tiny mammal *pika* avoids warm temperatures by living in crevices. In a warmed-up world, the heat may limit its daily foraging hours. Data from other alpine areas indicate a marked reduction in the population of this tiny mammal. In a warmer world many other animal species in alpine ecosystems will be faced with very different conditions, including different competitors, predators and food bases.

Rhododendrons and other woody species have already begun to invade alpine meadows in the Valley of Flowers of Uttarakhand. As herbs are replaced by woody species of greater heights, several changes can result. For example, there would be fewer lichens and mosses under the shade of woody plants (Olofsson, 2006), and allocations of biomass to below-ground parts and mycorrhizal fungi are likely to change. Some ectomycorrhizal woody genera such as *Betula* and *Salix* are known to give up to 30 per cent of net carbon fixation to symbiotic fungi (Read et al., 2004), and they capture nitrogen more effectively than arbuscular mycorrhizae (Leake et al., 2004; Wookey et al., 2009). On the other hand, grazing sheep, goats, horses and cattle will be able to move into higher altitudes and over a longer period may restrict the establishment of woody plants. Furthermore, the composition of plants and animals in meadows may change because of the arrival of many species from lower ranges and invasive alien species, which will have a competitive impact on existing species.

In brief, because of the occurrence of diverse plant functional types (e.g. both evergreen and deciduous woody plants, tall and rosette herbs, mosses and lichens), shifts in communities will result in a complex series of changes in ecosystem processes with a considerable involvement of the soil subsystem.

4. Role of the Himalayas as a refuge for migrating species in a changing climate

Since seasonal temperature variation is limited in the tropics, species occurring there are likely to be more vulnerable to large temperature changes, compared to temperate zone species that experience wide seasonal variations. Furthermore, many tropical species are already living at temperatures close to the upper limits of their tolerance ranges. Therefore, species living in lowland areas of the Indian subcontinent would have to migrate to cooler areas to survive. The Himalayas provide a large wilderness area with favourable growing conditions up to a considerably high altitude. The adjacent plains are heavily populated, with only a few islets of natural vegetation. The Himalayan mountains may indeed form the only refuge for species of the adjacent plains needing to migrate to cooler areas. Migration of tropical species, including some pines (e.g. *Pinus merkusii*), from the lowland areas of South Asia to the Himalayas is indicated to have occurred in the geological past during a warmer climate phase (Vishnu-Mittre, 1984). There are several tropical trees that have been able to penetrate into the Himalayan ranges along rivers that have cut deeply into mountains, for example, *Bombax ceiba* and *Butea frondosa*.

However, species migration could now be impeded by the lack of continuity between suitable habitats. They may need corridors and stepping stones to march upward through a landscape that is so heavily affected by urban development, dams, roads and agricultural fields. Large parts of the Gangetic plains are now agricultural fields, with only a few remnants of natural vegetation. The option of physically assisting species to move has so far hardly been considered. Scientists would need to undertake research to develop a suitable strategy of assisted migration based on knowledge about the habitat requirements of the species concerned, their migration behaviour and the hurdles they would encounter while marching upward. Invasive alien species may have the advantage here, and beat the local species in migration to the Himalayan ranges. Already *Eupatorium* spp. and *Parthenium* spp. have spread over large areas in the mountains and along roads and rivers.

The upward movement of species by 600–800 m by 2075 as predicted by a simulation model (Moen et al., 2004) would cause major changes in alpine and subalpine zones. *Quercus semecarpifolia* (brown oak), the principal oak of high elevations, is going to suffer most, as it already has an island-like distribution around mountain peaks. In many areas, such as the Cheena peak in Nainital, there is no upward area left to move into.

Large increases in the net primary productivity in India as predicted by certain models (Sathaye et al., 2006) are difficult to believe in the case of Himalayan forests, and may not be applicable in this situation. In a relatively undisturbed condition, a net primary productivity of 10 t C ha^{-1} year^{-1} is common. Doubling this (which Sathaye et al. suggest to be the likely effect of global warming) would mean 20 t C ha^{-1} year^{-1}, which is uncommon, even in a tropical rain forest.

5. Phenology and tree water potential: Responses to warming stresses

A condition of milder winters and hotter summers is likely to intensify summertime drought (Henson, 2006), when most species produce leaves. One of the features of dominant evergreen Himalayan tree species is that new leaf production and leaf shedding occur simultaneously during spring, the former often inducing the latter. Many deciduous species, including those of adjacent lowland areas, also shed their leaves during the height of summer drought, and then start producing new leaves after a few weeks when conditions are still dry. There are indications already that there is a greater rise in temperature during winters than summers. For example, on the Tibetan Plateau and surrounding areas, the average temperature rise from 1961 to 1990 was 0.46°C in winter compared to 0.14°C in summer (Liu and Hou, 1998). This will narrow down seasonal temperature variation within an annual cycle. These climatic changes may further promote evergreen species at the cost of deciduous species in the Himalayas and the adjacent plains.

Normally an increase in temperature hastens springtime leaf production. But warming may lead to extreme droughts by increasing evapotranspiration during a rainless period, such as the one experienced in 1999 in the central Himalayan region when the tree water potential in a population of *Quercus floribunda*, an evergreen oak, dropped to −5.5 MPa, compared to between −2.0 and −2.3 MPa during normal years (Singh et al., 2000). The severe drought of 1999 revealed that *Q. floribunda* has two populations: the one, which did not allow its water potential to go down steeply, could produce leaves in spring, whereas the other, which had no such control over water potential, had to wait until the start of the monsoon rain in June to leaf out (Singh et al., 2000). The delay in leafing in this population also delayed seed production and changed the timing of leaf decomposition and nutrient cycling. In brief, warming-induced water stress can disturb tree phenology and several connected processes, including nutrient cycling and food supply to wildlife. Such extreme events are expected to significantly influence species mix and populations.

In another study at Nainital in a dry year (though not as severe as 1999), we found that the banj oak (*Q. leucotrichophora*), instead of advancing leafing time as is generally held to happen in a dry year (Khanduri et al., 2008), withheld and staggered its leaf production because of carbon drain. What seemed to have happened was that the water stress caused by a relatively warmer spring hastened seed development. Since trees were left with insufficient carbon after investing in rapid seed development, they withheld the springtime leaf production and produced leaves in several steps, and did not reach their normal full quota. Disturbance in leaf phenology such as this can affect several other processes, such as insect herbivory, litter decomposition, and predations of birds and mammals that depend upon them. Furthermore, carbon drain may occur in combination with anthropogenic stresses, such as lopping of branches and litter collection, which are common in the region, and can lead to tree mortality (Thadani, 1999). Internal physiological stress and a decline in resource levels within trees, such as a paucity of nitrogen in xylem sap, precede obvious external senescence in trees (Zobel et al., 1995). These aspects need to be investigated, not only for scientific reasons but also because local people depend on natural forests for their day-to-day living. A recent study indicates that it is possible to link livelihood issues to conservation in a way that leads to enhanced forest carbon stocks. For example, development of fodder based on grasses and legumes can reduce the need for people to lop tree branches. Furthermore, improvements in litter composting can improve soil carbon, and there is evidence that biogas installations have improved forest cover in and around villages in many parts of the Himalayas (Singh, 2007a, b).

Warming by intensifying evapotranspiration can make conditions stressful for many dominant species. The occurrence of two or three dry spells annually, each generally lasting between 6 and 12 weeks, is a common feature in the region. Since species in monsoon climates have leaves that are still expanding at the height of summer drought, their leaf production and leaf cycle could be adversely affected by global warming. Many dominant species of widespread distribution (e.g. *Shorea robusta, Pinus roxburghii and Quercus* spp.) have a concentrated early summertime leaf production, which induces equally concentrated leaf fall (evergreen with about 1-year leaf life span). Thus, these evergreen species overhaul their canopies as do deciduous species before the rainy season begins to maximize the advantage of favourable months (warm and moist). Such an adaptation may have a competitive edge if summertime water stress were to further aggravate the situation. Even at present most species experience summertime water stress and pre-dawn tree water potential below −2 MPa at higher altitudes (above the *S. robusta* belt) where soils are shallow (Zobel et al., 2001).

5.1. Effects on regeneration of dominant species

In many dominant forest species such as sal, tilonj and kharsu (*S. robusta*, *Quercus floribunda* and *Q. semecarpifolia*, respectively), seed maturation and seed germination coincide with monsoon rainfall. In wet conditions these species show varying degrees of vivipary (germination of seeds while they are still on trees). A rise in temperature and water stress may advance seed maturation, which might result in the breakdown of the synchrony between the commencement of monsoon rains and seed germination. Already, oak seeds are observed to be larger in the summers than in the past, indicating early seed development.

Regeneration in sal (*S. robusta*) is known to be a problem, partly because its seeds are ready to germinate by mid-June when the start of the monsoon is uncertain. The warming-induced early maturation of seeds can easily disrupt this delicate relationship of events.

The problem with vivipary is that if a seed falls in an unfavourable place or at an unfavourable point (e.g. a rainless week), it has no chance of becoming a seedling.

6. Spread of diseases

A warmer and highly variable climate can affect human health in various ways, both directly and indirectly. For example, it can increase the transmission of diseases to new areas by adversely affecting agricultural production and causing malnutrition in some of the least developed countries, including those in the Himalayan region. It can decrease water supply in warm seasons and increase disease load, and cause hazardous extreme weather. Estimating the impact of climate change on human health in any one area is difficult, although a number of trends are clear. The people who are likely to bear most of the burden of disease are the poor, particularly children and women. In mountains women and children often make up the bulk of the population in villages where outmigration of males in search of employment is high.

Climate change is in general expected to increase the incidence of diseases like diarrhoea, vector-borne diseases like malaria, and infections associated with undernutrition (WHO, 2008). Until now, *Anopheles* mosquitoes failed to breed effectively above 1,500 m altitude (Craig et al., 1999). Malaria is projected to spread soon at the margins of its current upper altitudinal range, where cold temperatures have hitherto restricted its transmission (Ebi et al., 2007). Warmer conditions are predicted to weaken barriers to the spread of pathogens (Epstein, 1999) and shorten the generation times of these organisms. Global warming along with human movement and transport of food from lowland areas is likely to promote the upward movement of pathogens. Hill stations, generally located around 2,000 m (Nainital, Mussoorie, Shimla and Darjeeling), have hitherto been considered malaria-free areas, but the situation could change with warming. As for other diseases, in extreme droughts poor water availability leads to contamination of water by waterborne bacteria, and since temperature rise is expected to increase more during autumn and winter, the winter killing of microbes is likely to become less effective.

7. Impacts on agriculture in the Himalayas

Without doubt one of the major consequences of climate change is going to be the change in crop selection and increase in the altitudinal range of cultivated land. Delay in snowfall and early snow melt may encourage people to cultivate crops in alpine meadows: for example, crops like potato may expand to become a regular feature at what are now Alpine altitudes. Equally clearly, since about 90 per cent of agriculture in the Himalayas is rain-fed, agriculture is going to be severely affected in Western ranges (Vedwan and Rhoades, 2001) by more frequent and intense droughts caused by the increased drying power of the atmosphere.

Signs of change are already visible. In the Kullu valley of Himachal Pradesh, apple production has declined after the peak production season of 1988–1989. This is a serious problem because the rise in apple cultivation from about 600 ha in 1960–1961 to about 1,100,000 ha in 1995–1996 was considered one of the success stories of the region's mountain development. Apple cultivators (35,000 families) of the valley perceive that over the years the amount of snowfall has decreased, and that it occurs later than before. Not surprisingly, the farmers look at climate change primarily in relation to the decrease in their apple production, and as a 'deviation from the weather cycle ideal to apple production' (Vedwan and Rhoades, 2001). Because of the change in snowfall the chilling hours for apple trees are reduced, affecting the time of its bud-break. Early snow (December to early January) is preferred for its favourable effect on bud-break as well as on soil moisture. It provides a chilling period of about 10 weeks below 5°C, which is required to meet the internal conditions necessary for bud-break in apples in springtime (Abbott, 1984). Late snow (in late January and February), which is less durable, more watery and transitory, restricts bees' activities, including pollination of apple flowers.

8. Planned adaptation to climate change in the Himalayas

Human beings adapt, for better or for worse, to a changing climate. They may migrate, they may switch to other agricultural crops, or they may change their cropping technology (spraying the apples more often). They may also suffer and die from diseases that are a direct result of global warming. But there are ways in which adaptation can be assisted, and assisted along a route that is positive both for human welfare and for the environment. The problem is that such adaptation often requires funds that are not available locally. Although the possibility for international funds for climate adaptation exists under the United Nations Framework Convention on Climate Change (UNFCCC), negotiations on this have been proceeding rather slowly and the funds so far pledged are very limited. The international community under the UNFCCC and the Kyoto Protocol has given more attention to mitigation activities because this is a sector in which money can be earned at many levels. But there are mitigation activities that could also help to support positive adaptation, and combining these two climate-related functions may be the most efficient way to proceed. The need for an integrated approach in dealing with adaptation in Nepal has already been outlined by Gurung and Bhandari (2008). Two such possibilities for the Himalayas in general are briefly mentioned here.

The first concerns soil organic matter. With global warming, there is likely to be enhanced decomposition of soil organic matter and release of CO_2. Since 1850, 160 million metric tonnes of CO_2 have been emitted from soils and biomass worldwide (Paustian et al., 2006). However, through technology agricultural soils can be made net CO_2 accumulators by increasing productivity, improving cropping practices, using erosion control measures and reducing tillage. In much of the Himalayas, forest floor litter is collected and composted along with livestock dung. The partly decomposed organic matter is then transported to crop fields while preparing beds for seed sowing. In recent years some progress has been made in the region in promoting vermicomposting, which markedly improves nutrient delivery to crop plants. It is possible to further improve internal nutrient control in a cropland with the assistance of soil microbes. These practices can reduce the use of chemical fertilizers and hence GHG emissions associated with their manufacture. There are no possibilities for carbon crediting for reduced emissions in agriculture under the Clean Development Mechanism, but the UNFCCC is beginning to discuss a much broader Agriculture, Forestry and Land Use policy that, if agreed upon, could provide the financial basis for these kinds of interventions. Low- and no-tillage practices that help soil carbon accumulation in cereal production might also be included.

The second concerns carbon forestry. The Indian Himalayan forests alone contain about 5.4 billion tonnes of carbon and sequester nearly 65 million tonnes of carbon per year, largely as a result of forest management activities carried out by local people in *Van Panchyats* (village forests) (Singh, 2007a, b). This amount of carbon sequestered per year is equivalent to about 15 per cent of the CO_2 emissions from fossil fuels combustion from India in the year 2000. Obviously, the Himalayan region contributes substantially to the country-level carbon budget. A study carried out under the project 'Kyoto: Think Globally Act Locally' indicates that well-managed community forests in Uttarakhand sequestered 3.7 tonnes of carbon (13.32 tonnes of CO_2) per hectare per year, in addition to meeting the day-to-day needs of villagers for firewood, fodder and leaf litter, among other things (Banskota et al., 2008; see also Table 4). A programme promoting fodder production from grasses and legumes could substantially reduce the lopping of branches to gather leaves for fodder, and hence contribute to increasing the carbon sink as well as improving dairy production. At present, local people who manage these forests are not paid for this carbon function, but with new policy being developed under the UNFCCC, Reducing Emissions from Deforestation and Degradation (REDD), a possibility for this may be opened, particularly if REDD policy covers not only reductions in degradation but also enhancement of forests, an option that is now under discussion in an expanded form of REDD known as REDD+. Sale of carbon credits generated by communities in the Himalayas through managing their forests sustainably could help in the diversification of local income as other opportunities decrease as a result of climate change.

TABLE 4 Carbon sequestration rate in three *Van Panchyats* (community forests) of Lamgarha block of Uttarakhand, studied under the project 'Kyoto: Think Globally Act Locally'

Van Panchyat (VP)	t C ha^{-1} $year^{-1}$
Dhaili VP (mean of 3 years data collection)	
Even-aged banj oak	3.4
Dense mixed banj oak	4.2
Mixed banj oak/chir pine—degraded	2.2
Toli VP (mean of 3 years data collection)	
Mixed banj oak/chir pine – young	4.05
Mixed chir pine/banj in bush form[a]	3.05
Chir pine – young	4.25
Guna VP (mean of 2 years data collection)	
Chir pine – young	3.8
Mixed banj oak	4.4
Mean sequestration rate (of all eight forests)	3.7

Values in parentheses indicate period of data collection.

[a]While chir pine trees were healthy, banj oak trees were severely lopped, resulting in a bush form.

Source: Singh (2007a, b).

9. Conclusion

Climate change in the Himalayan region is critical because it will impact not only the environment of the mountains themselves but also the large and highly populated areas adjacent in the plains. The effects on glaciers have been very much in the public mind (as well as the scientific literature) recently, owing to an unfortunate quotation of a non-refereed source in an IPCC document, but other very important aspects of climate change in the Himalayan region have hardly received any attention. There is a need to develop a network for long-term data collection on various ecological and socio-economic aspects, not only of the Himalayan region but of the connected river basins, too. Many Himalayan countries do not have adequate scientific systems in place to do this research. And because of war, conflict and insurgencies, scientific cooperation between countries and regions is unlikely to improve. Evidently the politically unstable Himalayas are going to be one of the most vulnerable regions of the globe to climate change.

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