BUYING TIME:

A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems

CHAPTER 3: Montane

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Designing Strategies to Increase the Resilience of Alpine/Montane Systems to Climate Change

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MOUNTAIN REGIONS HAVE HIGH levels of biodiversity, due particularly to the compression of life zones into a small horizontal distance (Jeník, 1997; Körner, 2002). Many factors combine to create these high levels of biodiversity at the regional scale. One is the combination of steep altitudinal gradient, topographic variation and range of aspects, providing a rich variety of habitats at all scales. A second set of factors extends over geological time. As mountain ranges have developed, species have been able to migrate along new pathways, exploiting ecological niches as they have opened up. Yet interruptions in mountain-building phases, subsequent erosion, and changes in climate—especially ice ages—have also isolated species, so that they have evolved in different ways, a major reason for high levels of endemism in mountain areas. A third set of factors relates to human activities. Some mountain ecosystems have remained relatively unmodified by humans, while others have been heavily cultivated or otherwise altered for centuries or millennia. Regardless of degree of modification, montane regions often have higher levels of biodiversity than adjacent lowlands.

Although alpine terrain makes up only 3% of Earth's continents, it houses 10,000 species of higher plants, or 4% of the global total (Gough et al., 1994). Alpine plants are small in size, allowing a large number of individuals to live in the available microhabitats, leading to high levels of alpha diversity, which may be further increased by the isolation of individuals at the patch scale and frequent disturbance. Levels of genetic diversity are also high, due to polyploidy and a high degree of self-incompatibility (Körner, 2002). Despite this wealth of biodiversity, mountain ecosystems often have low resilience to anthropogenic impacts, taking longer to recover than many lowland ecosystems.

Mountains also play key roles in global climate processes, especially through interactions with convection and air mass systems, causing precipitation through the orographic effect, and by condensing and storing freshwater in the form of snow and ice (Bandyopadhyay et al., 1997). This function is important to billions of people who rely on mountains as 'water towers' for drinking and other domestic use, fisheries and agricultural irrigation, hydroelectric power, industrial use and transport or recreation (Mountain Agenda, 1998).

In addition to the variety of ecosystem services listed above, montane and alpine ecosystems also have a high intrinsic value in many of the world's mountain protected areas (Notaro and Signorello, 2001) and provide the 'capital' of tourism (Krippendorf, 1984). Consequently, changes in landscapes can have major effects on tourism markets, not only causing severe economic and social impacts for mountain people, but also affecting the budgets of mountain protected areas.

Finally, the fact that many alpine and montane ecosystems are situated on the boundaries between countries—and also the administrative areas of individual states—can lead to particular challenges in defining management strategies at the level of the ecosystem or mountain range. Thus, the alpine/montane biome is poorly placed to respond to conservation efforts in general, and climate change in particular.

Stresses and Vulnerabilities Due to Factors Other Than Climate Change

POLLUTION

Pollution from airborne contaminants affects all mountain areas, particularly those downwind of urban/industrial areas. Aerosols, which enter the snowpack and hydrological system via precipitation often far from their source, can have a detrimental impact on the freshwater environment, reducing the quality of water in alpine lakes and therefore having negative impacts on biodiversity (Koinig et al., 1998). Over the past century, there has been a global increase in nitrogen deposition (Vitousek et al., 1997), as well as increases in the deposition of nitrates and sulfates at high-altitude sites (Döscher et al., 1995). Acidification of rainfall can kill or seriously damage trees and smaller flora and reduce feeding quality for wildlife (Hamilton et al., 1997). High levels of tropospheric ozone can reduce the growth of plants and mosses and may affect the relative competitiveness of species (NEGTAP, 2001). Conversely, stratospheric ozone depletion due to anthropogenic emissions allows higher and more biologically damaging levels of ultraviolet radiation to reach Earth's surface, with negative effects on both flora and fauna (Bjorn et al., 1998; Blaustein et al., 1995; Kiffney et al., 1997).

AGRICULTURE

Agricultural activities often extend up mountainsides and have important effects on mountain environments, including poisoning of groundwater by agricultural chemicals or slurry and numerous physical impacts such as the construction of vehicular tracks or the installation of more agri-industrial forms of processing. High-altitude soils are thin and are therefore much more sensitive to disturbance, and take much longer to recover. Grazing and burning in many of the world's upland areas have reduced the biodiversity of mountain pastures (Körner, 2002), and in these sensitive areas much of the natural land cover has been significantly altered. The changes associated with agricultural abandonment often have a role in increasing the vulnerability of alpine/montane areas, particularly where the balance of the water supply is altered, or the stability of steep or terraced terrain is not maintained (MacDonald et al., 2000). Conversely, some alpine plants have extended locally into grasslands opened up by burning and grazing by introduced herbivores in New Zealand (Halloy and Mark, 2003) and other parts of the world. Thus, through a series of complex processes, agriculture has both reduced the extent of natural alpine and montane communities and allowed their extension into previously unavailable terrain.

FORESTRY

Forest plantations, often composed of alien species, are common in alpine and montane regions. Many aspects of forestry alter runoff and drainage patterns; forest road construction, planting, thinning, and harvesting can lead to the contamination of watercourses with sediments, machine oils, and other contaminants. (Hamilton and Bruijnzeel, 1997). Forestry also affects natural successional patterns, decreasing habitat area for species that depend on more established, old-growth forests. As with agriculture, forestry activities have also increased the extent of many alpine and montane habitats, allowing a downslope expansion into areas from which forests have been removed by cutting, burning, and/or grazing (Wielgolaski, 1997).

FRESHWATER ABSTRACTION

People whose supply of freshwater depends on mountain areas are often far removed from those areas, and thus relatively unaware of negative impacts of their water use on mountain ecosystems. Vulnerabilities associated with freshwater abstraction from mountain systems relate to the alteration of river channels; the construction of dams; and over-abstraction for water-thirsty cities and agriculture, often far downstream (Bandyopadhyay et al., 1997). All of these factors can influence aquatic and riparian habitat and the species dependent on them; as well as groundwater resources, sometimes over large areas.

TOURISM AND RECREATION

Tourism-related development affects diverse mountain environments, although it must be recognised that this phenomenon is distributed very unevenly at vary spatial scales across the world's mountain ranges (Price et al., 1997). Erosion, fires, trampling or other loss of flora by people, horses, and off-road vehicles, hunting and fishing, disturbance of fauna (the presence of people in and flying above habitats), and pollution (litter and human waste) are all serious problems related to human recreational use of mountain ecosystems (Buckley, 2000). Soil and biological systems in alpine/montane environments take far longer to recover from such impacts than in the lowlands (Gordon et al., 1998), and are therefore more vulnerable to such disturbances. Some high-impact mountain tourist industries, such as skiing and snowboarding resorts, may experience strong declines in days of operation due to climate change.

INFRASTRUCTURE DEVELOPMENT

Communications facilities (towers and masts for radio, TV, mobile phones, military communications, etc.) have been installed on many mountains. In most cases, this involves the construction of a road, which removes and damages habitat and may lead to long-term soil erosion. The road is then often used for access not only for the maintenance of the communications facilities, but also for hunting and other recreational activities. All of these activities may endanger populations of animals and plants, especially endemic species restricted to summits.

ALIEN SPECIES

Particularly because of their isolation, mountain species are often not able to compete with alien species, especially when their introduction is linked to habitat destruction. This is a problem in many mountain areas, but particularly those on isolated islands such as those of Hawaii (Loope and Giambelluca, 1998) and New Zealand (Halloy et al., 2001).

Present and Future Stress and Vulnerability Due to Climate Change

Increased concentrations of atmospheric CO_2, the primary cause of climate change, are likely to affect the physiology of alpine and montane plants. The exact outcomes are unclear, and will vary from species to species and be affected by factors such as inter-specific competition, grazing, physical site conditions, and levels of nitrogen deposition (Körner, 1999). As mountain climates are generally characterised by great variability and cycles at both diurnal and seasonal scales, some mountain biota are already stressed, which will influence their response not just to CO_2, but to all aspects of climate change (Price and Haslett, 1995).

ECOLOGY

A likely impact of climate change on mountain environments is upslope altitudinal migration of vegetation climatic belts, generally—but not always—leading to a decrease in their area, and the loss of the coldest climatic zones at the summits (Halpin, 1994). Thus all affected zones will experience increased vulnerability (Parry, 2000). Migration of vegetation zones around mountains to a different aspect is also possible, with implications for certain floral assemblages such as lichens, which depend greatly on living on a certain aspect for maximum insolation. Migration is typically severely restricted as a spatial response in mountain areas, however, because of their topography (Huntley and Baxter, 2002) and, often, the availability of suitable soils (Theurillat et al., 1998). Thus upslope migration will probably result in the contraction and fragmentation of populations of plants and associated fauna in the present montane, alpine, and nival belts. A key factor in the survival of plant populations will therefore be their dispersal capabilities, which tend to be low in alpine species; for instance, only 35% of alpine specialist plants in New Zealand were capable of long distance dispersal, as compared to 65% of non-specialists (McGlone et al., 2001). This is one of a range of key characteristics that make many alpine and montane species particularly sensitive to changes in climate—other characteristics are that they are: at the edge of their range; geographically localised; genetically impoverished; slow reproducers; or highly specialised (McNeely, 1990).

Changes in season length, and particularly earlier snowmelt dates and higher soil temperatures, could affect flowering and other aspects of plant phenology (Dunne et al., 2003; Thórhallsdóttir, 1998), as well as the annual cycles of pollinators, disease-causing insects, and other organisms. Equally, alien and invasive plant species may benefit more from climate change than native species, to the detriment of the latter (Dukes and Mooney, 1999). All of these trends will cause changes in inter-specific competition: some species will do better, but others will die. Thus, plant community composition will change, and some species that are now relatively uncommon, existing in isolated patches, will increase in abundance. Thus, while some species will benefit from climate change, others—particularly rare and endemic species—are likely to gradually become extinct, beginning with those found only at the highest altitude (Halloy and Mark, 2003). The impact on montane and alpine floral diversity could therefore be significant, especially in isolated mountain ranges (Körner and Spehn, 2002).

As current habitats change and are lost, fauna will also have to adapt or be forced to migrate upwards and polewards, following the altitudinal and latitudinal shifts of climate and vegetation belts, in order to survive. For insectivorous and carnivorous animals, the combination of climate and land-use change may lead to the loss of key elements of their diet, for both year-round residents and migrants that arrive earlier because of climate change, as shown for robins migrating to the Rocky Mountains of Colorado (Inouye et al., 2000). Also, as mentioned earlier, migration is a restricted strategy for isolated mountain areas or those at the continental margins (e.g., the Scandinavian mountains, the New Zealand mountain ranges, or the northern Rocky Mountains in Alaska). Thus, predicting rates of change in populations of both flora and fauna is highly complex, depending not only on changes in climate but on changes in biotic interactions as has been shown, for instance, for amphibians at Monteverde, Costa Rica (Pounds et al., 1999).

CRYOSPHERE

The shrinkage of glaciers is a global phenomenon, and rates of retreat are generally accelerating (Haeberli et al., 1999). Tropical glaciers are particularly sensitive because of the lack of seasonality and the fact that ablation is year-round (Arnell and Liu, 2001). In a number of mountain areas, the rapid melting of glaciers is leading to an increased risk of glacier lake outburst floods (GLOFs), which cause total destruction of habitats along affected watercourses, as well as loss of life and severe damage to infrastructure (Richardson and Reynolds, 2000). The melting of permafrost will lead to slope instability, loss of foundation stability for structures, and increased damage from freeze-thaw cycles (Haeberli, 1995).

For every °C increase in temperature, the snowline rises in altitude about 150 m (Parry, 2000). As a result, less snow will accumulate at lower elevations than at present. However, there could be more snow accumulation above the freezing level as both precipitation and temperatures increase. This may cause more frequent avalanches (Extreme events, pg. 94) and hinder the movement of large ungulates and skiers, but at the same time provide added protection to small plants and mammals (Scott and Suffling, 2000). In general, the trend will be for the snowpack to become unstable, snowpack duration to be reduced, and the profile of permanent snowpatches to change. These phenomena already appear to be resulting in changes in the emergence dates of marmots in the Rocky Mountains of Colorado (Inouye et al., 2000) and decreases in the area and occurrence of plant communities and endemic mammals in the Australian Alps (Green and Pickering, 2002).

Secondary effects of cryospheric dynamics are mainly with regard to hydrology. In alpine lakes in Norway, increased winter snowfall negatively correlates with the growth of brown trout *(Salmo trutta)* (Borgstrom, 2001). More generally, increased melt from receding glaciers and icefields will also increase water flows initially, although this effect will subside as the glaciers disappear. This will occur relatively quickly in the temperate mountain regions, and even faster in the tropics. Changing storage and release rates for precipitation will alter the timing of peak flows downstream; populations of aquatic species relying on late summer and early autumn melt may go extinct (Murray, pers. comm.). At the same time, a longer snow-free season, leading to a longer dry period, may lead to increased fire frequency.

HYDROLOGY

Hydrological stresses derive from the dependence of terrestrial, riparian, and aquatic ecosystems on freshwater from mountain sources. Changing precipitation patterns have been recorded world-wide (Folland and Karl, 2001) and inevitably affect runoff patterns, as will the changes in cryospheric dynamics noted above. As a greater proportion of total precipitation falls as rain rather than snow, the lag time due to snow precipitation and storage until meltwater enters the river system is reduced; in addition, melting glaciers will add a further volume of water into the systems until they too are gone. Then overall flow will decrease dramatically and become more variable (Arnell and Liu, 2001).

Increases in flows tend to increase sediment transport, turbidity, and bank erosion. Conversely, decreases in flows can increase pollution loads. Droughts, or decreased and earlier runoff from snow and ice melt may have important impacts on fish populations, especially those that rely on adequate late summer and early autumn flows for spawning (Levy, 1994). Changes in the seasonal distribution of precipitation may have other effects; for instance, an increase in summer precipitation could affect seed formation in species which have evolved to set seed during a dry summer period (Murray, pers. comm.). Given the importance of mountain water to downstream populations and economies, decreased and less reliable runoff may lead to increased demands for water storage in alpine and montane areas.

EXTREME EVENTS

In addition to more variable precipitation, it is predicted that the incidence of severe storms, floods, droughts and—in tropical and subtropical areas—tropical storms and hurricanes will increase (Arnell and Liu, 2001). Increases in flooding frequency are perhaps among the most feared physical impacts of climate change (Arnell, 1996), with critical impacts for ecosystems, human populations, and infrastructure in mountain areas and downstream. However, there have been few studies of this problem, mainly due to the difficulties involved with identifying credible scenarios for changes in flood-producing climatic events. Furthermore, many floods have multiple causes; they may be purely a product of rainfall or snowmelt or a combination of the two (Arnell and Liu, 2001). Impacts of floods can include greatly increased sediment loads and bedload transport and river channel scour, with losses in riparian ecosystems and negative impacts on aquatic flora and fauna (Wohl, 2000). Conversely, low summer flows and droughts also have negative impacts on riparian and aquatic ecosystems, and cause reductions in water storage, which could lead to demands for new storage infrastructure.

Rockfalls, landslides, and debris flows are likely to increase as a result of increases in precipitation or porewater, or by increased mechanical weathering, with release zones at higher altitudes (Rebetez et al., 1997). As mentioned earlier, more frequent and/or larger avalanches will result from changes in weather patterns, including more frequent high-intensity winter storms, and other changes in the cryosphere or permafrost layers (Evans and Clague, 1997). For both landslides and avalanches, there would be changes in runout zones, which would be likely to increase in area; the vegetation would be kept at earlier successional stages. This could be beneficial for species adapted to these habitats (Suffling, 1993). Increased avalanche management could scare wildlife and affect patterns of visitor use, as they might not wish to visit areas where active avalanche control is being practiced (Murray, pers. comm.).

OTHER CURRENT OR FUTURE STRESSES

There are a host of additional stresses that may affect montane systems as climate change progresses. These include:

- soil changes, with influences on the growth of plants (Kundzewicz and Parry, 2001; Theurillat et al., 1998);
- changes in fire frequencies, with effects on heathlands, grasslands and forest ecotones (Gitay et al., 2001);
- changes in cloudiness, humidity, and precipitation in areas covered by tropical montane cloud forests, and resultant changes in these ecosystems and associated hydrological regimes (Foster, 2001);
- increasing wind velocities, especially associated with intensified tropical cyclones (Giorgi and Hewitson, 2001) affecting evapotranspiration rates, fire probabilities, wind erosion, etc.;
- changes in populations of insects and diseases and their impacts on host plant or wildlife populations (Scurrah, pers. comm.), and the effect of the spread of malaria, leishmaniasis, dengue fever and other diseases on tourism and travel markets in mountain areas currently free of these diseases (McMichael and Githeko, 2001).

Potential Adaptation Options

Adaptation is a potentially useful tool to alleviate some of the negative impacts of climate change, or to take advantage of the positive effects. Adaptation will not halt climate change; rather, it is a strategic tool to manage vulnerability and alleviate impacts to ecosystems. Adaptations can be either in response to observed climate changes or anticipatory. Anticipatory adaptation is more difficult as it relies on sound scientific predictions of the likely impacts of climate change in specific areas, but there is often great uncertainty about these effects, particularly in mountain areas (Smith, 1997). However it is very unlikely that adaptation after the fact could prove successful.

Mountain areas are characterized by a great diversity of situations: ecological, economic, cultural, administrative, political, etc. There is also great diversity in the number and extent of protected areas in particular mountain ranges. Many mountain ranges have no protected areas (e.g., the Atlas, Papua New Guinea, mountains of Myanmar), and existing reserves often protect only the summits with no provisions for connectivity among reserves or the maintenance of entire ecosystems (Hamilton, 2002). Climate change provides an added impetus to the need to address the conservation of alpine and montane biodiversity at regional and global scales, recognizing that, as many mountains are the frontiers between protected areas, administrative areas or states, transboundary cooperation is often necessary.

IDENTIFYING FUTURE CHANGE

General Circulation Models (GCMs) have been widely used to try to predict climate change. When coupled with atmosphere-ocean circulation theories (Atmosphere-Ocean General Circulation Models or AOGCMs), these are the most powerful tools currently available for climate change prediction (Giorgi and Francisco, 2001) (although see Hannah 2003, this volume regarding Regional Circulation Models). They are most useful at the regional scale: e.g., sizeable portions of continents, such as northern Europe, or western North America. However, as mountain terrain and microclimates are complex systems with many interlinkages and autovariations, prediction models may become insufficient, a problem exacerbated by the fact that few mountain ranges have adequate data for validation (Beniston et al., 1997; see discussion by Hannah, this volume, on strengths and weaknesses of models). While different climate models are generally in agreement on certain issues, such as an intensified summer monsoon (Cusbasch and Meehl, 2001), they also predict quite different futures for the same region not only in terms of temperature and precipitation (Hay et al., 2000; Whetton et al., 2001), but also the frequency of El Niño events (Cusbasch and Meehl, 2001), which are key drivers for the climates of sub-tropical and tropical mountain regions. Nevertheless, such models have been used to predict environmental changes and species distribution under future climates in mountain areas, e.g., in Canada (Scott and Suffling, 2000), Mexico (Townsend Peterson et al., 2002) and Tibet (Ni, 2000).

Other approaches for defining possible future climates include scenario techniques (e.g., Parry et al., 1988), which may be more appropriate in mountain regions as climatic data are generally temporally and spatially limited (especially at higher altitudes), yet much local expert knowledge is often available. Scenario modeling approaches have been used to evaluate the potential distribution of mammals on isolated mountains in the southwest USA (McDonald and Brown, 1992); alpine plants in New Zealand (Halloy and Mark, 2003), South Africa (McDonald et al., 2002), Norway (Sætersdal and Birks, 1997), and the Alps (Gottfried et al., 1999; Lischke et al., 1998); and plant species and vegetation types in western North America (Fagre and Peterson, 2002).

STRATEGY DESIGN

It is vital to identify what is to be protected: which species, species assemblage(s), habitat(s), or landscape(s) should take priority? In alpine and montane zones, there is likely to be competition between several ecosystem types which could become established under altered climate regimes, and these often require very different management strategies (Price and Haslett, 1995). For those concerned with conservation, it is also important to recognize the need for the continued availability of key resources, including personnel and infrastructure, and the need to operate within a regional cultural and economic context. According to the Intergovernmental Panel on Climate Change (IPCC) (Gitay et al., 2001), adaptation options are limited in mountain areas because these biomes are the most vulnerable and will respond most strongly to changes in climate.

To understand likely vulnerabilities of natural and cultural resources to climate change, it may be appropriate to conduct an integrated assessment (e.g., Yin and Cohen, 1994) or climate sensitivity analysis (Peine and Berish, 1999), including the following stages:

- identify ecosystems, ecotones, species, and ecosystem processes that are particularly sensitive to climate change;
- evaluate protected area and forest resource monitoring programs as to their capability to detect ecosystem dynamics associated with climate change;
- utilise results of the analysis for education materials and services;
- devise a regional research and monitoring agenda;
- identify all significant non-climate related threats and plans to minimize them.

While quantitative approaches will be essential at all of these stages, they should be complemented with approaches drawing on traditional ecological knowledge (Thomson et al., 2000). Knowledge derived from long-term experience is important for addressing an issue as long-term and complex as climate change.

Possible adaptation options are grouped into eight sets below: protected areas, conservation networks, bioregional approaches, participation and active management, monitoring, infrastructure, supporting policies and minimizing non-climate-related stresses. In all cases, the key principle is to maintain the maximum variety of possible options, recognizing that they will not necessarily help species and ecosystems at the highest elevations. In addition, means to minimize non-climate stresses (Stresses and vulnerabilities, pg. 90)—for instance, minimizing pollution and pressures from land-use practices and change, appropriate and controlled tourism and infrastructure development, limiting water use, control of alien species—should always be implemented as integral components of adaptation strategies.

PROTECTING ADEQUATE AND APPROPRIATE SPACE

Given the prospect of upslope shift of habitat space, one key element of adaptation is to ensure that each mountain protected area—and especially its core zone(s) if zoning is practised—has as great a range of elevations, slope aspects, and habitat mosaics as possible, and is as large as possible. The principle of maximizing diversity also applies to protected area systems, which should include several replicates of different ecosystem types, to permit adjustment to rapid climate shifts and survive major events (e.g., hurricanes and tropical storms) (Barborak, pers. comm.). Consideration may be given to designing mountain protected areas to be climatic refugia, in particular where this has occurred in the past, so that these areas can act as potential habitat for climatic migrant species. This requires, however, adequate connectivity within the landscape (Markham and Malcolm, 1996), as discussed below.

CONSERVATION NETWORKS

A conservation network is a further strategy towards the protection of landscapes, habitats, or species threatened by climate change (Bennett, 1999; Bridgewater, 1996; Hannah, 2001). Adaptation is allowed in such a network through species migration via buffer zones, protected corridors (especially along watercourses), matrices or landscape connections, 'stepping stones' through anthropogenically altered terrain (e.g., agricultural land, planted forests, urban areas). Such networks need to be designed carefully—in mountain areas this is particularly important where spatial variability and migration routes for range-shifts are limited. Protected area systems should be designed to maximise connections, corridors or landscape units. These must be able to cross political boundaries, especially in mountains, which often form such boundaries. Such a system must be both dynamic and large-scale (regional to global), requiring regional co-ordination, a focus on biodiversity hotspots, and a proactive adaptation strategy (Hannah, 2001). Such networks are under development in a number of mountain regions, including the Albertine Rift, the Andes, the Apennines, the Australian Alps, the Rocky Mountains, and the Western Ghats (Hamilton, 2002).

At the global scale, one key initiative is UNESCO's World Network of Biosphere Reserves (WNBR). There are currently 408 sites in 94 countries; nearly half of these are in mountain areas (Price, 2001). They differ from national protected areas in that they are designated internationally, forming a global network; have transitional zones ('zones of cooperation') with flexible boundaries; and can straddle international boundaries. Integrated monitoring of biosphere reserves is being undertaken at the global scale through the Biosphere Reserve Integrated Monitoring Program (BRIM), which includes floral, faunal, and socio-economic data. While not all biosphere reserves are currently managed according to the principles laid down in the Statutory Framework of the WNBR

(Price, 2002), they do represent a unique structure for addressing many of the adaptation options listed previously, and for global exchange of experience and best practice. A new program involving mountain biosphere reserves within the Mountain Research Initiative is currently under development (www.mri.unibe.ch).

BIOREGIONAL APPROACHES

From the Convention on Biological Diversity to the EU Natura 2000 and other regional networks to smaller-scale action plans, biodiversity strategies now acknowledge that bioregional approaches are necessary (Johnson et al., 2001). They can be used as a tool for adapting to global climate change in the following ways:

- large regions accommodate full ecosystem functions and habitats, fostering ecological viability over the long term;
- different zones can be used to experiment on and study the impacts of climate change;
- monitoring can happen in a more controlled manner in protected core areas;
- adaptive management responses can be tried in both buffer zones and more widely within the bioregion, especially in areas adjacent to protected areas;
- effective partnerships involving many stakeholders take account of the multiple needs of the strategic approach, including economic sustainability and social acceptance;
- strategic models can be developed to work within limits imposed by increasing fragmentation.

Bioregional strategies allow managers to establish and maintain protected area boundaries which are flexibly designed to adjust to changing climatic regimes, and if necessary, to move upslope with protected habitat(s), providing buffer zones and refugia. Such approaches also take into consideration resource uses at the regional scale, recognising that climate changes will result in changed pressures from local people as conditions for cultivation and settlement change (Price and Barry, 1997).;

Particularly because alpine and montane ecosystems do not usually cover large contiguous areas, their conservation has to be considered within the context of the management of surrounding forest ecosystems (whether or not within protected areas) and other regional land uses, using conservation networks and bioregional approaches. Again, the great variety of land ownership and use patterns in mountain regions around the world makes it difficult to be prescriptive. Nevertheless, one relatively common feature of mountain regions is communal ownership and/or management, particularly at higher altitudes, especially for grazing. Even where these institutions have lapsed or been removed by government action, the cultural roots often remain and can be built on. This is a critical link to modern approaches to conservation, which recognise the need to involve local people in the management of projected areas (e.g., Stevens, 1997; Stolton and Dudley, 1999), whether as park staff or involved in economic activities based on either the utilisation of resources within protected areas (e.g., grazing, collecting plants and mushrooms, hunting) or providing services to tourists. In Hawaii, the value of the traditional ahupua`a system, involving experts and diverse stakeholders, has been specifically recognized as appropriate for adapting to climate change (Shea et al., 2001).

PARTICIPATION AND ACTIVE MANAGEMENT

All of the spatial approaches mentioned above require the explicit consideration of land uses within and adjacent to mountain protected areas, and therefore the active involvement of local people as partners in the conservation of biodiversity. The involvement of local people in conservation is particularly important in mountain areas, where spatial networks are essential to minimise the risk of loss of small isolated populations and to allow more mobile species to move along altitudinal and ecological gradients. Equally, people whose families have been established in a mountain area for many generations will have extensive traditional ecological knowledge with regard to issues such as responses to past periods of environmental change (Glantz, 1988) and the existence of key resources, such as the last streams to dry up in periods of drought. Especially, but not only, in developing countries, achieving conservation goals in mountain areas—whose people are often among the poorest at national scales (Huddleston et al., 2003)—may require the coordination of a number of approaches aimed at improving local people's livelihoods in order to decrease their dependence on natural resources. This can include supporting local people in the management and conservation of natural resources, providing academic and skill enhancement training or financial support, or investing in small businesses or infrastructure, such as micro-hydro schemes (Sherpa, pers. comm.). NGOs often have key roles to play in such initiatives. They, the protected area, and other conservation-oriented personnel may be involved in specific management strategies such as:

- prioritizing actions to protect key threatened species, particularly 'keystone species', such as important pollinators or seeders. This is of particular value in mountain areas where altitudinal range may be utilised to maintain high levels of biodiversity in the face of greater biological redundancy;

- protecting valuable species in situ and avoiding or reducing additional stress on their habitats, for instance through the control of grazing or recreational pressures;

- constructing snow barriers to 'catch' snow potentially increasing the likelihood that snow is available for plants and animals that depend on it during the winter months (Good, pers. comm.);

- modifying site conditions to ensure that decreasing plant communities are replaced by other naturally occurring communities of lesser extent, e.g., snowpatch communities by others that occur naturally in areas with little or no snow—an approach comparable to that implemented successfully in highly eroded areas following many years of domestic stock grazing in the Australian Alps (Good, pers. comm.);

- propagating endangered species *ex situ* and, possibly, transplanting them to sites where they have a reasonable chance of survival (Good, pers. comm.; Halloy and Mark, 2003);

- management of invasive/alien species according to the strategy: 1) prevent any new introductions of invasives; 2) ensure early detection and eradication of new infestations; 3) contain any established populations that are too large to eradicate; 4) prevent the largest infestations from spreading (Wittenberg and Cock, 2001);

- releases of water from dams to allow the survival of riparian and aquatic populations and the continuity of key annual activities (e.g., fish spawning) (Parkstrom, pers. comm.).

MONITORING

A key element of every adaptation strategy must be to monitor both its implementation and the changes in the physical and biological environment (e.g., with long-term meteorological stations and regular biological surveys). Monitoring should be interdisciplinary and integrated, and is also necessary to assess model-based predictions (Fagre and Peterson, 2002). While specific monitoring approaches must be developed and implemented for individual protected areas and/or mountain ranges, it is also worth considering involvement in one or more of the relevant international programs that have been, or are being, developed for mountain areas.

The Global Observation Research Initiative in Alpine Environments (GLORIA) aims to establish an effective long-term observation network for detecting the effects of climate change on mountain biota on a global scale. The GLORIA Multi-Summit approach (Pauli et al., 2001) provides such a method, and is designed to compare biodiversity patterns along fundamental climatic gradients, vertically as well as horizontally. GLORIA is a contribution to Activity 1 of the global Mountain Research Initiative (Becker and Bugmann, 2001), developed within the context of the International Geosphere-Biosphere Programme (IGBP), International Human Dimensions Programme on Global Environmental Change (IHDP) and the Global Terrestrial Observing System (GTOS). It includes four activities:

1) Long-term monitoring and analysis of indicators of environmental change in mountain regions;

3) Integrated model-based studies of environmental changes in different mountain regions;

4) Process studies along altitudinal gradients and in associated headwater basins;

5) Sustainable land use and natural resource management

All of these activities, as well as those considered in the previous paragraphs, require suitably-trained on-the-ground, research, and management personnel. The knowledge of local people (‘traditional ecological knowledge’) may also be valuable both for monitoring and for developing testable hypotheses for research (Danby et al., 2003).

INFRASTRUCTURE

To facilitate adaptation measures, physical infrastructure is essential, particularly in the many mountain areas where accessibility is a challenge. Management for the survival of specific species and habitats—as well as travel, both seasonally or year-round—may require the stabilisation of slopes, especially after damage resulting from extreme events. Given the limited availability of resources, mapping of risks may be necessary to assist in prioritising actions (Rossi, pers. comm.).

POLICIES

The essential underpinning to all adaptation options comprises appropriate plans and policies, both for specific areas (e.g., protected areas and administrative regions) and for sectors and agencies (Kumaran, pers. comm.). These need to identify problems and priorities, and include appropriate legal provisions and economic instruments to ensure their application. Again, given the fact that many alpine and montane ecosystems straddle state or administrative frontiers, transboundary instruments (Sandwith et al., 2001; Villeneuve et al., 2002) may often be necessary.

MINIMIZING NON-CLIMATE-RELATED STRESSORS

Interactive effects between climate-related and non-climate-related stressors are common, and organisms and communities that are already stressed may be less resistant and resilient to the challenges posed by a changing climate. Thus any attempts to mitigate effects of climate change must consider ways to reduce the influence of other anthropogenic stressors. Siting reserves in remote locations relatively unaffected by human activities is one way to do this; when creating reserves in less pristine environments, every effort should be made to control human impacts. Even human activities that have been sustainable in the past may cease to be so as climate change alters mountain ecosystems which, as discussed earlier, tend to be less resilient than other terrestrial ecosystems even under the best of conditions. It may be necessary to revisit extractive and development uses of montane regions, and increase our efforts to further limit them. Issues such as water abstraction may require particular attention as human uses compete with biodiversity needs as water becomes scarcer in mountain regions.

Implementation of actions and/or policies

As noted in Policies section, above, adequate information and appropriate plans and policies, including economic instruments, are essential for adaptation. Individual protected areas require effective management plans which are implemented, but it is critical that these are embedded in, and supported by, government policies that recognise that the conservation of biodiversity requires appropriate information and has to be undertaken at the landscape scale, within the context of regional economies—and that many environmental services and other benefits derive from the wise management of mountain resources, particularly those of protected areas (Phillips, 1998). This means that regional and national planning and land-use plans and policies should incorporate guidelines and indicators that ensure that biodiversity conservation targets are met—as required under the Convention on Biological Diversity to which most governments are signatories.

ECONOMIC AND LEGAL INCENTIVES

To assure the implementation of such plans and policies, new economic approaches are being developed. Examples include schemes in Colombia, Costa Rica, and Ecuador under which downstream irrigators and hydro-electricity companies pay upstream landowners to ensure reliable flows (Koch-Weser and Kahlenborn, 2004); and other schemes in Latin America through which landowners are paid to maintain biodiversity through national funds deriving from energy taxes, debt swaps, and carbon offsets (Barborak, pers. comm.). While the funds deriving from these schemes have mainly been provided to people owning forests (Pagiola et al., 2002), the same people often own or manage land higher in watersheds; and grazing regimes often have important consequences on runoff patterns, as well as biodiversity. Key points are that:

- economic incentives are generally needed to ensure the stewardship of private land and water resources within wider conservation networks, and must be supported by appropriate legal mechanisms;

- compensation payments must be based on recognition by the ‘downstream’ beneficiaries of the (increasing) scarcity of resources for which they are willing to pay compensation;

- these payments should be high enough to serve as an incentive to upstream land owners/managers to change their practices; often payments should be linked to the provision of other services and facilities, e.g., for education, health, and access;

- the long-term success of conservation strategies, especially outside protected areas, requires understanding and acceptance—thus existing laws, customs, and institutions must be taken into account, and targeted education is often essential;

- some key areas of land need to be managed for specific conservation goals; this may require purchase, which implies the availability of appropriate funds (Barborak, pers. comm.);

- funding has to be consistent; there have been too many ‘boom-and-bust’ large projects (Kumaran, pers. comm.).

FINANCIAL RESOURCES

In many mountain areas around the world, tourism is a major element of regional economies (Godde et al., 2000). Revenues from tourism are both of importance for development, and also current or potential sources of income for biodiversity conservation, whether in protected areas or in wider networks. The need to link biodiversity conservation and development is evident in the many projects of the Global Environmental Facility (GEF) in mountain ecosystems, which are the topic of one of the 10 operational programs with regard to biological diversity within the GEF Operational Strategy. In 2002 this program was funding 107 mountain projects—including initiatives in Central and South America and the Caribbean, East and Southern Africa, and Central Asia (Global Environment Facility, 2002). Also of note, given the likelihood of the expansion of invasive species into montane and alpine zones, is the Secretariat of the Global Invasive Species Program, supported by the World Bank, with projects in areas such as the mountain fynbos of South Africa (World Bank, 2002).

As well as multilateral funding, bilateral and NGO funding can be directed towards activities that contribute to adaptation in relation to climate change, again stressing the links between development (including tourism) and biodiversity conservation. Such activities may be within one country or at regional scales, though transboundary projects can run into funding difficulties where mountain ranges fall within more than one of the administratively-defined regions of a funding agency, e.g., the Albertine Rift which straddles both the East and Central African regions (Plumptre, pers. comm.). Funding, for instance through trust funds, may also be essential for the purchase of key parcels of land, e.g., adjacent to the core areas of existing protected areas, or to create corridors or buffer zones (Barborak, pers. comm.). National-level funding, from government agencies and/or NGOs, is essential for all aspects of adaptation, from research and monitoring through planning and land acquisition to active management activities.

Conclusion

Even if the resources can be found to implement many of the actions discussed above, with support from local people, governments, and the private sector, there are likely to be significant losses of many alpine and montane species in coming decades—though it should also be recognised that certain species will benefit from climate change. Climate change is a new factor of change affecting montane and alpine ecosystems and species, adding to the existing stresses described in Stresses and vulnerabilities section, pg. 90, deriving from local pollution, agriculture, forestry, freshwater abstraction, tourism and recreation, infrastructure development, and the introduction of alien species. Reductions in these direct stresses are an essential prerequisite to all adaptation strategies; to be ensured through actions at all levels from individual behavior to the effective implementation of national and international legal instruments.

Yet the key focus for adaptation is not in the mountains, but among the people, governments, and businesses of an increasingly urbanized planet whose people are ever more dependent both on the fossil fuels whose combustion causes climate change and on water deriving from mountain areas. To make these links, those responsible for mountain protected areas should take the lead in promoting the development of, and utilising, state-of-the-art technologies in alternative energy sources and energy conservation. These are often particularly appropriate in mountain areas because of their high solar radiation, steep watercourses, and windiness, and because costs of connection to regional or national grids and of transmission are high (Schweizer and Preiser, 1997). Similarly, state-of-the art methods of water use and management should be implemented in mountain protected areas. The implementation of such technologies locally will have minimal direct effect on alpine and montane ecosystems. However, well-illustrated, clear interpretative materials and programs addressed to the millions of people who visit mountain protected areas could have an important impact in raising awareness of the vital heritage they protect—and the ways in which it is endangered by climate change.

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Literature Cited

Arnell, N. 1996. *Global Warming: River Flows and Water Resources.* Wiley, Chichester.

Arnell, N. and Chunzhen Liu. 2001. Hydrology and water resources. *In* Canziani, O.F., Dokken, D.J., Leary, N.A., McCarthy, J.J. and White, K.S. (Eds.) Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge: 191-233.

Bandyopadhyay, J., J.C. Rodda, R. Kattelmann, Z.W. Kunzewicz and D. Kraemer. 1997. Highland waters—a resource of global significance. *In* Messerli, B. and Ives, J.D. (Eds.) Mountains of the World: A Global Priority. Parthenon, London: 131-155.

Becker, A. and H. Bugmann. 2001. Global Change and Mountain Regions: The Mountain Research Initiative. IGBP Report 49, IGBP Secretariat, Stockholm.

Beniston, M., H.F. Diaz and R.S. Bradley. 1997. Climatic change at high elevation sites: An overview. Climatic Change **36**:233-251.

Bennett, A.F. 1999. Linkages in the Landscape: The Role of Corridors and Connectivity in Wildlife Conservation. IUCN, Gland.

Bjorn, L.O., T.V. Callaghan, C. Gehrke, U. Johanson, M. Sonesson and D. Gwynn-Jones. 1998. The problem of ozone depletion in northern Europe. Ambio **27**:275-279.

Blaustein, A.R., B. Edmond, J.M. Keisecker, J.J. Beatty and D.G. Hokit. 1995. Ambient ultraviolet radiation causes mortality in salamander eggs. Ecological Applications **5**:740-743.

Borgstrom, R. 2001. Relationship between spring snow depth and growth of brown trout, *Salmo trutta*, in an alpine lake: predicting consequences of climate change. Arctic Antarctic and Alpine Research **33**: 476-480.

Bridgewater, P.B. 1996. Protected area management in the face of climate change. Parks **6**(2): 4-13.

Buckley, R.C., Pickering, C.M. and Warnken, J. 2000. Environmental management for alpine tourism and resorts in Australia. *In* Godde, P.M., Price, M.F. and Zimmermann, F.M. (Eds.). Tourism and development in mountain regions. CABI, Wallingford: 27-45.

Cusbasch, U. and G.A. Meehl. 2001. Projections on climate change. *In* Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell and C.A. Johnson (Eds.). Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge: 525-582.

Danby, R.K., D.S. Hik, D.S. Slocombe and A. Williams. 2003. Science and the St. Elias: an evolving framework for sustainable development in North America's highest mountains. The Geographical Journal 169: in press.

Döscher A, Gäggeler HW, Schotterer U, and Schwikowski M. 1995. A 130 years deposition record of sulfate, nitrate and chloride from a high-alpine glacier. *Water, Air, and Soil Pollution* **85**:603-609.

Dukes, J.S. and H.A. Mooney. 1999. Does global change increase the success of biological invaders? Trends in Ecology and Evolution **14**:135-139.

Dunne, J.A., J. Harte and K.J. Taylor. 2003. Subalpine meadow flowering phenology responses to climate change: integrating experimental and gradient methods. Ecological Monographs **73**:69-86.

Evans, S.G. and S.G. Clague. 1997. The impact of climate change in catastrophic geomorphic process in the mountains of British Columbia, the Yukon and Alberta. *In* Taylor, E. and Taylor, R. (Eds.). Responding to Climate Change in British Columbia and Yukon. British Columbia Ministry of Environment, Lands and Parks, and Environment Canada, Vancouver.

Fagre, D.B. and D.L Peterson. 2002. Modelling and monitoring ecosystem responses to climate change in three North American mountain ranges. *In* Körner, C and E.M. Spehn (Eds.). Mountain Biodiversity: A Global Assessment. Parthenon, New York and London: 249-259.

Folland, C.K. and T.R. Karl. 2001. Observed climate variability and change. *In* Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell and C.A. Johnson (Eds.). Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge: 99-181.

Foster, P. 2001. The potential negative impacts of global climate change on tropical montane cloud forests. Earth-Science Reviews **55**:73-106.

Giorgi, F. and Francisco, R. 2001. Uncertainties in the prediction of regional climate change. *In* Visconti, G., Beniston, M, Iannorelli, E.D. and Barba, D. (Eds.). Global Change and Protected Areas. Kluwer Academic Publishers, Dordrecht: 127-139.

Giorgi, F. and B. Hewitson. 2001. Regional climate information—Evaluation and projections. *In* Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell and C.A. Johnson (Eds.). Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge: 583-638.

Gitay, H., Brown, S., Easterling W. and Jallow, B. 2001. Ecosystems and their goods and services. *In* Canziani, O.F., Dokken, D.J., Leary, N.A., McCarthy, J.J. and White, K.S. (Eds.). Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge: 235-342.

Glantz, M.H. (Ed.). 1988. Societal Responses to Regional Climatic Change: Forecasting by Analogy. Westview, Boulder.

Global Environmental Facility. 2002. High Priorities: GEF's Contribution to Preserving and Sustaining Mountain Ecosystems. Global Environmental Facility, Washington DC.

Godde, P.M., M.F. Price and F.M. Zimmermann (Eds.). 2000. Tourism and Development in Mountain Regions. CABI Publishing, Wallingford.

Gordon, J.E., Thompson, D.B.A., Haynes, V.M., Brazier, V. and MacDonald, R. 1998. Environmental sensitivity and conservation management in the Cairngorm Mountains, Scotland. Ambio **27**(4):335-344.

Gottfried, M., Pauli, H., Reiter, K. and Grabherr, G. 1999. A fine-scaled predictive model for climate warming induced changes of high mountain plant species distribution patterns. Diversity and Distributions **5**:241-251.

Gough, L., J.B. Grace and K.L. Taylor. 1994. The relationship between species richness and community biomass: the importance of environmental variables. Oikos **70**:271-279.

Green, K. and C.M. Pickering. 2002. A scenario for mammal and bird diversity in the Snowy Mountains of Australia in relation to climate change. *In* Körner, C and E.M. Spehn (Eds.). Mountain Biodiversity: A Global Assessment. Parthenon, New York and London: 239-247.

Haeberli, W. 1995. Climate change impacts on glaciers and permafrost. *In* A. Guisan, J.I. Holten, R. Spichiger, L. Tessier (Eds.). Potential Ecological Impacts of Climate Change in the Alps and Fennoscandian Mountains: Geneva University Press, Geneva: 97-103.

Haeberli, W., R. Frauernfelder, M. Hoelzle and M. Maisch. 1999. On rates and acceleration trends of global glacier mass changes. Geografisker Annaler A *81A*: 585-591.

Halloy, S.R.P and A.F. Mark. 2003. Climate-change effects on alpine plant biodiversity: A New Zealand perspective on quantifying the treat. Arctic, Antarctic and Alpine Research *35*:248-254.

Halloy, S.R.P, A.F. Mark and K.J.M. Dickinson. 2001. Management of New Zealand's terrestrial biodiversity as a complex adaptive system. Complexity International 8: http://journal-ci.csse.monash.edu.au/ci/vol08/halloy02/

Halpin, P.N. 1994. GIS analysis of the potential impacts of climate change on mountain ecosystems and protected areas. *In* Price, M.F. and D.I Heywood (Eds.). Mountain Environments and Geographic Information Systems. Taylor and Francis, London: 281-301.

Hamilton, L.S. 2002. Conserving mountain biodiversity in protected areas. *In* Körner, C and E.M. Spehn (Eds.). Mountain Biodiversity: A Global Assessment. Parthenon, New York and London: 295-306.

Hamilton, L.S. and L.A. Bruijnzeel. 1997. Mountain watersheds—integrating water, soils, gravity, vegetation, and people. *In* Messerli, B. and Ives, J.D. (Eds.). Mountains of the World: A Global Priority. Parthenon, London: 337-370.

Hamilton, L.S., D.A. Gilmour and D.S. Cassells. 1997. Montane forests and forestry. *In* Messerli, B. and Ives, J.D. (Eds.). Mountains of the World: A Global Priority. Parthenon, London: 281-311.

Hannah, L. 2001. The role of a global protected area system. *In* Visconti, G., Beniston, M., Iannorelli, E.D. and Barba, D. (Eds.). Global Change and Protected Areas. Kluwer Academic Publishers, Dordrecht: 413-422.

Hay, L.E., R.L. Wilby and G.H. Leavesley. 2000. A comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States. Journal of the American Water Resources Association **36**:387-397.

Huddleston, B. et al. 2003. Towards a GIS-based Analysis of Mountain Environments and Populations. FAO, Rome.

Huntley, B. and Baxter, R. 2002. Climate change and wildlife conservation in the British uplands. *In* Burt, T.P., Thompson, D.B.A. and Warburton, J. (Eds.). The British Uplands: Dynamics of Change. Report No 319, Joint Nature Conservation Committee, Peterborough: 41-47.

Inouye, D.W., B. Barr, K.B. Armitage and B.D. Inouye. 2000. Climate change is affecting altitudinal migrants and hibernating species. Proceedings of the National Academy of Sciences **97**:1630-1633.

Jeník, J. 1997. The diversity of mountain life. *In* Messerli, B. and Ives, J.D. (Eds.) Mountains of the World: A Global Priority. Parthenon, London: 199-231.

Johnson, N., Miller, K. and Miranda, M. 2001. Bioregional approaches to conservation: local strategies to deal with uncertainty. *In* Handmer, J.W., Norton, T.W. and Dovers, S.R. (Eds.) Ecology, Uncertainty and Policy: Managing Ecosystems for Sustainability. Prentice Hall, Harlow: 43-65.

Kiffney, P.M., W.H. Clements and T.A. Cady. 1997. Influence of ultraviolet radiation on the colonization dynamics of a Rocky Mountain stream benthic community. Journal of the North American Benthological Society **16**:520-530.

Koch-Weser, M.R. and W. Kahlenborn. 2004. Legal, economic and compensation mechanisms in support of sustainable mountain development. *In* Price, M.F., A. Iatsenia and L. Jansky (Eds.). Key Issues for the World's Mountain Regions. UNU Press, Tokyo: in press.

Koinig, K.A., S. Sommaruga-Wögrath, R. Schmidt, R. Tessadri and R. Psenner. 1998. Acidification processes in high alpine lakes. *In* Haigh, M.J., J. Krecek, G.S. Rajwar and M.P. Kilmartin (Eds.). Headwaters: Water Resources and Soil Conservation. Balkema, Rotterdam: 45-54.

Körner, C. 1999. Alpine Plant Life: Functional Plant Ecology of High Mountain Ecosystems. Springer, Berlin.

Körner, C. 2002. Mountain biodiversity, its causes and function: an overview. *In* Körner, C and E.M. Spehn (Eds.). Mountain Biodiversity: A Global Assessment. Parthenon, New York and London: 3-20.

Körner, C and E.M. Spehn (Eds.). 2002. Mountain Biodiversity: A Global Assessment. Parthenon, New York and London.

Krippendorf, J. 1984. The capital of tourism in danger. *In* Brugger, E.A., Furrer, G., Messerli, B. and Messerli, P. (Eds.). The Transformation of Swiss Mountain Regions. Haupt, Bern: 427-450.

Kundzewicz, A.W. and M.L Parry. 2001. Europe. *In* Canziani, O.F., Dokken, D.J., Leary, N.A., McCarthy, J.J. and White, K.S. (Eds.). Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge: 641-692.

Levy, D.A. 1994. Potential Impacts of Global Warming on Salmon Production in the Fraser River Watershed. Climate Change Digest 94-04, Atmospheric Environment Service, Downsview.

Lischke, H., A. Guisan, A. Fischlin, J. Williams and H. Bugmann. 1998. Vegetation responses to climate change in the Alps: modeling studies. *In* Cebon, P., U. Dahinden, H.C. Davies, D. Imboden and C.C. Jaeger (Eds.). Views from the Alps: Regional Perspectives on Climate Change. MIT Press, Cambridge: 309-350

Loope, L.L. and T.W. Giambelluca. 1998. Vulnerability of island tropical montane cloud forests to climate change, with special reference to East Maui, Hawaii. Climatic Change **39**:503-517.

MacDonald, D., J.R. Crabtree, G. Wiesinger, T. Dax, N. Stamou, P. Fleury, J.G. Lazpita and A. Gibon. 2000. Agricultural abandonment in mountain areas of Europe: environmental consequences and policy response. Journal of Environmental Management **59**:47-69.

Markham, A. and J. Malcolm. 1996. Biodiversity and wildlife conservation: adaptation to climate change. *In* Smith, J., Bhatti, N., Menzhulin, G., Benioff, R., Campos, M., Jallow, B. and Rijsberman, F. (Eds.). Adaptation to Climate Change: Assessment and Issues. Springer, New York: 384-401.

McDonald, D.J., G.F. Midgley and L. Powrie. 2002. Scenarios of plant diversity in South African mountain ranges in relation to climate change. *In* Körner, C and E.M. Spehn (Eds.). Mountain Biodiversity: A Global Assessment. Parthenon, New York and London: 261-266.

McDonald, K.A. and J.H. Brown. 1992. Using montane mammals to model extinctions due to global change. Conservation Biology **6**: 409-415.

McGlone, M.S., R.P. Duncan and P.B. Heenan. 2001. Endemism, species selection and the origin and distribution of the vascular plant flora of New Zealand. Journal of Biogeography **28**:199-216.

McMichael, A. and A. Githeko. 2001. Human health. *In* Canziani, O.F., Dokken, D.J., Leary, N.A., McCarthy, J.J. and White, K.S. (Eds). Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge: 451-485.

McNeely, J.A. 1990. Climate change and biological diversity: policy implications. *In* Boer, M.M. and De Groot, R.S. (Eds.). Landscape-ecological Impact of Climatic Change. IOS Press, Amsterdam: 406-429.

Mountain Agenda. 1998. Mountains of the World: Water Towers for the 21st Century. Mountain Agenda, Bern.

National Expert Group on Transboundary Air Pollution (NEGTAP). 2001. Transboundary Air Pollution: Acidification, Eutrophication and Ground-level Ozone in the UK. Centre for Ecology and Hydrology, Edinburgh.

Ni, J. 2000. A simulation of biomes on the Tibetan Plateau and their responses to global climate change. Mountain Research and Development **20**:80-89.

Notaro, S. and Signorello, G. 2001. Economic evaluation of Italian National Parks and Natural Areas. *In* Visconti, G., Beniston, M, Iannorelli, E.D. and Barba, D. (Eds.). Global Change and Protected Areas. Kluwer Academic Publishers, Dordrecht: 359-372.

Pagiola, S., J. Bishop and N. Landell-Mills (Eds.). 2002. Selling Forest Environmental Services: Market-based Mechanisms for Conservation and Development. Earthscan, London.

Parry, M.L. (Ed.). 2000. Assessment of the potential effects and adaptations for climate change in Europe: The Europe ACACIA project. Jackson Environment Institute, University of East Anglia, Norwich.

Parry, M.L., T.R. Carter and N.T. Konijn (Eds.). 1988. The Impact of Climatic Variations on Agriculture (2 vols.) Kluwer, Dordrecht.

Pauli, H., M. Gottfried, D. Hohenwallner, K. Hülber, K. Reiter and G. Grabherr (Eds.). 2001. GLORIA - Global Observation Research Initiative in Alpine Environments: The Multi-Summit Approach Field Manual. University of Vienna (http://www.gloria.ac.at/res/gloria_home/)

Peine, J.D. and C. Berish. 1999. Climate change: Effects in the Southern Appalachians. *In* Peine, J.D. (Ed.). Ecosystem Management for Sustainability: Principles and Practices Illustrated by a Regional Biosphere Reserve Cooperative. Lewis, New York: 397-415.

Phillips, A. (Ed.). 1998. Economic Values of Protected Areas: Guidelines for Protected Area Managers. WCPA Best Practice Protected Area Guidelines No. 2, IUCN, Gland and Cambridge.

Pounds, J.A., M.P.L. Fogden and J.H. Campbell. 1999. Biological response to climate change on a tropical mountain. Nature **398**:611-615.

Price, M.F. 2001. The World Network of Biosphere Reserves: a Flexible Structure for Understanding and Responding to Global Change. *In* Visconti, G., Beniston, M., Iannorelli, E.D. and Barba, D. (Eds.). Global Change and Protected Areas. Kluwer Academic Publishers, Dordrecht: 403-411.

Price, M.F. 2002. The Periodic Review of Biosphere Reserves: A mechanism to foster sites of excellence for conservation and sustainable development. Environmental Science and Policy **5**(1):13-19.

Price, M.F. and Barry, R.G. 1997. Climate change. *In* Messerli, B. and Ives, J.D. (Eds.). Mountains of the World: A Global Priority. Parthenon, London: 409-445.

Price, M.F. and Haslett, J.R. 1995. Climate change and mountain ecosystems. *In* Allen, N.J.R. (Ed.). Mountains at Risk: Current Issues in Environmental Studies. Manohar, New Delhi: 73-97.

Price, M.F., L.A.G. Moss and P.W. Williams. 1997. Tourism and amenity migration. *In* Messerli, B. and Ives, J.D. (Eds.) Mountains of the World: A Global Priority. Parthenon, London: 249-280.

Rebetez, M., R. Lugon and P-A. Baeriswyl. 1997. Climatic change and debris flows in high mountain regions: The case study of the Ritigraben torrent (Swiss Alps). Climatic Change **36**:371-389.

Richardson, S.D. and J.M. Reynolds. 2000. An overview of glacial hazards in the Himalayas. Quaternary International **65/66**:31-48.

Sætersdal, M. and H.J.B. Birks. 1997. A comparative ecological study of Norwegian mountain plants in relation to possible future climatic change. Journal of Biogeography **24**:127-152.

Sandwith, T., C. Shine, L. Hamilton and D. Sheppard. 2001. Transboundary Protected Areas for Peace and Co-operation. WCPA Best Practice Protected Area Guidelines No. 7, IUCN, Gland and Cambridge.

Schweizer, P. and K. Preiser. 1997. Energy resources for remote highland areas. *In* Messerli, B. and Ives, J.D. (Eds.). Mountains of the World: A Global Priority. Parthenon, London: 157-170.

Scott, D. and R. Suffling (Eds.). 2000. Climate Change and Canada's National Park System: A Screening Level Assessment. Parks Canada, Hull.

Shea, E.L. et al. 2001. Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change for Pacific Islands. The East-West Center, Honolulu.

Smith, J.B. 1997. Setting priorities or adapting to climate change. Global Environmental Change **7**: 251-264.

Stevens, S. (Ed.). 1997. Conservation through Cultural Survival: Indigenous Peoples and Protected Areas. Island Press, Washington D.C.

Stolton, S. and N. Dudley (Eds.). 1999. Partnerships for Protection: New Strategies for Planning and Management for Protected Areas. Earthscan, London.

Suffling, R. 1993. Induction of vertical zones in sub-alpine valley forests by avalanche-formed fuel breaks. Landscape Ecology **8**:127-138.

Theurillat, J-P. et al. 1998. Sensitivity of plant and soil ecosystems of the Alps to climate change. *In* Cebon, P., U. Dahinden, H.C. Davies, D. Imboden and C.C. Jaeger (Eds.) Views from the Alps: Regional Perspectives on Climate Change. MIT Press, Cambridge: 225-308.

Thomson, A.J., M.N. Jimmie, N.J. Turner and D. Mitchell. 2000. Traditional knowledge, Western science and environmental ethics in forest management. *In* Price M.F. and N. Butt (Eds.). Forests in Sustainable Mountain Development: A State of Knowledge Report for 2000. CABI Publishing, Wallingford: 181-186.

Thórhallsdóttir, T.E. 1998. Flowering phenology in the central highland of Iceland and implications for climatic warming in the Arctic. Oecologia **114**:43-49.

Townsend Peterson, A., M.A. Ortega-Huerta, J. Bartley, V. Sanchez-Cordero, J. Soberon, R.H. Buddemeier and D.R.B. Stockwell. 2002. Future projections for Mexican faunas under global climate change scenarios. Nature **416**:626-629.

Villeneuve, A., A. Castelein and M.A. Mekouar. 2002. Mountains and the Law—Emerging Trends. Rome, FAO.

Vitousek, P.M., J.D. Aber, R.W. Howarth, G.E. Likens, P.A. Matson, D.W. Schindler, W.H. Schlesinger and D.G. Tilman. 1997. Human alteration of the global nitrogen cycle: sources and consequences. Ecological Applications **7**:737-750.

Whetton, P.H., J.J. Katzfey, K.J. Hennessey, X. Wu, J.L. McGregor and K. Nguyen. 2001. Using regional climate models to develop fine resolution scenarios of climate change: An example for Victoria, Australia. Climate Research **16**:181-201.

Wielgolaski, F.E. (Ed.). 1997. Polar and Alpine Tundra. Elsevier, Amsterdam.

Wittenberg R. and Cock M.J.W. 2001. Invasive alien species: A Toolkit of Best Prevention and Management Practices. CABI Publishing, Wallingford.

Wohl, E.E. (Ed.). 2000. Inland Flood Hazards: Human, Riparian and Aquatic Communities. Cambridge University Press, Cambridge.

World Bank. 2002. Conservation of Biodiversity in Mountain Ecosystems—At a Glance. The World Bank, Washington DC.

Yin, Y. and S. Cohen. 1994. Identifying regional goals and policy concerns associated with global climate change. Global Environmental Change **4**:246-260.

WWF Climate Change Program

Climate change poses a serious threat to the survival of many species and to the well-being of people around the world.

WWF's program has three main aims:

- to ensure that industrialized nations make substantial reductions in their domestic emissions of carbon dioxide—the main global warming gas—by 2010
- to promote the use of clean renewable energy in the developing world
- to reduce the vulnerability of nature and economies to the impacts of climate change

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WWF's mission is to stop the degradation of the planet's natural environment and to build a future in which humans can live in harmony with nature, by:

- conserving the world's biological diversity
- ensuring that the use of renewable resources is sustainable
- promoting the reduction of pollution and wasteful consumption

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