Maintaining mountain biodiversity in an era of climate change

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Abstract

Mountain regions are centres of biodiversity. Climate change is adding to existing stresses and vulnerabilities due to anthropogenic factors. Evidence of climate change in the mountains includes the upwards movement of plant species, losses of habitats, and changes in the cryosphere. Likely future mountain climates are not easily predicted. Options for adaptation to maintain biodiversity in mountain areas include the protection of adequate and appropriate space, conservation networks, bioregional approaches, and participation and active management – all supported by monitoring, and appropriate infrastructure and policies both in mountain areas and in urban areas.

Keywords: climate change, mountain, adaptation, biodiversity

In 2004, the seventh meeting of the Conference of Parties (COP) to the Convention on Biological Diversity (CBD) adopted a programme of work on mountain biological diversity (CBD 2004). One of the four key challenges identified in this document is "The fragility of mountain ecosystems and species and their vulnerability to human and natural disturbances, in particular to land-use change and global climate change (such as the retreat of glaciers and increased areas of desertification)". A number of the actions relate directly to climate change, such as:

- 1.1.5: Monitor and exchange information on the impacts of global climate change on mountain biological diversity, and identify and implement ways and means to reduce the negative impacts;
- 1.1.7: Identify factors responsible for and possible measures to prevent the retreat of glaciers in some mountain systems and implement measures to minimise the impact of this process on biodiversity;
- 1.2.1: Develop and implement programmes to restore degraded mountain ecosystems and protect natural dynamic processes and maintain biological diversity in order to enhance the capacity of mountain ecosystems to resist and adapt to climate change, or recover from its negative impacts including, *inter alia,* by establishing corridors and taking appropriate measures to maintain ecological functions of natural corridors, where appropriate, to enable vertical migration of species, ensuring minimal viable population sizes to enable genetic adaptation to changing environmental conditions. These programmes should include socio-economic considerations, especially in relation to indigenous and local communities.

This paper has been prepared within the context of this programme of work, which is scheduled for in-depth review by the tenth meeting of the COP in 1010, following review by the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA), based on information which will be requested from Parties and other organisations during 2008.

Two key reasons for a programme of work focusing specifically on mountain biodiversity are that mountain ecosystems provide many essential ecosystem services (Körner & Ohsawa 2005) and that these are linked to their high levels of biodiversity (Jeník 1997, Spehn & Körner 2005). The small size of Alpine plants leads to high levels of alpha diversity, and levels of genetic diversity are also high (Körner 2002). Many factors interact to cause such high levels of biodiversity. The combination of steep altitudinal gradient, topographic variation and range of aspects provides a variety of habitats at all scales. A second set of factors extends over geological time. As mountain ranges have developed, species have migrated along new pathways, exploiting emerging ecological niches. Yet interruptions in mountain-building, subsequent erosion, and changes in climate have also isolated species, so that they have evolved in different ways: a major reason for high levels of endemism. Other factors relate to human activities. Some mountain ecosystems are relatively unmodified by humans, others have been heavily cultivated or otherwise altered for centuries or millennia. This paper focuses especially on Alpine ecosystems, given their particularly high biodiversity and the unique threats they face as the highest ecosystems within regional landscapes. However, many of the issues raised are equally relevant to lower mountain ecosystems, and many of the proposed adaptation options are even more widely applicable.

Present and future stresses and vulnerabilities due to climate change

Mountain climates are generally characterised by great diurnal and seasonal variability and cycles, creating natural stresses for many mountain species. Many are also subject to stresses and vulnerabilities due to anthropogenic factors other than climate change, including land use practices and changes, freshwater abstraction, tourism and recreation, infrastructure development, the introduction and expansion of alien species, and air and water pollution (Price & Neville 2003, Huber et al. 2005). Increased concentrations of atmospheric CO_2, the primary cause of climate change, may eventually have significant impacts on Alpine biodiversity because of species' differential responses (Körner 2005).

Habitats, flora and fauna

Research in Austria, Norway and Switzerland has shown increasing numbers of plant species on many summits (Parolo & Rossi 2008), and many Northern Hemisphere treelines have shifted upwards (Rosenzweig & Casassa 2007). A likely impact of cli-

mate change is upslope 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 (Wilson et al. 2005). Migration of habitats around mountains to a different aspect may also be possible. Yet migration is typically severely restricted as a spatial response in mountain areas because of their topography and, often, the availability of suitable soils and past and present land uses (Theurillat & Guisan 2001). Thus upslope migration will probably result in the contraction and fragmentation of populations of plants and fauna in present montane, Alpine, and nival belts.

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

As current habitats change and are lost, fauna will also have to adapt or migrate upwards and polewards, as already shown for diverse species (e.g., Parmesan & Yohe 2003, Root et al. 2003, Wilson et al. 2005). 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 (e.g., Chambers et al. 2005). Increases in infectious diseases may also be a factor, especially for amphibians (Pounds et al. 2006). Also, as mentioned earlier, migration is a restricted strategy for isolated mountain areas or at continental margins.

In conclusion, many Alpine biota are highly vulnerable to climate change. It is likely that species will be reshuffled along altitudinal gradients, and many endemic species in diverse mountain ecosystems, such as tropical montane cloud forests, other tropical mountains, and Mediterranean mountains, have a particularly high risk of extinction (Fischlin et al. 2007, Thuiller et al. 2005). 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 (e.g., Klanderud 2005, Pounds et al. 1999).

Cryosphere

The shrinkage of glaciers is a global phenomenon; rates of retreat are generally accelerating, especially in the tropics (Lemke et al. 2007). In a number of mountain areas, the rapid melting of glaciers is leading to an increased risk of glacier lake outburst floods. Similarly, the lower elevation of permafrost is likely to rise by several

hundred metres, leading to slope instability and increased damage from freeze-thaw cycles (Kääb et al. 2005).

For every °C increase in temperature, the snowline rises in altitude about 150 m (Parry 2000). In general, less snow will accumulate at lower elevations than at present, exposing plants and animals to frost and influencing water supplies (Keller et al. 2005). Conversely, more snow could fall above the freezing level, as both precipitation and temperatures increase. This may cause more frequent avalanches and hinder the movement of large ungulates and skiers, but also provide added protection to small plants and mammals (Scott & Suffling 2000). For plants, it appears likely that changes in the duration of snow cover and growing season length will have more pronounced effects than direct effects of temperature changes on metabolism (Körner 2003). In general, the snowpack will become unstable, its duration will be reduced, and the profile of permanent snowpatches will change; phenomena that appear to be resulting in changes in the emergence dates of marmots in Colorado (Inouye et al. 2000) and decreases in the area and occurrence of plant communities and endemic mammals in the Australian Alps (Green & Pickering 2002).

Secondary effects of cryospheric dynamics are mainly with regard to hydrology. 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 increase water flows initially. This effect will subside as the glaciers disappear; relatively quickly in temperate mountains, even faster in the tropics. Changing storage and release rates for precipitation will alter the timing of peak flows downstream; aquatic species relying on late summer and early autumn melt may go extinct. Furthermore, 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 mountain freshwater. Changing precipitation patterns have been recorded world-wide and affect runoff patterns, as will the changes in cryospheric dynamics noted above. As more of total precipitation falls as rain rather than snow, the lag time due to snow precipitation and storage until meltwater enters the river system decreases; in addition, melting glaciers will add further water until they too are gone. Then overall flow will decrease dramatically and become more variable (Trenberth et al. 2007).

Increases in flows tend to increase sediment transport, turbidity, and bank erosion. Conversely, decreased flows can increase pollution loads. Droughts, or decreased and earlier runoff from snow and ice melt may have important impacts on fish, especially those relying on late summer and early autumn flows for spawning (Meyer et al. 1999). Changes in the seasonal distribution of precipitation may have other effects; for instance, increased summer precipitation could affect seed formation in species which have evolved to set seed during a dry summer period. Given the importance of mountain water to downstream populations and economies (Vi-

viroli et al. 2007), decreased and less reliable runoff may lead to increased demands for water storage in mountain areas; the construction of new reservoirs will further impact biodiversity.

Extreme events

The incidence of severe storms, floods, droughts and – in tropical and subtropical areas – tropical storms and hurricanes is predicted to increase (Meehl et al. 2007). Increases in flooding frequency will have critical impacts for ecosystems, human populations, and infrastructure in mountain areas and downstream. These 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.

Disturbances such as avalanches, rockfall, fire, wind and herbivore damage interact and depend strongly on climate (Fischlin et al. 2007). More frequent and/or larger avalanches will result from changes in weather patterns and other changes in the cryosphere or permafrost layers (Evans & Clague 1997) and are also likely to change in timing (Lazar & Williams 2008). 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.

Other stresses

Many other stresses may also affect mountain ecosystems as climate change progresses, including:

- soil changes, influencing plant growth (Kundzewicz & Parry 2001, Theurillat & Guisan 2001);
- changes in fire frequencies (Schneider et al. 2007);
- 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 (Giorgi & 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;
- the spread of malaria and other diseases in mountain areas currently free of these diseases (Confalonieri et al. 2007).

Identifying future change

When coupled with atmosphere-ocean circulation theories, General Circulation Models are the most powerful tools for climate change prediction (Randall et al. 2007) and, while many uncertainties remain, confidence in projected patterns of warming and other regional-scale features, including changes in wind patterns, precipitation and some aspects of extremes is increasing (IPCC 2007). They are most useful at the regional scale, i.e., sizeable portions of continents; and increasingly reliable regional predictions are emerging (Christensen et al. 2007). However, as mountain terrain and microclimates are complex systems with many interlinkages and autovariations, prediction models may become insufficient; and this is exacerbated by the lack of adequate data for validation for most mountain ranges (Beniston 2004). Nevertheless, such models have been used to predict environmental changes and species distribution under future climates in specific mountain areas (e.g., Moen et al. 2004, Ni 2000, Townsend Peterson et al. 2002, Fagre et al. 2005), sometimes also taking land use changes into account (e.g., Bomhard et al. 2005); regionally (e.g., Scott & Suffling 2000, Thuiller et al. 2005); and globally (e.g., Malcolm et al. 2006, Nogues-Bravo et al. 2007).

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: e.g., Lundquist et al. 2003), yet much local expert knowledge is often available. Scenario modeling has been used to evaluate the potential distribution of mammals (McDonald & Brown 1992); Alpine plants (Halloy & Mark 2003, McDonald et al. 2002; Sætersdal & Birks 1997, Gottfried et al. 1999, Lischke et al. 1998); and plant species and vegetation types (Fagre & Peterson 2002).

Adapting to climate change

Mountain areas are characterised 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; many mountain ranges have no protected areas, and existing reserves often protect only the summits with no provisions for connectivity among reserves or the maintenance of entire ecosystems (Hamilton 2002, Kollmair et al. 2005). Climate change provides an added impetus to the need to address the conservation of mountain biodiversity at regional and global scales, recognising that, as many mountain ranges are the frontiers between protected areas, administrative areas or states, transboundary cooperation is often necessary (Harmon & Worboys 2004).

Adaptations are strategic tools to manage vulnerability and alleviate impacts to ecosystems. They can be either in response to observed climate changes or anticipatory; they can alleviate negative impacts, or take advantage of positive effects. Anticipatory adaptation is more difficult as it relies on sound scientific predictions of the likely impacts of climate change, but there is often great uncertainty about these

effects, particularly in mountain areas, as noted above. However, adaptation after the fact is generally unlikely to prove successful. According to the Intergovernmental Panel on Climate Change (Gitay et al. 2001, Alcamo et al. 2007), adaptation options are limited in mountain areas, particularly because they are the most vulnerable biomes and will respond most strongly to changes in climate.

In a conservation context, it is vital to identify what is to be protected: which species, species assemblage(s), habitat(s), or landscape(s) should take priority (Barber 2004a)? In mountain areas, there is likely to be competition between several ecosystem types which could become established under altered climate regimes; these often require very different management strategies. Key issues include the need for the continued availability of vital resources, including personnel and infrastructure, and to operate within a regional cultural and economic context. To understand likely vulnerabilities of natural and cultural resources to climate change, it may be appropriate to conduct an integrated assessment (e.g., Yin & Cohen 1994) or climate sensitivity analysis (Peine & Berish 1999), including quantitative approaches complemented with others drawing on traditional ecological knowledge (Ramakrishnan 2005). As discussed below, 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 minimising non-climate-related stresses. In all cases, the key principle is to maintain the maximum variety of possible options, recognising that they will not necessarily help species and ecosystems at the highest elevations. In addition, means to minimise non-climate stresses should always be implemented as integral components of adaptation strategies.

Protecting adequate and appropriate space

Existing quantitative methods to identify the optimum locations for protected areas have generally not taken climate change into account (Araujo et al. 2004). Nevertheless, given the prospect of upslope shift of habitat space, one key element of adaptation is to ensure that each mountain protected area – especially its core zone(s) if zoning is practised – has the greatest possible extent, range of elevations, slope aspects, habitat mosaics. The principle of maximising diversity also applies to protected area systems, which should include several replicates of different ecosystem types. Consideration may be given to designing mountain protected areas to be climatic refugia, particularly where this has occurred in the past, so these areas can act as potential habitat for climatic migrant species. This requires, however, adequate connectivity within the landscape, as discussed below.

Conservation networks

A conservation network is a further strategy towards protecting landscapes, habitats, or species threatened by climate change (Bennett 1999, Hannah 2001). A network allows adaptation through species migration via buffer zones, protected corridors, matrices or landscape connections, and/or 'stepping stones' through anthropogenically altered terrain. Such networks need to be designed carefully, especially where spatial variability and migration routes for range-shifts are limited. Protected area systems should be designed to maximise connections, corridors or landscape units; though further work on dispersal mechanisms is needed (Pearson & Dawson 2005). Such means to maximise connectivity must be able to cross political boundaries, especially in mountains, which often form such boundaries and 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, Barber et al. 2004). Various regional networks are under development (Harmon & Worboys 2004), sometimes based on quantitative modelling (e.g. Williams et al. 2005). One key global initiative is UNESCO's World Network of Biosphere Reserves (WNBR), including over 200 in mountain areas (Price 2001), which represents a unique structure for addressing many of the adaptation options listed below, and for global exchange of experience and best practice (Björnsen Gurung 2006).

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 climate change because:

- large regions accommodate full ecosystem functions and habitats, fostering long-term ecological viability;
- different zones can be used to experiment on and study the impacts of climate change;
- monitoring in protected core areas can be better controlled;
- adaptive management responses can be tried both in buffer zones and more widely;
- partnerships involving many stakeholders respect the multiple needs of the strategic approach;
- 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 consider resource uses at the regional scale, recognis-

ing that both ongoing land-use changes and changes in climate will result in changed pressures on protected areas (Hansen & DeFries 2005).

Particularly because Alpine ecosystems do not usually cover large contiguous areas, their conservation has to be considered within the context of the management of surrounding forest ecosystems and other regional land uses. While the great variety of land ownership and use patterns in mountain regions around the world makes it difficult to be prescriptive, 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 recognising the need to involve local people in managing projected areas (e.g. Stolton & Dudley 1999, Brown et al. 2005), whether as park staff or involved in economic activities based either on utilising resources within protected areas or on providing services to tourists.

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 biodiversity conservation (Barber 2004b). Such involvement 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 regarding 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 different approaches aimed at improving local people's livelihoods in order to decrease their dependence on natural resources. This can include supporting local people in managing and conserving natural resources, providing academic and skill enhancement training or financial support, or investing in small businesses or infrastructure, such as micro-hydro schemes. NGOs often have key roles to play in such initiatives. They, protected area staff, and other conservation-oriented personnel may be involved in specific management strategies such as:

- prioritising actions to protect key threatened species, particularly 'keystone species';
- protecting valuable species *in situ* and avoiding or reducing additional stress on their habitats;
- constructing snow barriers to 'catch' snow, potentially increasing its availability for plants and animals that depend on it in winter;

- modifying site conditions to ensure that decreasing plant communities are replaced by other naturally occurring communities of lesser extent;
- propagating endangered species *ex situ* and, possibly, transplanting them to sites where they have a reasonable chance of survival (Halloy & Mark 2003);
- management of invasive/alien species (Wittenberg & 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).

Monitoring

A key element of every adaptation strategy must be to monitor both its implementation and the changes in the physical and biological environment. Monitoring should be interdisciplinary and integrated, and is also necessary to assess model-based predictions (Guisan & Theurillat 2005). While specific monitoring approaches must be developed and implemented for individual protected areas and/or mountain ranges, it is also worth considering involvement in relevant international programmes. One example is the Global Observation Research Initiative in Alpine Environments (GLORIA), a long-term observation network for detecting the effects of climate change on mountain biota on a global scale (Pauli et al. 2005) which contributes to the global Mountain Research Initiative (mri.scnatweb.ch).

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 from extreme events. Given the limited availability of resources, mapping of risks may be necessary to assist in prioritising actions.

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; institutional structures may also need to be strengthened (Lillo et al. 2004). Plans and policies need to identify problems and priorities, and include appropriate legal provisions and economic and financial instruments to ensure their application (Bieberstein Koch-Weser 2005). As many mountain ecosystems straddle state or administrative frontiers, transboundary instruments (Sandwith et al. 2001, Castelein et al. 2006) are often necessary.

Minimising non-climate-related stressors

Climate change does not take place in isolation: 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 (Agrawala 2005, Williams & Wahren 2005, Fischlin et al. 2007). 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 minimise human impacts through participatory management. Even human activities that have been sustainable in the past may cease to be so as climate change alters mountain ecosystems. It may be necessary to revisit extractive and development uses of mountain regions, and increase 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.

Conclusion

Even if the resources can be found to implement many of the actions discussed above, with support from local people, governments, NGOs, and the private sector, there are likely to be significant losses of many mountain species in coming decades – though certain species will benefit from climate change. Climate change is an increasingly important factor of change affecting mountain ecosystems and species, adding to existing stresses. Reductions in these stresses are an essential prerequisite to all adaptation strategies; to be ensured through actions at all levels from individual behaviour 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 urbanised planet whose people are ever more dependent both on fossil fuels, whose combustion causes climate change, and on water from mountain areas. To make these links, those responsible for mountain protected areas should promote the development of, and utilise, 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 & 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 will have minimal direct effect on mountain ecosystems. However, they will directly benefit mountain people; and well-illustrated, clear interpretative materials and programmes addressed to the millions 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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References

Agrawala, S. (ed.) 2005, *Bridge over Troubled Waters: Linking Climate Change and Development.* OECD, Paris

Alcamo, J. et al. 2007, "Europe", in: Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden & C.E. Hanson (eds.), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge UK, 541–580

Araujo, M.B., C.M Thuiller, W. Hannah, & P.H. Williams 2004, Would climate change drive species out of reserves? An assessment of existing reserve-selection methods *Global Change Biology* 10, 1618–1626

Barber, C.V 2004a, "Designing protected area systems for a changing world", in: Barber, C.V., K.R. Miller & M. Noness (eds.), *Securing protected areas in the face of global change: Issues and strategies* IUCN, Gland, Cambridge UK, 41–95

Barber, C.V. 2004b, "Parks and people in a world of challenges: Governance, participation and equity", in: Barber, C.V., K.R. Miller & M. Noness (eds.), *Securing protected areas in the face of global change: Issues and strategies* IUCN, Gland, Cambridge UK, 97–135

Beniston M 2004 *Climatic change and its impacts: An overview focusing on Switzerland*, Dordrecht

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

Bieberstein, A. & M. Koch-Weser 2005, "Overcoming the vertical divide: Legal, economic and compensation approaches for sustainable management of mountain watersheds", in: Huber, U.M. et al. (eds.), *Global Change and Mountain Regions*, Dordrecht, 627–636

Björnsen Gurung, A. 2006, *Global change and mountain regions research strategy*, Zurich.

Bomhard, B. et al. 2005, "Potential impacts of future land use and climate change on the red List status of the Proteaceae in the Cape Floristic Region, South Africa", *Global Change Biology* 11, 1452–1468

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

Brown, J., N. Mitchel & M. Beresford (eds.) 2005, *The protected landscape approach: Linking nature, culture and community* IUCN, Cambridge

Castelein, A., T.T.V. Dinh, M.A. Mekouar & A. Villeneuve 2006, *Mountains and the law: Emerging trends* Legislative study 75, Rev.1. Rome

Chambers, L.E., L. Hughes & M.A. Weston 2005, "Climate change and its impact on Australia's avifauna", *Emu* 105, 1–20

Christensen, J.H. et al. 2007, "Regional Climate Projections", in: Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds *Climate Change 2007: The Physical Sci-*

ence Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge, UK, 847–940

Confalonieri, U. et al. 2007: "Human health", in: M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden & C.E. Hanson (eds.), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, UK, 391–431

Dukes, J.S.S. & 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 & 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. & 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. & R. Taylor (eds.), *Responding to Climate Change in British Columbia and Yukon,* Vancouver

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

Fagre, D.B., S.W. Running, R.E. Keane & D.L. Peterson 2005, "Assessing climate change effects on mountain ecosystems using integrated models: A case study", in: Huber, U.M. et al. (eds.*), Global Change and Mountain Regions*, Dordrecht, 489–500

Fischlin, A. et al. 2007, "Ecosystems, their properties, goods, and services", in: Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, 211–272

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

Giorgi, F. & B. Hewitson 2001, "Regional climate information – Evaluation and projections", in: Houghton, J.T. et al. (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 UK, 583–638

Gitay, H., Brown, S., Easterling W. & Jallow, B. 2001, "Ecosystems and their goods and services", in: Canziani, O.F., D.J. Dokken, N.A. Leary, J.J. McCarthy & K.S. White (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 UK, 235–342

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

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

Green, K. & 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. & E.M. Spehn (eds.), *Mountain Biodiversity: A Global Assessment.* New York, London: 239–247

Guisan, A. & J.-P. Theurillat 2005, "Monitoring networks for testing model-based scenarios of climate change impact on mountain plant distribution", in: Huber, U.M. et al. (eds.), *Global Change and Mountain Regions*, Dordrecht, 467–476

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

Hamilton, L.S. 2002, "Conserving mountain biodiversity in protected areas", in: Körner, C. & E.M. Spehn (eds.), *Mountain Biodiversity: A Global Assessment.* New York, London, 295–306

Hannah, L. 2001, "The role of a global protected area system", in: Visconti, G., M. Beniston, E.D. Iannorelli & D. Barba (eds.), *Global Change and Protected Areas,* Dordrecht, 413–422

Hansen, A.J. & R.S. deFries 2005, "Land use intensification around nature reserves in mountains: implications for biodiversity", in: Huber, U.M. et al. (eds.), *Global Change and Mountain Regions,* Dordrecht, 563–571

Harmon, D. & G.L. Worboys (eds.) 2004, *Managing mountain protected areas: Challenges and responses for the 21st century*, Colledara

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

Huber, U.M., H.K.M. Bugmann & M.A. Reasoner (eds.) 2005, *Global Change and Mountain Regions*, Dordrecht

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

IPCC 2007, "Summary for Policymakers", in: Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor & H.L. Miller (eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge UK, New York

Jeník, J. 1997, "The diversity of mountain life", in: Messerli, B. & J.D. Ives (eds.) *Mountains of the World: A Global Priority.* London, 199–231

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

Kääb, A., J.M. Reynolds & W. Haeberli 2005, "Glacier and permafrost hazards in high mountains", in: Huber, U.M. et al. (eds.), *Global Change and Mountain Regions*, Dordrecht, 225–234

Keller. F., S. Goyette & M. Beniston 2005, "Sensitivity analysis of snow cover to climate change scenarios and their impact on plant habitats in alpine terrain", *Climatic Change 72,* 299–319

Klanderud, K. 2005, "Climate change effects on species interactions in an alpine community", *Journal of Ecology 93*, 127–137

Kollmair, M., G.S. Gurung, H. Hurni & D. Maselli 2005, "Mountains: Special places to be protected? An analysis of worldwide nature conservation efforts in mountains", *International Journal of Biodiversity Science and Management 1,* 181–190

Körner, C. 2002, "Mountain biodiversity, its causes and function: an overview", in: Körner, C. & E.M. Spehn (eds.), *Mountain Biodiversity: A Global Assessment.* New York and London, 3–20

Körner, C. 2003, *Alpine Plant Life: Functional Plant Ecology of High Mountain Ecosystems,* Berlin.

Körner, C. 2005, "The green cover of mountains in a changing environment", in: Huber, U.M. et al. (eds.), *Global Change and Mountain Regions*, Dordrecht, 367–375

Körner, C. & M. Ohsawa 2005, "Mountain systems", in: Hassan R. et al. (eds.), *Ecosystems and Human Well-being: Current State and Trends*, Vol. 1, Washington DC, 681–716

Körner, C. & E.M. Spehn (eds.) 2002, *Mountain Biodiversity: A Global Assessment.* New York, London

Kundzewicz, A.W. & M.L. Parry 2001, "Europe2, in: Canziani, O.F., D.J. Dokken, N.A. Leary, J.J. McCarthy & K.S. White, (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 UK, 641–692

Lazar, B. & M. Williams 2008, "Climate change in western ski areas: Potential changes in the timing of wet avalanches and snow quality for the Aspen ski area in the years 2030 and 2100", *Cold Regions Science and Technology 51,* 219–228

Lemke, P. et al. 2007, "Observations:Changes in Snow, Ice and Frozen Ground", in: Solomon, S. et al. (eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge UK, New York, 337–383

Lillo, J.C., M. Boness, J. de la Maza & R. Cadena Gonzalez 2004, "Building capacity to manage protected areas in an era of global change", in: Barber, C.V., K.R. Miller & M. Noness (eds.), *Securing protected areas in the face of global change: Issues and strategies* IUCN, Gland, Cambridge UK, 137–167

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

Lundquist, J.D., D.R. Cayan & M.D. Dettinger 2003, "Meteorology and hydrology in Yosemite National Park: A sensor network application", in: Zhao, F. & L. Guibas (eds.), *Information Processing in Sensor Networks*, LNCS 2634: 518–528

MacDonald, D. et al. 2000, "Agricultural abandonment in mountain areas of Europe: environmental consequences and policy response", *Journal of Environmental Management 59,* 47–69

Malcolm, J.R., C. Liu, R.P. Neilson, L. Hansen & L Hannah 2006, "Global warming and extinctions of endemic species from biodiversity hotspots", *Conservation Biology 20,* 538–548

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

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

Meehl, G.A. et al. 2007, "Global Climate Projections", in: Solomon, S. et al. (eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge UK, New York, 747–845

Meyer, J.L., M.J. Sale, P.J. Mulholland & N. LeRoy Poff 1999, "Impacts of climate change on aquatic ecosystem functioning and health", *Journal of the American Water Resources Association 35*, 1373–1386

Moen, J., K. Aune, L. Edenius & A. Angerbjörn 2004, "Potential effects of climate change on treeline position in the Swedish mountains", *Ecology and Society 9(1),* 16

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

Nogues-Bravo, D. M.B. Araujo, M.P. Errea & J.P. Martinez-Rica 2007, "Exposure of global mountain systems to climate warming during the 21st Century", *Global Environmental Change 27,* 420–428

Parmesan. C. & G. Yohe 2003, "A globally coherent fingerprint of climate change impacts across natural systems", *Nature 421*, 37–42

Parry, M.L. (ed.) 2000, *Assessment of the potential effects and adaptations for climate change in Europe: The Europe ACACIA project,* Norwich

Parolo, G. & G. Rossi 2008, "Upward migration of vascular plants following a climate warming trend in the Alps", *Basic and Applied Ecology 9,* 100–107

Parry, M.L., T.R. Carter & N.T. Konijn (eds.) 1988, *The Impact of Climatic Variations on Agriculture* (2 vols.), Dordrecht

Pauli, H., M. Gottfried, D. Hohenwallner, K. Reiter & G. Grabherr 2005, "Ecological climate impact research in high mountain environments: GLORIA (Global Observation Research Initiative in Al-

pine Environmetns) – its roots, purpose and long-term perspectives", in: Huber, U. M. et al. (eds.), *Global Change and Mountain Regions*, Dordrecht, 383–391

Peine, J.D. & 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,*. New York, 397–415

Pounds, J.A., M.P. Fogden & J.H. Campbell 1999, "Biological response to climate change on a tropical mountain", *Nature 398,* 611–615

Pounds, J.A. et al. 2006, "Widespread amphibian extinctions from epidemic disease driven by global warming", *Nature 439,* 161–167

Price, M.F. 2001, "The World Network of Biosphere Reserves: a Flexible Structure for Understanding and Responding to Global Change", in: Visconti, G., M. Beniston, E.D. Iannorelli & D. Barba (eds.), *Global Change and Protected Areas,* Dordrecht, 403–411

Price, M.F. & G.R. Neville 2003, "Designing strategies to increase the resilience of alpine/montane systems to climate change", in: Hansen, L., J. Biringer & J. Hoffman (eds.), *Buying Time: A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems*, Gland, 73–94

Ramakrishnan, P.S. 2005, "Mountain biodiversity, land use dynamics and traditional ecological knowledge", in: Huber, U.M. et al. (eds.), *Global Change and Mountain Regions,* Dordrecht, 551–561

Randall, D.A. et al. 2007, "Climate Models and Their Evaluation", in: Solomon, S. et al. (eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge UK, New York, 589–662

Rebetez, M., R. Lugon & 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

Root, T. et al. 2003, "Fingerprints of global warming on wild animals and plants", *Nature 421,* 57–60

Rosenzweig, C. et al. 2007, "Assessment of observed changes and responses in natural and managed systems", in: Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden & C.E. Hanson (eds.), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge UK, 79–131

Sætersdal, M., & 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 & D. Sheppard 2001, *Transboundary Protected Areas for Peace and Cooperation.* WCPA Best Practice Protected Area Guidelines No. 7, IUCN, Gland, Cambridge UK

Schneider, S.H. et al. 2007, "Assessing key vulnerabilities and the risk from climate change", in: Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden & C.E. Hanson (eds.), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge UK, 779–810

Schweizer, P. & K. Preiser 1997, "Energy resources for remote highland areas", in: Messerli, B. & J.D. Ives (eds.), *Mountains of the World: A Global Priority,* London, 157–170

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

Spehn. E.M. & C. Körner 2005, "A global assessment of mountain biodiversity and its function", in: Huber, U.M. et al. (eds.), *Global Change and Mountain Regions,* Dordrecht, 393–400.

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

Stolton, S. & N. Dudley (eds.) 1999, *Partnerships for Protection: New Strategies for Planning and Management for Protected Areas.* 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. & A. Guisan, 2001, "Potential impact of climate change on vegetation in the European Alps: a review", *Climatic Change 50*, 77–109

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

Thuiller. W., S. Lavorel, M.B. Araujo, M.T. Sykes & I C Prentice 2005, "Climate change threats to plan diversity in Europe", *Proceedings of the National Academy of Sciences 102(23),* 8245

Townsend Peterson, A. et al. 2002, "Future projections for Mexican faunas under global climate change scenarios", *Nature 416*, 626–629

Trenberth, K.E. et al. 2007: "Observations: Surface and Atmospheric Climate Change", in: Solomon, S. et al. (eds.), *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge UK, New York

Viviroli, D., H.H. Dürr, B. Messerli, M. Meybeck, & R. Weingartner 2007, "Mountains of the world, water towers for humanity: Typology, mapping, and global significance", *Water Resource Research 43*

Williams, R.J. & C.-H. Wahren 2005, "Potential impacts of global change in vegetation in Australian alpine landscapes: Climate change, landuse, vegetation dynamics and biodiversity conservation", in: Huber. U.M. et al. (eds.), *Global Change and Mountain Regions,* Dordrecht, 401–408

Wilson, R.J. et al. 2005, "Changes to the elevational limits and extent of species ranges associated with climate change", *Ecology Letters 8,* 1136–1146

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

Wohl, E.E. (ed.). 2000, *Inland Flood Hazards: Human, Riparian and Aquatic Communities,* Cambridge UK

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