Strasbourg, 12 October 2010 **T-PVS/Inf (2010) 8**
[Inf08e_2010]

CONVENTION ON THE CONSERVATION OF EUROPEAN WILDLIFE
AND NATURAL HABITATS

Standing Committee

30th meeting
Strasbourg, 6-9 December 2010

IMPACTS OF CLIMATE CHANGE ON MOUNTAIN BIODIVERSITY IN EUROPE

- Final -

12th October 2010

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EXECUTIVE SUMMARY

The measured yearly mean air temperatures in Europe have increased by 0.9 °C during the last century. In the European Alps the increase was 1.5 °C and thus much higher. Temperature projections predict an increase between ca. 2 and >4 °C within the next decades, with a probably stronger increase in mountain regions. It is expected that in the future small glaciers will disappear while large glaciers will experience significant volume reductions between 30% and 70% by 2050. Below treeline the duration of snow cover is expected to decrease, while increased annual precipitation with changing seasonality might even lead to regionally increased snowpack at higher elevations.

Mountain ecosystems are characterised by steep environmental gradients, e.g. of temperature and moisture. They represent islands of high-elevation habitats, isolated by surrounding lowlands. Changes in environmental conditions are especially threatening endemic species that occur in very limited areas. Of these changes, a shorter snow cover duration below treeline or changes in water availability are considered to be more important drivers than temperature changes themselves. The likely losers of climate warming among plant species in mountains are late successional species, species with small restricted populations, and species confined to summits or the plains, whereas ruderal species (weeds), widespread species with large populations and mid-slope species are likely to win.

Increasing temperatures have caused an earlier onset of spring activities of plants like budburst or flowering. Another widely observed phenomenon is upward or poleward migration of plant species, which has led to an overall increase in species on mountain summits. Immigration of species from lower elevations changes species composition and competitive interactions among species, and in some places a decrease of cold adapted (subnival and nival) species was observed. There is some evidence that the observed upward migration is a result of a natural dispersal process that was triggered by the temperature increase at the end of the Little Ice Age and that is still in progress, mostly due to the dispersal limitation of the species involved. Since both the natural dispersal process and a potential upward migration due to anthropogenic climate warming are taking place at the same time, we suggest seeding and transplanting experiments in order to assess their respective roles in the increase in species number on mountain summits.

Recent surveys demonstrated upward migration of animal species, e.g. in butterflies or the pine processionary moth in line with increasing temperatures. As in plant and animal species huge differences in their reaction to environmental changes have been observed, species interactions are also likely to be modified by climate change. However, there is strong evidence that changes in agricultural land use and increased nitrogen deposition are the most important drivers affecting plant and animal species in mountain ecosystems.

Predictions of future effects of climate change on plant and animal species in mountain ecosystems vary to a huge extent, depending on the model and spatial resolution of climate variables feeding the models, among other factors. For European mammals it is predicted that future potentially species-rich areas will be found in montane and northern regions, while southern, lowland regions are expected to lose up to 100% of mammalian species. In the Western Swiss Alps it is predicted that the majority of studied plant species will risk disappearing from the study region within the next 100 years, especially short dispersal and alpine species. Plant species with a narrow temperature tolerance are expected to be more severely threatened than others in another study. It might, however, be expected that the topographic richness of mountain habitats offers opportunities for survival not accounted for in space for time projections based on weather station derived data. The mosaic of microhabitat temperatures offers refuges or stepping stones in a warming climate and might mitigate the effects of climate warming to some extent.

To improve forecasting the effects of climate warming on mountain biodiversity, the quality of predictive models has to be enhanced. This requires data for model parameterization, training and assessment that are usually sparse, poorly collected, statistically insufficient, and biased. An alternative is to use the increasingly available georeferenced species occurrence and natural history databases. The Global Biodiversity Information Facility (GBIF) has catalysed agreements on the standards and protocols required to make datasets compatible and accessible (King and Rogers, 2010). Over 195 million records from over 8,000 datasets from 260 institutions worldwide are now accessible

online through the GBIF data portal. Additionally, the Global Mountain Biodiversity Assessment (GMBA) of DIVERSITAS recently launched a thematic mountain portal to GBIF data in mountains that allows specific searches of species or taxonomic groups in mountains and their different thermal life belts (e.g. montane, alpine, nival belts), which will help to understand global mountain biodiversity patterns and to inform policy for mountain biodiversity protection.

To protect biodiversity most efficiently, it is important to identify regions with a high biodiversity value. These should be considered priority areas based on data on species and habitats and expert evaluation. This has been done in the example of the WWF European Alpine Programme, a successful collaboration of four conservation organisations. Regions with a high biodiversity value should preferably be connected among each other to enable species migration, as it is e.g. the aim of the Ecological Continuum Project for the European Alps.

Important approaches in mountain to adapt to climate change are:

1) Improve Protected Areas (PAs) in mountains: Re-evaluate management goals and assure continued protection and appropriate management of existing PAs.

2) Connect: Create latitudinal and altitudinal ecological continuums will be a crucial element in adaptation to changing conditions for many species and populations. However, there is also a risk of distribution of diseases, “pests” and invasive plants along corridors.

3) Permeable landscapes: Enhance existing incentive schemes promoting lower intensity land management and the development of greater landscape heterogeneity.

4) Reduce anthropogenic stresses: Minimize localised human-cased disturbances (e.g. fragmentation, nitrogen addition or other pollution) that hinder the ability of species or ecosystems to withstand climatic events.

5) Protect key ecosystem features: Manage to maintain structural characteristics, organisms or areas that support the overall system, such as keystone organisms. Protect variant forms of a species or ecosystem so that, as climate changes, there may be populations that survive and provide a source for recovery.

6) Restore: rehabilitate ecosystems that have been lost or compromised. Restore or facilitate recovery of missing keystone species (e.g., wolf, beaver).

7) Identify refugia: use areas that are less affected by climate change than other areas as sources for recovery or as destinations for climate sensitive migrants and maximise populations of rare and threatened species.

8) Relocate: transplant organisms from one location to another in order to bypass a barrier (e.g. urban area). Translocation of genotypes, species or soil invertebrates or microbes, Captive breeding programs.

Preparing for and adapting to climate change is as much a cultural and intellectual as an ecological challenge. Boundary organizations could prove useful for managing the transdisciplinary nature of adaptation to climate change, providing communication and brokerage services between scientists, practitioners, and interested publics. Integrative research that combines conservation planning, climate change, adaptive capacity, human livelihoods, and implementation must become the rule rather than the exception.

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1. CLIMATE CHANGE PREDICTED FOR EUROPEAN MOUNTAINS

The European Alps warmed by 1.5°C during the last century (from 1901 to 2005) compared with the average of 0.9 °C of surface temperatures in Europe, with a considerably stronger increase towards the end of this period (Alcamo et al., 2007). Temperature change scenarios in Europe for 2080 vary regionally, but show a clear trend toward warming (IPCC, 2007, Schröter et al., 2005). The average projected increase in Europe ranges from 2.1° to 4.4°C, with considerable seasonal and regional variation of changes in precipitation (Schröter et al., 2005). In mountainous regions trends are even higher (Böhm et al., 2001). In winter, temperatures are increasing more than in summer (Jones and Moberg, 2003). It is assumed that average temperatures during the second half of the 20th century in the Northern Hemisphere were likely the highest in at least the past 1300 years (IPCC, 2007). Warmer temperatures were coupled with a decrease in mountain glacier area, duration of snow cover (at elevations below treeline) and increased annual precipitation with changing seasonality, i.e. not excluding periodic drought in summer (IPCC, 2007). It is expected that in the future small glaciers will disappear while large glaciers will experience significant volume reductions between 30% and 70% by 2050, with concomitant reductions in discharge in spring and summer (Schneeberger et al., 2003, Paul et al., 2004). Climate-induced changes in the timing of runoff in small alpine catchments result from impacts of rising temperatures on snow cover dynamics, which may enhance winter runoff, reduce summer runoff, and shift monthly peak flows by up to two months earlier than present (Zierl and Bugmann, 2005). A trend towards earlier peak streamflow and increased winter base flows has been observed in Eurasia and North America (IPCC WGII 1.3.2). The duration and depth of snow cover, often correlated with mean temperature and precipitation (Keller et al., 2005, Monson et al., 2006), is a key factor in many alpine ecosystems (Körner, 1999). Missing snow cover exposes plants and animals to frost, and influences water supply in spring (Keller et al., 2005). For each 1°C temperature increase, the duration of snow cover is expected to decline by several weeks at mid-elevations in the European Alps. At higher elevations, enhanced winter precipitation may, however, increase snowpack regionally.

Climate change is coupled with an increase in atmospheric concentrations of greenhouse gases (Carbon dioxide CO_2, Methane CH_4, Nitrous oxide N_2O, halocarbons) caused by human activities. Greenhouse gases affect the absorption, scattering and emission of radiation in the atmosphere and at the Earth’s surface (IPCC, 2007). Nogués-Bravo et al. (2007) projected warming in mountain areas under different emission scenarios. They showed that temperatures are very likely to increase even more in the 21st century than in the 20th century all over the world and independent of the scenario used.

2. MOST VULNERABLE MOUNTAIN ECOSYSTEMS IN THE CONTEXT OF CLIMATE CHANGE

Mountains are one of the major “experimental fields of nature”, because of the steep environmental gradients they cover and their spatial fragmentation at otherwise global occurrence of wilderness and habitat types. Mountains exhibit the most pronounced climatic gradients on earth. They represent islands, archipelagos of high-elevation habitats, isolated by their lowlands. The zonation of ecosystems along mountain gradients is mediated by temperature and soil moisture. Recent studies (Bates et al., 2008) have shown the disproportionate risk of extinctions in mountain ecosystems and, in particular, among endemic species (IPCC WGII 4.4.7). Many species of amphibians, small mammals, fish, birds and plants are highly vulnerable to the ongoing and projected changes in climate that alter their highly specialised mountain niche (IPCC WGII 1.3.5.2, 4.4.7, 9.4.5).

The European mountain flora will undergo major changes in response to climate change, with changes in snow cover duration below treeline being a more important driver than the direct effects of temperature (IPCC WGII 12.4.3). Changing runoff from glacier melt has significant effects on downstream aquatic ecosystems. Biota of small watershed streams sustained by glacial melt are highly vulnerable to extirpation (IPCC WGII 1.3.1, 3.2, 3.4.3). Of all ecosystems, freshwater ecosystems will have the highest proportion of species threatened with a likelihood of regional extinction due to climate change (IPCC WGII 4.4.8). High latitude mountain areas in Europe will be more exposed to climate change than those at mid-latitudes (Nogués-Bravo et al., 2007). Not even 20 years ago, scientific papers were predominantly concerned with global change factors like land use change, nitrogen fertilisation, and effects of increased atmospheric CO_2-concentration on plant ecophysiology (Parmesan, 2006). Climate change was attributed to have a great potential to alter the functioning of the Earth system, but effects only were expected to be detectable in the distant future (Vitousek, 1992). Nowadays, independent syntheses of studies worldwide show a globally coherent picture that twentieth-century anthropogenic global warming has already affected Earth's biota (see Parmesan, 2006 and references therein).

Theurillat and Guisan (2001) conclude in their review of climate change studies on European mountain plants, that the European Alps appear to tolerate an increase of 1-2°C of mean air temperature, but that for an increase of the order of 3°C or more, profound changes may be expected. In addition, the impact of land use (such as afforestation, grassland management, urbanization) is very likely to worsen the situation.

3. CLIMATE CHANGE EFFECTS ON PLANTS IN EUROPEAN MOUNTAINS: WINNERS AND LOOSERS

When environmental conditions change, organismic populations either have to adapt, escape, or become extinct. We will show characteristics of organisms who are likely to win and of those likely to lose under climate warming in mountain ecosystems.

There is no common biotic response to climate warming, increasing CO_2 concentration or enhanced soluble nitrogen deposition (Körner, 2005). Responses to these drivers are rather context driven and dependent on plant species and vegetation type (e.g. Körner et al., 1997). Which species will be forced upslope in a warmer climate? More ruderal (pioneer) taxa on open ground migrate fast (Grabherr et al., 1994, Pauli et al., 2007), whereas other, long-lived late-successional species can even persist at the same place for an extremely long time, as Steinger et al. (1996) observed in the slow-growing clonal sedge *Carex curvula.* Based on the maximum diameter of a large clone of more than 7000 tillers defined by DNA-analyses and estimates of annual expansion growth of rhizomes, they calculated the age of this clone to be around 2,000 years. This implies that this clone has persisted over a long period with a climate ranging from rather mild periods in the Middle Ages to cool periods during the Little Ice Age in the last century.

Low temperatures can affect plant growth through their influence on plant development and season length (Körner, 2005). Plants in cold climates have a number of safety measures to mitigate the effects of cold temperatures. They use the warm boundary layer near the ground and beginning and end of meristematic activities are controlled by photoperiodic signals. Therefore, true high altitude specialists do not suffer from cold temperatures as one might expect and they do not show short term reactions on a warm spell during cold (winter) periods (Körner, 1999). The photoperiodic constraints diminish the potential benefit of a longer thermal growing season for ca. half of the alpine taxa (Keller and Körner, 2003). The other half are ‘opportunistic’ taxa confined to ‘safe’ snow cover microhabitats. Their phenology is tied to snow cover. Late snowmelt habitats may not necessarily take advantage from a warmer climate, if associated with greater snow pack due to enhanced precipitation, reverting the consequences of warming into a negative trend (Körner, 2005). Similar to photoperiod-sensitive alpine taxa, long-lived late-successional tree species that become dominant in mature forests commonly are sensitive to photoperiod (Körner and Basler, 2010). They are therefore not expected to experience a substantially prolonged growing season due to climate warming. Shorter lived, early successional tree species, however, have a more risky life strategy (Körner, 2007).

To summarize, the likely losers of climate warming among plant species in mountains are late successional species, species with small restricted populations, and species confined to summits or the plains, whereas ruderal species (weeds), widespread species with large populations and mid-slope species are likely to win.

3.1 Changes in phenology

Changes in phenology of plant species can express e.g. as changes in time of budburst, flowering, fruiting, leaf coloration, or leaf-fall. There are many examples in the literature proving an earlier spring flowering of individual plants (Miller-Rushing et al., 2008, Menzel et al., 2006) and an earlier spring green-up of the land surface revealed in satellite images (Cleland et al., 2007, Badeck et al., 2004) in many locations all around the world, while effects of increased temperatures towards the end of the growing season are more ambiguous (Cleland et al., 2007)(Walther et al., 2002). Miller-Rushing et al. (2008) point out that earlier observations of flowering individuals may just reflect changes in population size or sampling frequency and do not necessarily represent the phenological behaviour of whole populations. We therefore have to be careful when interpreting changes in first flowering dates. However, examples using long-term observations and multiple species clearly show an effect of warmer temperatures on the first flowering date. E.g. Miller-Rushing et al. (2008) demonstrated an effect of mean monthly temperatures on flowering date in Concord, Massachusetts, USA, but also found strong differences in the response among plant species. These changes will probably alter the balance of reproductive success among competing genotypes (i.e. adaptation to change) within species, but also affect relations within communities.

Phenology is not only affected by temperature, but also by rainfall and water availability, as Peñuelas et al. (2004) showed in a Mediterranean mountain forest and in Mediterranean shrubland. These changes can cause complex phenological shifts with likely far-reaching consequences for ecosystem and biosphere functioning and structure. Prieto et al. (2008) found an even stronger effect of water availability than temperature on autumn flowering of *Globularia alypum* and *Erica multiflora.*

Studies investigating effects of climate change on phenology in European mountains are scarce, but as it has been shown that temperatures are rising even more in mountain areas and water relations are changing accordingly, it may well be assumed that impacts on plants are similar to the examples above, always keeping in mind that there is a high variability within and among plant species.

3.2 Changes observed in the recent past: Upward shifts of species ranges

Parmesan and Yohe (2003) applied meta-analyses to more than 1,700 species and showed that climate change is indeed significantly causing range shifts averaging 6.1 m per decade upward (or km per decade towards the poles), and advancing spring events by 2.3 days per decade. Causal attribution of recent biological trends to climate change is difficult because non-climatic influences dominate local, short-term biological changes. Changes in any individual species, taxon or geographic region may have a number of possible explanations, however, the overall effects of most confounding factors decline with increasing numbers of species/systems studies.

Lenoir et al. (2008) show evidence of upslope migration of plant species in the montane belt, by assessing changes in the optimum elevation of 171 forest plant species over six mountain ranges in France between 1905-1985 and 1986-2005. Two thirds of the studied plant species showed an upward shift with an average of 29.4 m per decade. Their results suggest that both the upper and lower distributional margins have shifted upward, showing that climate change does not only affect species at their range boundaries but in their whole range. Although species showed specific reactions to climate warming, similar patterns within groups sharing ecological properties could be detected. The shift is larger for species restricted to mountain habitats and for grassy species, which are characterized by faster population turnover, than for long-lived trees and shrubs.

Upslope migration in the alpine/nival belt was shown by various studies in the European Alps. Walther et al. (2005) resurveyed the floristic composition of the uppermost altitudinal 10 m of ten high mountain summits in the Bernina area in the southeastern Swiss Alps. They applied the same methodology of former two surveys (1905 and 1985) and recorded the presence of all vascular plant species. More than 90% of the species listed in 1912 and almost 90% listed in 1992 were re-found and a strong general trend towards increasing species numbers on all but one summit was recorded. In total, Walther et al. (2005) found an increase of 1.3 species/decade between 1912 and 1992/1985, and of 3.7 species/decade between 1992/1985 and 2003. These results suggest a rapid response of alpine vegetation to conditions in the warmest decade of the 1990s and an accelerating trend in the upward shift of alpine plants. So far, the observed increase in species numbers does not entail the replacement of high alpine specialists by species from lower altitudes, but rather an enrichment of the overall summit plant diversity. There is also evidence for substantial resistance to centennial climatic forcing in clones of alpine plants which have been identified to inhabit the very same location over thousands of years (Steinger et al., 1996, Bahn and Körner, 2003).

Parolo and Rossi (2008) recorded plant species richness in the years 2003-2005 in the Italian Alps and compared the results to records of the years 1954-1958. Species richness had increased and one third of the species occurred at higher altitudes than fifty years before. The highest increase in species richness was found between 2800 and 3100 m a.s.l., which seemed to be related to the upwards shift of the permafrost limit. The calculated upward shift per species varied remarkably among species, indicating different abilities of species to deal with climate warming. Therefore, they suggest species-specific conservation measures.

One of the most important projects studying vascular plant species richness on mountain summits is GLORIA (Global Observation Research Initiative in Alpine Environments). Over the last 10 years, GLORIA observation sites were established on over 60 mountain summits all over the world, applying the same monitoring scheme, and 15 more are about to be established or in planning. After some years, sites were or will be revisited, to detect climate change signals in plant species distribution. On Mount Schrankogel, the GLORIA master site in the Tyrolean Alps (Austria), vascular plant species richness increased by 11.8% within 10 years (Pauli et al., 2007). The increase comprised alpine and nival species and was higher in subnival/nival vegetation plots than in alpine grassland vegetation. Alpine pioneer species increased in cover while all subnival to nival plants significantly declined. The results indicate an ongoing range contraction of subnival to nival species at their lower edge and an expansion of alpine pioneer species at their leading edge. This phenomenon might endanger subnival and nival species because they get threatened by stronger competition by alpine species and cannot expand their habitat range at mountain tops.

Short-term changes in plant species number, frequency and composition were studied along an altitudinal gradient crossing four summits from the treeline ecotone to the subnival zone in the South Alps (Dolomites, Italy) by Erschbamer et al. (2009). Re-visitation of the summit areas after 5 years only revealed a considerable increase of species richness at the upper alpine and subnival zone (10% and 9%, respectively) and relatively modest increases at the lower alpine zone and the treeline ecotone (3% and 1%, respectively). At the small scale, the results were partly different, with species richness decreasing at the lower summits and increasing at the higher summits. The changes can most likely be attributed to climate warming effects and to competitive interactions. The main newcomers at the lower three summits were species from the treeline and the lower altitudinal zones. Only at the highest summit, the newcomers came from the alpine species pool. At the treeline ecotone, the abundance of *Pinus cembra*, of dwarf shrubs and clonal graminoid species increased. Here, displacements of alpine species may be predicted for the near future.

Upward shifts of the treeline is expected by many, as this is the most prominent boundary in mountain ecosystems, and driven by temperature. Indeed, a significant increase of forest cover between 1985 and 1997 could be observed at altitudes between 1650 and 2450 m a.s.l. in the Swiss Alps (Gehrig-Fasel et al., 2007). However, 90% of this increase was due to invasion into abandoned grasslands, while only 10 % represented a true upwards shift of the treeline. Most upward shift activities occurred within a band of 300 m below the potential tree line and indicated land use as the most likely driver. Only 4 % of the upwards shifts of tree line rose above the potential regional tree line indicating climate change. Gehrig-Fasel et al. (2007) conclude that land abandonment was the most dominant driver for establishing new forest areas but climate change could become more and more important. However, in an undisturbed site in the Central Swiss Alps an upslope expansion of *Pinus cembra* began at the treeline around 1850 at the end of the Little Ice Age, simultaneously with an increase of tree-ring growth (Vittoz et al., 2008). In this altitudinal treeline ecotone, growth and establishment seem to be mainly linked with temperature.

3.3 Natural dispersal process or upward migration due to anthropogenic climate warming?

Over the last 20 years, several studies comparing recent survey data with historical data from the early 20th century documented an increase in species numbers on high mountain summits of the European Alps. This increase has more or less explicitly been attributed to an upward migration of plant species due to anthropogenic climate warming. However, a reconsideration of the historical and recent data by Kammer et al. (2007) has revealed that more than 90% of the recent species occurrences on mountain summits concern species that were already present at the same or even at higher altitudes within the study region at the time of the historical surveys. This finding suggests that suitable habitats already occurred on these summits under the mesoclimatic conditions prevailing at the beginning of the 20th century and that these habitats were, at least in part, occupied by these plant species. Consequently, the observed increase in species number during the last century does not require the additional temperature increase due to anthropogenic climate change. We therefore consider the phenomenon of increasing species number on high mountain summits to be primarily the result of a natural dispersal process that was triggered by the temperature increase at the end of the Little Ice Age and that is still in progress, mostly due to the dispersal limitation of the species involved. Since both the natural dispersal process and a potential upward migration due to anthropogenic climate warming would take place at the same time, we suggest seeding and transplanting experiments in order to assess their respective roles in the increase in species number on mountain summits.

3.4 Climate effects on growth and productivity and implications on biodiversity

Trees at the climatic treeline have never before grown as fast as today. Radial stem diameter increments at the treeline are as high as they were 100 years ago in the montane forest belt (Körner, 2009b). Paulsen et al. (2000) could show that elevational differences in radial growth across the uppermost 300 m of altitude in the Alps have nearly disappeared in recent years, while tree height gradually decreases towards the treeline. This underlines that trees in this area are not under thermal constraints anymore (Körner, 2009b). For alpine grassland seasonal warming has been shown to enhance growth (Körner et al., 1997) and nitrogen deposition is likely to further enhance productivity (Körner, 2009b), at the likely loss of less responsive taxa.

Erschbamer (2007) found differences in growth responses of fast- and slow-growing glacier foreland species on experimental manipulation of microclimate change. Temperatures were increased with open top chambers (OTCs) by ca. 1 °C (soil surface) and ca. 0.7 °C (soil) during the growing season. Juvenile plants of *Artemisia genipi* (pioneer species), *Trifolium pallescens* (mid-successional species), *Anthyllis vulneraria* ssp. *alpestris* (late-successional species), *Poa alpina*, and *Poa alpina* ssp. *vivipara* (ubiquitous species) were planted into plots with OTCs and adjacent control plots and harvested after three, four, and five years, respectively. The *Artemisia* and *Poa* (R- and S-selected species) showed little response to changes in microclimate, whereas *Trifolium* and *Anthyllis* (plastic species, CSR/CS strategists) had significantly higher dry weights and enhanced reproduction.

Kikvidze et al. (2005) compared productivity and diversity of 18 plant communities spread throughout nine Northern Hemisphere high-mountain subalpine and alpine meadow systems. Sites with comparatively mild climates had greater plant biomass, and at these sites strong competition corresponded with over-dispersed distribution of plants, reducing intraspecific patchiness and in turn increasing local richness. Sites with cold climates had less biomass, and at these sites a high proportion of species benefitted from strong facilitative effects of neighbours, leading to an aggregated distribution of plants.

4. CLIMATE CHANGE EFFECTS ON ANIMALS IN EUROPEAN MOUNTAINS

It is well known that several groups of animals react on changes in the local climate. Observations of northward range shifts of butterflies and birds during warmer periods in Northern Europe have been described as well as subsequent retreats following cooler periods (see Parmesan, 2006, Thomas and Lennon, 1999). Compared to the latitudinal shifts, which may well be detected using historical and recent distribution maps, there is relatively little evidence for changes in altitudinal distribution of animal species and the available results are often of local character. Hill et al. (2002) analysed distribution records for 51 British butterfly species. During the twentieth century, the distribution of northern and southern species shifted upwards, but the increase was higher in northern species (41 m and 22 m, respectively). Northern and/or montane species were more likely to become extinct from low-elevation sites than southern species and had colonised new sites at higher elevations. The authors also observed a northwards expansion of the range margins of a number of southerly distributed habitat generalist species and interpret this result as likely to be a response to climate warming. Most southern species have declined during this period of climate warming. This might result from a loss of breeding habitat that has outweighed the positive impacts of climate warming (Warren et al., 2001). In the Sierra de Guadarrama/Spain an upwards shift of the lower elevational limits of 16 butterfly species within 30 years, in line with increasing mean annual temperatures, has been observed (Wilson et al., 2005). Konvicka et al. (2003) also found an increased altitudinal distribution in more than 10 Czech mountain and non-mountain butterfly species.

A repeated survey of diurnal Lepidoptera communities of semi-natural grasslands in the subalpine zone found significant changes in species composition between 1977-79 and 2002-04 (Hohl, 2006). Thirty-one species showed a statistically significant decrease in abundance, while 15 species showed a significant increase. Lepidoptera restricted to extensively managed grasslands decreased, and species with a wide habitat range increased. This suggests that the grassland management was intensified over the last 25 years. At the same time, subalpine-alpine species experienced losses and lowland species immigrated into the valley, indicating a vertical shift of species into higher elevations, probably due to the effects of global warming.

Effects of climate warming can have a significant time-lag, as a study on spiders in a glacier foreland in the Italian Alps showed (Gobbi et al., 2006). Spider species richness increased with soil age, i.e. years after glacier retreat, with a threshold between 100 and 155 years. There was one group of species that quickly moved along the glacier and another group of species that did not move for at least one century until there were stable conditions in the glacier foreland.

In the pine processionary moth Thaumetopea pityocampa, *Battisti et al. (2005) reported an altitudinal shift of 110-230 m upwards between 1975 and 2004 in the Italian Alps. This shift was in line with increased daily minimum temperatures in winter. A threshold minimum daytime temperature of 6° C determines whether larvae can feed during the night or not.*

5. CLIMATE CHANGE EFFECTS ON SPECIES INTERACTIONS

Species interactions are likely to be modified by climate change. The wide variability in the magnitude of optimum elevation shifts among forest plant species in France may likely disrupt biotic interactions and the ecological networks wherein these species are embedded (Lenoir et al., 2008). In alpine plant populations in the alpine region of south Norway, experimental warming (open top chamber), nutrient addition and experimental removal of the dwarf shrub *Dryas octopetala* all had significant positive effects on neighbouring plant species (*Thalictrum alpinum* and *Carex vaginata*), suggesting competition for nutrients, but also facilitative shelter effects of *Dryas* on its neighbours (Klanderud, 2005).

For many species, the direct impact of climate change may be mediated through effects with that species' food and habitat resources (Parmesan, 2006). The potential disruption of coordination in timing between the life cycles of predators and their prey, herbivorous insects and their host plants, parasitoids and their host insects, and insect pollinators with flowering plants is more crucial than any absolute change in timing of a single species (Harrington et al., 1999, Visser and Both, 2005). A delayed spring arrival of migratory birds led to increased competition for nest sites with species arriving earlier (Both and Visser, 2001). Warmer spring weather in Europe has disrupted synchrony between winter moth hatching and oak bud burst, which led to a mismatch between peak in insect availability and the peak food demands of great tits (Parus major; Visser et al., 1998, Visser and Holleman, 2001).

6. ACCOUNT FOR MULTIPLE DRIVERS OF CHANGE IN MOUNTAIN BIODIVERSITY

6.1 Land use and climate change

In many mountainous regions it is difficult to investigate effects of climate change because they are so often linked with changes in land use and increased nitrogen deposition. Vittoz et al. (2009) investigated effects of climate change and land use in two regions of the Swiss Northern Alps. They compared the actual vegetation composition of subalpine grasslands to that observed in 1970-80 and found small changes in species composition. Only a few species appeared or disappeared and changes were generally limited to increasing or decreasing frequency and cover of certain taxa. Declining species were predominantly alpine and low-growing species. The authors concluded that these changes were mainly driven by changes in land management.

The dual forces of habitat modification and climate change are likely to cause specialists to decline, leaving biological communities with reduced numbers of species and dominated by mobile and widespread habitat generalists. Warren et al. (2001) evaluated changes in the distribution sizes and abundances of 46 species of butterflies that approach their northern climatic range margins in Britain, where changes in climate and habitat are opposing forces. These insects might be expected to have responded positively to climate warming over the past 30 years, yet three-quarters of them declined: negative responses to habitat loss have outweighed positive responses to climate warming. Half of the species that were mobile and habitat generalists increased their distribution sites over this period (consistent with a climate explanation), whereas the other generalists and 89% of the habitat specialists declined in distribution size (consistent with habitat limitation). Changes in population abundances closely matched changes in distributions.

The occurrence of extreme events, such as wildfires and droughts, constitute a source of uncertainty in scenarios of land cover change and climate change due to the unpredictable nature of disturbance events (Zaehle et al., 2007).

6.2 Nitrogen increase and climate change

Effects of nitrogen deposition on biodiversity are likely to exceed those by climatic change in many places (Bobbink et al., 2010). Atmospheric nitrogen (N) deposition is a recognized threat to plant diversity in temperate and northern parts of Europe and North America. Bobbink et al. (2010) clearly show that N accumulation is the main driver of changes to species composition across the whole range of different ecosystem types by driving the competitive interactions that lead to composition change and/or making conditions unfavourable for some species. Critical loads are effect thresholds for N deposition, and the critical load concept has helped European governments make progress towards reducing N loads on sensitive ecosystems. More needs to be done in Europe and North America, especially for the more sensitive ecosystem types, including several ecosystems of high conservation importance.

Increased nitrogen deposition favours early successional, relatively fast growing plant species. In an experiment in the Swiss Alps, slow growing species, such as cushion plants or low-stature shrubs, were rapidly overgrown by grasses when nutrients were added (Heer and Körner, 2002). Such effects on biodiversity cause major shifts in ecosystem properties. Fast growing species mostly have soft leaves and are therefore more sensitive to mechanical forces on slopes. They are also more intensively grazed and provide better habitats for certain rodents who transform habitats, but they may also regenerate faster after disturbance (Körner, 2005). However, these experiments have been conducted with very high rates of N-addition. On the other hand, more realistic rates in the range of 5-25 kg N ha-1 a-1 have also clearly stimulated alpine plant growth (Körner, 2009b, Bobbink et al., 2010). The best estimate for critical loads of N to alpine biota is currently believed to be in the range of 5-8 kg n ha-1 a-1 at a background of 4-5 kg N ha-1 a-1 (Hiltbrunner et al., 2005, Bobbink et al., 2010).

A transplantation experiment in the Swiss Central Alps simulated warming and nitrogen addition (Hiltbrunner and Körner, 2004). Results indicate that alpine plant species are sensitive to both warming and low rates of N addition. Effects were species or functional type specific, and graminoids were found to be particularly responsive to increases in N deposition.

Recent changes in the floristic composition and nature conservation value of nutrient-poor, semi-natural grasslands of the Swiss Alps (Peter et al., 2009) revealed a higher proportion of nutrient-demanding species. 151 phytosociological relevés in four regions, originally recorded between 1975 and 1985 were revisited. In the original surveys, the mean number of plant species per plot (25–100 m$_2$) ranged from 47.1 to 58.1 per region. The flora included a total of 18 species that are protected in Switzerland and a high proportion of habitat specialists of nutrient-poor grasslands (NPG-species). In the second survey, conducted between 2002 and 2004, both species number and species evenness per plot were higher in most regions. Changes were greatest in pastures, and in meadows converted to sheep pastures, while the NPG-species were maintained in unfertilized meadows that were managed as ecological compensation areas.

7. EXAMPLES FROM OTHER MOUNTAIN REGIONS THAN THE ALPS

7.1 Pyrenees

Thuiller et al. (2005b) predicted that under a severe climate scenario up to 62% of plant diversity in the Mediterranean mountains could be lost by 2080. Projections of species loss tend to have high levels of uncertainty, because it is difficult to predict factors such as species ability to disperse and successfully colonise new areas, effects of climate change on species physiological responses and biotic interactions in changed communities (Thuiller et al., 2005b, Thuiller et al., 2008).

7.2 Carpathians

Büntgen et al. (2007) analysed growth responses to climate of 24 tree-ring width and four maximum latewood density chronologies from the greater Tatra region in Poland and Slovakia. four conifer species (*Picea abies* (L.) Karst., *Larix decidua* Mill., *Abies alba* (L.) Karst., and *Pinus mugo* (L.)) between 800 and 1550 m a.s.l. Twenty ring-width chronologies significantly correlated ($P < 0.05$) with June–July temperatures, whereas the latewood density chronologies were correlated with the April–September temperatures. Climatic effects of the previous- year summer generally did not significantly influence ring formation, whereas site elevation and frequency of growth variations (i.e., inter-annual and decadal) were significant variables in explaining growth response to climate. Response to precipitation increased with decreasing elevation. Correlations between summer temperatures and annual growth rates were lower for *Larix decidua* than for *Picea abies*. growth responses to climate revealed by the 28 chronologies support common knowledge, such as temperature sensitivity toward higher elevations and drought-stress toward lower elevations, and within species coherency

7.3 Apennin Mountains

Species richness changes due to climatic change were analysed along an altitudinal gradient (2405 m versus 2730 m a.s.l.) in the Apennine Mountains by Stanisci et al. (2005). Seventy per cent of species do not reach the highest summit and only 11% of the overall flora are shared by all of the three summits examined. They show that the slopes facing east, which are the ones with great species richness and vegetation cover, will be the first to be affected by the immigration of subalpine species from below, whereas northward exposures will be the most conservative, showing greater inertia towards the invasive process caused by climate warming.

7.4 Mountain ranges of Spain

- *Sierra Nevada*

Mendoza et al. (2009) looked at climate change effects on seedling establishment in the Mediterranean mountain forests. They experimentally sowed seeds of two Mediterranean (*Quercus ilex* and *Q. pyrenaica*), two Sub-Mediterranean (*Acer opalus* subsp. *granatense* and *Sorbus aria*), and two boreo-alpine (*Pinus sylvestris* and *Taxus baccata*) species into woodland, shrubland, and open areas. Half of the seeds were irrigated simulating a rainy summer in terms of Mediterranean ecosystems. Seedling survival was strongly affected by the type of habitat as well as irrigation, and results indicate that the maintenance of current species composition in Mediterranean mountain forests is critically dependent on the periodic, scattered occurrence of wet summers. From a conservational standpoint, the predictions of less rainy summers and greater aridity in the future imply a change in the relative abundance of species in the mature forest, with Mediterranean species becoming dominant and boreo-alpine species becoming even rarer and, consequently, a serious threat for the persistence of boreo-alpine species at their southern distribution limit.

Climatic warming promotes the distribution and dynamics of the pine processionary caterpillar *Thaumetopoea pityocampa*, a Mediterranean pest causing severe defoliation, negatively affecting the relict Andalusian Scots pine *Pinus sylvestris nevadensis* in the Sierra Nevada mountains (southeastern Spain; Hódar and Zamora, 2004, Hódar et al., 2003). Defoliation intensity shows a significant association with previous warm winters, implying that climatic warming will intensify the interaction between the pest and the Scots pine. The homogeneous structure of the afforested pine woodlands favours the outbreak capacity of the newcomer, promoting this new interaction between a

Mediterranean caterpillar pest and a boreal tree at its southern distribution limit. Hódar et al. (2003) suggest mitigation actions based on managing habitat structure, in order to reduce or avoid such negative impacts.

- ***Sierra de Guadarrama***

Within 30 years, the lower elevation limits of 16 butterfly species have risen on average by 212 m, coupled with a temperature increase of 1.3° C in mean annual temperature (Wilson et al., 2005). These elevation shifts signify an average reduction in habitable area by one-third. Losses of 50-80% are predicted for the coming century if the species maintain their thermal associations.

7.5 Scandes

In the southern Swedish Scandes, the tree lines of the tree species *Betula pubescens* ssp. *czerepanovii*, *Picea abies*, and *Pinus sylvestris* rose at 95% of a large number of sites over an area of 8,000 km^2 during the last century (Kullman and Öberg, 2009). The mean upshift observed was 70-90 m with maximums of 200 m for all three species. This was in equilibrium with air temperature change during this time. Maximum shifts could only be observed in particular topographic situations showing heterogeneous and site-dependent reactions. The trees showed species specific reactions. Between 1975 and 2007 the tree lines of *Picea* and *Pinus* advanced more rapidly towards the alpine region than that of *Betula*. For nearly 10,000 years, tree lines have been regressing in the Holocene driven by average climate cooling. The maximum tree line rise by 200 m represents a unique trend break in the long-term tree line regression (Kullman and Öberg, 2009).

In the same region, saplings of the thermophilous tree species *Quercus robur*, *Ulmus glabra*, *Acer platanoides*, *Alnus glutinosa*, and *Betula pendula* have dispersed around 50-300 km northwards and 500-800 m upwards between 1988 and 2005 (Kullman, 2008).

7.6 Scottish Highlands

A re-survey of a long-term dataset in the Scottish Highlands provides evidence for vegetation changes that are consistent with the predicted impacts of climate change. In an analysis across a range of habitats and a wide geographic spread, Scottish alpine vegetation data collected 1963–1987 was used to assess biodiversity changes over a 20–40 years period (Britton et al., 2009) by calculating a variety of metrics including α- and β-diversity indices. Biodiversity changes were compared between habitats and areas. Species richness increased in most habitats, while plant diversity at the plot scale and β-diversity declined, reflecting an increased homogeneity of vegetation. The fact that this occurred in closed alpine communities over a 20–40 years period, implies that these communities are considerably more dynamic than previously thought. While lowland generalist species increased, key northern and alpine species declined.

8. CLIMATE CHANGE PREDICTIONS FROM MODELLING FUTURE DISTRIBUTIONS OF MOUNTAIN SPECIES

Using bioclimatic envelope models, Levinsky et al. (2007) evaluated the potential impact of climate change on the distributions and species richness of 120 native terrestrial nonvolant European mammals under two of IPCC's future climatic scenarios. Assuming unlimited and no migration, respectively, their model predicts that 1% or 5–9% of European mammals risk extinction, while 32–46% or 70–78% may be severely threatened (lose > 30% of their current distribution). Under the no migration assumption, endemic species were predicted to be strongly negatively affected by future climatic changes, while widely distributed species would be more mildly affected. Changes in spatial patterns of potential mammalian species richness have only been computed for the universal migration assumption. Future potentially species-rich areas are predicted to be found in montane and northern regions, while southern, lowland regions are expected to lose a lot of mammalian species. The greatest decreases are expected to occur in southern Europe, where parts of the Iberian, Italic and Greek peninsulas, as well as the majority of the Mediterranean islands are conditionally expected to lose up to 100% of current potential species richness. The most pronounced increases are predicted to occur in Fennoscandia, the Pyrenees and the Alps, with gains of over 200%. However, bioclimatic envelope models do not account for non-climatic factors such as land use, biotic interactions, human interference, dispersal or history, and these results should therefore be seen as first approximations of the potential magnitude of future climatic changes.

In the Alps, upward shifts of the treeline ecotone have been documented since the end of the Little Ice Age (e.g. Vittoz et al., 2008) and increases in species richness in alpine and subnival vegetation have been observed (e.g. Pauli et al., 2007). A future increase of these changes is widely supported by a number of species distribution model (SDM) studies (e.g. Engler et al., 2009). In this context, Randin et al. (2010) carried out projections of future distribution for 287 mountain plant species in the Western Swiss Alps, based on four different IPCC climate projections (Nakicenovic and Swart, 2000). The authors showed that 77% of the species may lose between 80% and 100% of their suitable habitat and therefore will risk disappearing from the study region by the year 2100 under a scenario with an average temperature increase of 7.6°C and 54% of the species under a scenario with a 4.4°C increase. The proportion of species losing colonisable habitat was particularly high for short dispersal species, alpine species, and for species with growth forms that are common at high elevations, such as cushion plants, prostrate shrubs, and nanophanerophytes.

The future distribution of 1,200 European plant species was predicted by niche-based models using seven climate variables known to have an important role in limiting plant species distributions by Thuiller et al. (2005a). Ecological niche properties were estimated using a multivariate analysis. Species range changes were then related to species niche properties using generalized linear models. The relationship between niche position on the temperature gradient and percentage of stable climatically suitable habitat was almost linear, showing that species occurring in colder regions (negative side) are expected to lose larger proportions of habitat than species from warmer regions (positive side). The positive linear relationship between niche breadth on the temperature gradient and the remaining suitable habitat showed that species with narrow temperature tolerance were expected to lose large proportions of habitats (40–60%), whereas aridity tolerant species were predicted to be the most stable under future conditions. They concluded that (1) Niche characteristics are powerful indicators of species' sensitivity to climate change. (2) Boreo-alpine species, being marginal at the cold end of the temperature gradient, with a narrow niche breadth are predicted to be highly sensitive as they occur in the most exposed regions to climate warming. (3) Alpine species, which are also marginal at the cold end of the temperature gradient, but have a larger niche breadth than boreo-alpine species, are under pressure by climate change, but could also gain large amounts of suitable habitat by upslope migration, a feature that was not captured by the resolution of their models. In another study, Thuiller et al. (2005b) considered range responses of 1,350 European plant species, including most of the life forms and phytogeographic patterns found among plant species in Europe, to climate change. They contrasted a "future climate" as the projected mean for the period from 2051 to 2080 with today's climate (averaged from 1961 to 1990). Under the no-migration assumption and the most severe climate change scenario, 22% of the species became critically endangered (>80% range loss), and 2% extinct by 2080. Regional deviations from the inferred relationship (positive and negative residuals) they interpreted as indications of particularly high or low species vulnerability because of ecological and historical characteristics of the flora, and/or specific environmental conditions.

Severe climatic conditions have occurred in mountains over evolutionary times, promoting highly specialized species with strong adaptation to the limited opportunities for growth and survival (Körner, 1999). However, Scherrer and Körner (2010) contradict the notion that narrow habitat tolerances of the mountain flora, in conjunction with marginal habitats for many species, are likely to promote higher rates of species loss in European mountains. The topographic richness (geo-diversity) offers opportunities for survival not accounted for in space for time projections, based on weather station derived data (isotherms). Scherrer and Körner (2010) documented large and persistent variation in microhabitat temperatures (root zone and surface) over large alpine terrain and systematic deviations of plant temperature from air temperature, with differences in microhabitat temperature larger than the temperature change predicted by IPCC (Meehl et al., 2007). The mosaic of temperature offers refuges or stepping stones in a warming climate, and is likely to contribute to the patchy vegetation in treeless alpine landscapes and explain the lack of clear species limits such as those for tree taxa at the tree line. Plants do not necessarily need to climb several hundred meters in elevation to find suitable new habitats in case of warming, but may find conditions matching their 'thermal niche' over very short distances. In the light of these data, biodiversity of alpine landscapes may in fact be less endangered by climate change than is often assumed, although the abundance of certain habitat types will become reduced and additional factors such as changes in precipitation regime (snow cover duration, etc.) might influence the future plant species distribution as well.

9. IMPROVE FORECASTING THE EFFECTS OF CLIMATE WARMING ON MOUNTAIN BIODIVERSITY

In predictive models, mountains were shown to be disproportionately sensitive to climate change (e.g. Schröter et al., 2005, Thuiller et al., 2005b, Thuiller et al., 2005a). However, predictive models of climate change effects on biodiversity need to be treated with care unless all assumptions and limitations of a given model are understood. Fossil evidence and recent ecological and genetic research, along with specific problems with present forecasting methods, lead Botkin (2007) to believe that current projections of extinction rates are overestimates. Commonly, the models simply correlate present distribution of species with climate variables obtained from weather stations, and only few models that forecast the impacts of climate change on biodiversity are validated (Botkin et al., 2007). Some more recent studies have shown that continental scale models may either overestimate (Randin et al., 2009a; “local high-refuge” hypothesis) or underestimate (Trivedi et al., 2008; “species trap” hypothesis) the rate of local extinction of species due to the coarse resolution of the climatic data, reflecting the mean climatic conditions within the cells and thus providing imprecise values of the probability of occurrence of species along thermal gradients of mountain landscapes. As the sensitivity of mountain ranges to climatic change mainly depends on the macro-topography, land cover and human land use, high resolution predicting variables (i.e. 1m-resolution Digital Elevation Models) are required for safer predictions of alpine species distribution at high elevation (Lassueur et al., 2006). Including geomorphic perturbations or information on land-use practices in SDMs (in addition to only topoclimatic variables), significantly changed predicted suitable surfaces and connectivity between predicted potential habitats of mountain species (Randin et al., 2009c, Randin et al., 2009b, Scherrer and Körner, 2010). More importantly, the future range size of the species will then determine the sensitivity of these species to changing conditions.

In addition, the full realized niche of species may be captured incompletely at local scale owing to the limited geographic – and therefore environmental – extent considered. In this case, truncated response curves for some species (especially low-elevation ones) may contribute to spurious predictions of future species distributions. This suggests a combination of regional and continental geodatabases for safer projections of species distribution models (Randin et al., 2009a). The use of topography driven “true” climatic conditions illustrates that high mountains are in fact saver places for biota under climatic change than the lowlands (Scherrer and Körner, 2010), Fig. 1.

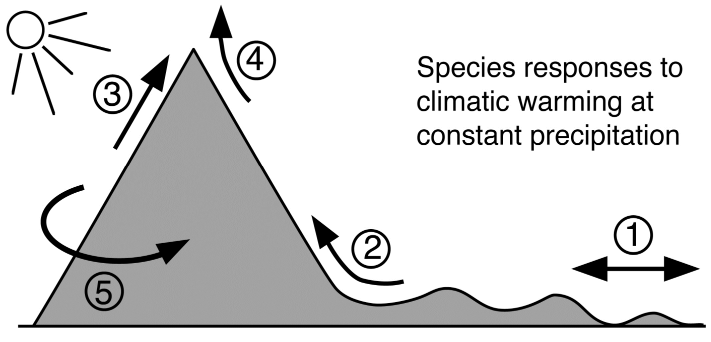

Fig 1: A schematic presentation of migrations of organisms in response to climatic warming. 1 lowland species, lacking close distance escapes from too warm conditions, 2 foothill species migrating upslope, 3 high elevation species migrating toward summit regions, 4 summit species with no upslope escape, but increasing competition from immigrants from lower elevations, 5 short distance escapes in highland taxa using microhabitat diversity in rugged terrain, changing community mosaics at a given elevation.
Source: (Körner, 2009a)

Using weather station data (isotherms), Schröter et al. (2005) applied a statistical modelling framework (‘Space for time’ modelling) to project the distribution of more than 2,000 plant and animal species across Europe with conservative estimates, neglecting the (additional or interacting) effects of habitat loss or landscape fragmentation. However, projections using climatic data of weather stations may be relevant for tall trees, but recent evidence suggests great care when low stature plants and animals associated with them come into play (Scherrer and Körner, 2010). Such vegetation decouples effectively from atmospheric condition and shows mosaics of thermal life conditions that offer both refuge and stepping stones for biota that are likely to prove isotherme based projections for alpine life to be wrong. In addition, the trends for summits reported in these works are likely to overestimate the speed of current climatic warming driven change, because much of the early 20th century change was due to a relaxation from the impact of the "little ice age" (18th -19th century cold period; Kammer et al., 2007). However, if changes in habitat diversity can be predicted (e.g. by thermometry of whole alpine landscapes, Scherrer and Körner, 2010), they should predict changes in species diversity more accurately than would changes in area, the basis of prediction in models using the species-area relationship (e.g. Thomas et al., 2004).

Botkin et al. (2007) suggest an integrated framework for forecasting the impacts of global warming on biodiversity. Such a framework could consider multiple causes of biodiversity change and integrate models for species persistence, e.g. the ability of species to survive in local 'cryptic' refugia, that is, to exist in a patchy, disturbed environment whose complexity allows faster migration than predicted for a continuous landscape. Mountain environments are 'by nature' patchy and disturbed, with a huge habitat complexity on a small scale, the main reason for high mountain biodiversity. Another reason why mountain species might be more persistent than predicted is their greater genetic heterogeneity within species, including local adaptations, which allows rapid evolution.

10. TOWARDS A DIGITAL CULTURE FOR EUROPEAN MOUNTAINS: OBTAIN GOOD INFO AND MAKE BETTER USE OF IT, E.G. TO SUPPORT ADAPTIVE MANAGEMENT

Forecasting future ecological impacts requires data for model parameterization, training and assessment. Data that scientists and policy makers need most, are usually inadequately available-and available data are sparse, poorly collected, statistically insufficient, and biased. These include basic information on the abundance and geographic patterns of most species, as well as the data necessary to estimate the probability of extinction for a species (Botkin et al., 2007). As collecting new data is costly, an alternative is to use the increasingly available georeferenced species occurrence and natural history databases. Biological archives cover areas and time periods far bigger than any researcher can dream of surveying. The variety of environmental conditions covered by such archive data exceed anything one can reasonably think of simulating in growth chambers and laboratories. Mobilising the millions of biodiversity records already in existence is critical to establishing baseline knowledge of species and ecosystems, against which changes can be tracked and enabling forecasts of future trends. This process of transforming data to knowledge will improve decision-making around threat mitigation, resilience and ecosystem restoration. The Global Biodiversity Information Facility (GBIF) has catalysed agreements on the standards and protocols required to make disparate datasets compatible and accessible (King and Rogers, 2010). Over 195 million records from over 8000 datasets from 260 institutions worldwide are now accessible online through the GBIF data portal (http://data.gbif.org), creating a global biodiversity commons, as a 'public good'. On top of that, the Global Mountain Biodiversity Assessment (GMBA) of DIVERSITAS recently launched a thematic mountain portal (www.mountainbiodiversity.org) to GBIF data in mountains that allows analyses which were previously impossible, improving understanding and informing new policy development in mountain regions.

Forecasting methods must not only target key information gaps but also make the best possible use of existing data. For example, models of species distribution may combine available environmental layers with data from museum collections, compensating to some extent for the weakness of either form of data on its own. Applications using predictive modelling allow to show for how these data can enter and support various monitoring and management schemes (e.g. GEOSS), and can serve as powerful decision-support tools for local, regional and global scales. Once these data are served and linked with GBIF, they are freely accessible for the global village. Underlying data flows, taxonomic compatibilities via ITIS (Integrated Taxonomic Information System www.itis.org) and WORMS (World Register of Marine Species; http://www.marinespecies.org/), georeferencing (BioGeomancer), ISO compliant metadata creation and applications of webportals and webservices have been worked out and are further improved, allowing for an efficient data mining, data visualization, modeling and various in-time web services, e.g. connections with Genbank (http://www.ncbi.nlm.nih.gov/Genbank/) and OpenModeller (http://openmodeller.sourceforge.net/).

11. HOW TO BEST MANAGE THESE IMPACTS AND HOW TO PLAN FOR THE NECESSARY ADAPTATION MEASURES

Flexibility in management approaches will be critical to maintaining biodiversity and ecological resilience in mountains in a changing climate. Baron et al. (2008, 2009) provide guidelines for helping natural resourced to adapt to climate change, based on case studies from different case studies from the US. We follow along their guidelines, add some guidance from others (Chettri and Worboys, 2009, Brooke, 2008), and specifically focus on biodiversity as the natural resource and on mountain habitats.

11.1 Identifying regions with high biodiversity value- example of the European Alps

Areas with high biodiversity values have already been identified in the European Alps, e.g. by Priority Conservation Areas PCA or NATURA 2000 criteria. In addition, WWF, ALPARC, CIPRA and ISCAR, four important conservation organisations, were working together to contribute to the preservation of biodiversity in the European Alps, the WWF European Alpine Programme (Mörschel, 2004). They identified regions with high biodiversity value in the European Alps and provide a list of 24 priority areas for biodiversity conservation based on existing data on species and habitats and expert evaluation, and a gap analysis with existing protected areas. They selected species and ecosystems characteristic of the Alps according to their importance with regard to biodiversity and the availability of information about them. The WWF European Alpine Programme collected data on biodiversity, but also on socio-economic issues available for the entire Alps, and transferred them into a Geographic Information system. Based on this information and expert knowledge from all Alpine countries, areas most important for different species groups (flora, insects, reptiles and amphibians, birds and mammals) and for freshwater ecosystems were drawn on maps and then overlayed to identify the areas with the greatest overlap, to arrive at the 24 conservation priority areas in the Alps, important for the largest number of animals, plants and ecosystems (Mörschel, 2004). E.g. for flora, some extraordinary groups of plants and vegetation types unique and/or typical for the Alps were chosen, such as centres of endemic species (350 out of 4500 species in the Alps only occur there), centres of rare species (e.g. the Bergamo region or in the Engadine), large, continuous forest areas (refuges for rare species and corridors for capercaillies, large herbivores and large carnivores), distinct dry areas with drought-tolerant vegetation (e.g. grasslands with *Stipa* or *Festuca* in the dry valleys of the central part of the Alps, such as Valais), and habitats harbouring particular ecological phenomena special to the Alps, such as peat bogs or glacier forelands. In the case of mammals, special attention was given to the following groups: Large carnivores (such as wolf, lynx, and brown bear), large herbivores (such as the Alpine ibex, Alpine chamois, and red deer, whose traditional migration between winter and summer habitats mostly has been cut off by roads, settlements, etc. in the valleys), and small and medium mammals, especially endemic species (e.g. Alpine mouse, Bavarian vole*)*, bats (vulnerable to disturbance) and otter, indicating good habitat quality.

More information became available recently by the Atlas of the Alps (Tappeiner et al., 2008), offering a suite of maps of key indicators on the ecology, economy and society of the Alps. The Atlas of the Alps is the outcome of the EU-financed DIAMONT project (Interreg IIIb, Alpine Space) and serves as an example on how to create a monitoring and information system, which also can be used for informed biodiversity conservation decisions.

11.2 Connecting regions with high biodiversity value- example of the Ecological Continuum project in the European Alps

Biodiversity aspects should be considered in planning decisions, that appropriate and efficient measures are taken to implement an ecological network of protected areas and that areas outside protected areas are managed in a sustainable way, especially in the regions of high biodiversity values, where conservation efforts should be concentrated. Maintaining or restoring ecological connectivity between important areas for nature conservation in the Alps is the aim of the Ecological Continuum Project started in 2007 by ALPARC (Alpine Network of Protected Areas), CIPRA (International Commission for the Protection of the Alps), ISCAR (International Scientific Committee Alpine Research) and the European Alpine Programme of the World Wide Fund for Nature (WWF). These four organisations started to implement the ecological continuum network (Scheurer et al., 2008, Kohler and Heinrichs, 2009) in the Alps, in cooperation with local people, relevant authorities and interest groups within the identified high biodiversity value regions. The following type of regions (defined by the Platform Ecological Network of the Alpine Convention) were given high priority.

- Areas with high biodiversity values (Priority Conservation Areas PCA, Natura 2000, etc.)
- Riverine systems as connectivity elements of the wider landscape
- Densely populated areas in low altitudes
- Areas with high pressure through intensive agriculture, tourism, energy infrastructures, etc.
- Border areas of the existing protected areas
- Areas linked to large-scale European networks such as PEEN, Alpine-Carpathian network, IBA etc.
- Large scale forest areas

11.3 Adaptive management at multiple scales

There is a need for management plans that are highly precautionary, rather than plans that assume that specific management actions will have specific outcomes, due to the complexity of ecosystems and their changes resulting from interactions of natural dynamics, anthropogenic change, and novel climates. Adaptive management, which is a process that integrates learning with management actions, is applicable to circumstances, where there is ability to influence an ecological process, but uncertainty as to the best methods. It allows to take action today using the best available information while also providing the possibility of ongoing future refinements through an iterative learning process. Scenario based planning provides a way of envisioning a range of quantitative or qualitative plausible futures. Adaptation responses can then be developed for the range of plausible futures, which is more robust than managing for any single projection of the future.

11.4 Approaches in mountains to adapt to climate change

Improve Protected Areas (PAs) in mountains: Re-evaluate management goals of protected areas, ensure continued protection and appropriate management of existing PAs. Increase the effective size of the protected area where and when possible (e.g., enlarged core protection zone and buffer zone with nature-friendly land use) or create new protected areas. Protect altitudinal gradients. Cooperate to develop common approaches with adjacent or nearby protected areas.

Connect: The safeguard of latitudinal and altitudinal ecological continuums will be a crucial element in adaptation to changing conditions for many species and populations, mainly in areas of actual or potential treeline and in urbanised areas in the Alps (Scheurer et al., 2008). However, improving ecological connectivity also improves the distribution of diseases, “pests” and invasive plants along corridors. And it is not clear yet, where connectivity is appropriate, for which taxa, and how ecological connectivity improves biodiversity and ecological persistence.

Permeable landscapes: Enhance existing incentive schemes promoting lower intensity land management and the development of greater landscape heterogeneity. Retain as many patches of “semi-natural habitats”, especially in urbanised or intensively used areas.

Reduce anthropogenic stresses: minimize localised human-cased disturbances (e.g. fragmentation, nitrogen addition or other pollution) that hinder the ability of species or ecosystems to withstand climatic events (Baron et al., 2008, 2009). It can also mean to keep traditional land use in regions where this has been the predominant management, in order to preserve species diversity and sensitive ecosystems (Theurillat and Guisan, 2001).

Protect key ecosystem features: manage to maintain structural characteristics, organisms or areas that support the overall system, such as keystone organisms. Protect variant forms of a species or ecosystem so that, as climate changes, there may be populations that survive and provide a source for recovery. Maintain or establish more than one example of each ecosystem or population within a management systems, such that if one area is affected by disturbance, replicates in another area may reduce risk of extinction and provide a source for recolonisation (Baron et al., 2008, 2009). Sustain the slow variables (e.g., soil resources and the species' pool) that accumulate slowly and provide buffers. Sustain both ecological legacies (e.g., old forest growth, woody debris) and cultural legacies (e.g. people's connection to land) (Chettri and Worboys, 2009).

Restore: rehabilitate ecosystems that have been lost or compromised. Restore or facilitate recovery of missing keystone species (e.g., wolf, beaver).

Identify refugia: use areas that are less affected by climate change than other areas as sources for recovery or as destinations for climate sensitive migrants and maximise populations of rare and threatened species.

Relocate: transplant organisms from one location to another in order to bypass a barrier (e.g. urban area). Translocation of genotypes, species or soil invertebrates or microbes, Captive breeding programs.

11.5 The importance of communication and scientist-manager-public partnerships

Preparing for and adapting to climate change is as much a cultural and intellectual challenge as an ecological challenge. Most conservation organizations deal with complex systems in which adaptation to climate change involves making decisions on priorities for biodiversity conservation in the face of dynamic risks and involving the public in these decisions. Discursive methods have been shown to be useful for integrating scientific knowledge with public perceptions and values, particularly when large uncertainties and risks are involved (Brooke, 2008).

Boundary organizations—organizations or institutions that bridge different scales or mediate the relationship between science and policy—could prove useful for managing the transdisciplinary nature of adaptation to climate change, providing communication and brokerage services between scientists, practitioners, and interested publics (Vogel et al., 2007, Brooke, 2008). The fact that some nongovernmental organizations (NGOs) are active across the areas of science, policy, and practice makes them well placed to fulfill this role in integrated assessments of biodiversity conservation and adaptation to climate change.

The use of scenarios in conservation planning is a useful way to build shared understanding at the science–policy interface. For example Spangenberg (2007) developed a scenario of the risks to biodiversity to identify pressures and drivers, and to derive effective policy strategies by an interdisciplinary team of economists, climatologists, land-use experts and modellers. Integrative research that combines conservation planning, climate change, adaptive capacity, human livelihoods, and implementation must become the rule rather than the exception.

ACKNOWLEDGEMENTS

We are grateful to Christian Körner, Daniel Scherrer, Christophe Randin, Falk Huettmann, and many other colleagues from the Global Mountain Biodiversity Assessment (GMBA) of DIVERSITAS for their comments and contributions to this report, and David Genney and Deborah Procter for providing information about the Scottish Highlands.

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