Generalisation of drought effects on ecosystem goods and services over the Alps

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ABSTRACT **3**

Abstract

Climate change and increased drought risk have been recognised as serious threats for ecosystem goods and services worldwide. This report summarises the most probable consequences of droughts for ecosystem services with the focus on the European Alps. The report concentrates on some of the most relevant ecosystem goods and services regarding agriculture, forestry, water resources and tourism. A list of ecosystem goods and services is presented, and the probability of future droughts in the Alps is shortly discussed. For each group of services, a discussion of drought effects worldwide, in Europe and in the Alps is presented. Finally, an overview of some adaptation options is given.

While it is difficult to separate drought effects from heat effects, the effects of drought on ecosystem services in the Alps is rather ambiguous. Prolonged droughts together with shrinkage of glaciers and decreasing snow cover will affect the security of water supply, decrease summer river run-off and water oxygen level, and intensify cross-sectoral water competition even in mountain regions. There is also some evidence for increased risk of pest outbreaks, due to an increase of drought induced vulnerability of plants and a temperature driven expansion of pest species to higher altitudes. More extreme and prolonged droughts can alter species ranges of forest trees, alter forest communities, affect primary production, and may facilitate the invasion of alien species. Decreasing water supply for hydropower may conflict with increasing demand of electricity for indoor cooling. On the other hand, prolonged drier periods in summer will have positive effects for summer tourism in the Alps. Agricultural production, particularly crop production, will be positively effected by warmer and drier conditions on average, especially in the more humid and higher parts of the Alps. However, demands for agricultural irrigation will increase in drier valleys. Generally, productivity is more related to temperature, and drought effects are species specific which gives opportunity for adaptation in the agricultural and forestry sector.

Introduction

Heat waves like that in summer 2003 gave a foretaste to the potential impacts of higher temperature and droughts on ecosystem services and human well being. Prolonged drought periods will intensify cross-sectoral water competition in the Alps. Increased demand for agricultural irrigation could reduce water availability for other sectors such as drinking water, energy production etc. and vice versa. Increased water demands for tourism in summer season will compete with agriculture and demands for hydropower (European Environment Agency, 2009). Decreasing water supply for hydropowers may conflict with increasing demand of electricity for indoor cooling in summer (Prettenthaler et al., 2007). Additionally, drought will decrease the productivity of agriculture and forests. Lower water levels, higher temperatures and lower oxygen contents will pose serious threats to freshwater ecosystems. Pollution of rivers is likely to increase in drought periods due to insufficient dilution of waste waters (OcCC/Proclim, 2007). These are only some of the possible consequences of heavy droughts and adaptation measures are urgently required. The EU adaptation white paper (EC, 2009) identifies the Alps as among the most vulnerable regions for climate change. Adaptation measures should increase the resilience to climate change impacts.

In this report, we will concentrate on some of the most relevant ecosystem goods and services regarding agriculture, forestry, water resources and tourism. A list of ecosystem goods and services is presented, and the probability of future droughts in the Alps is shortly discussed. For each group of services, a review of worldwide trends is given, followed by a discussion of drought effects in Europe and especially in the Alps. Finally, an overview of adaptation options is given.

Definition of Ecosystem Services

"Ecosystem services are the benefits people obtain from ecosystems. These include provisioning services such as food and water; regulating services such as regulation of floods, drought, land degradation, and disease; supporting services such as soil formation and nutrient cycling; and cultural services such as recreational, spiritual, religious and other nonmaterial benefits" (Millennium Ecosystem Assessment, 2005).

List of Ecosystem services
(modified from Millennium Ecosystem Assessment, 2005)

Provisioning services

- food
- fresh water for drinking and irrigation
- wood and fiber, pharmaceuticals, biochemicals
- energy (bio-fuel, hydropower)

Regulating services

- carbon sequestration and climate regulation
- waste decomposition and detoxification
- purification of water and air
- flood regulation
- pest and disease control
- soil conservation and protection of land degradation

Supporting services

- nutrient dispersal and cycling
- soil formation
- seed dispersal
- crop pollination
- primary production

Cultural services

- cultural, intellectual and spiritual inspiration
- recreational experiences (including ecotourism)
- scientific discovery

Probability of droughts in the Alps

The inter-annual variability of summer climate and the frequency of heat waves is predicted to increase in whole Europe (Schar et al., 2004; Seneviratne et al., 2006). More extreme intra-annual precipitation regimes (i.e. intense heavy rainfall events and longer dry intervals in between) together with higher temperatures, elevated evapotranspiration and increased anthropogenic water demands will increase the probability of droughts (Briffa et al., 2009). However, climate change impacts will be unevenly distributed between regions and seasons (Matulla et al. 2003). Analyses of precipitation time series revealed a significant increase of frequency and duration of droughts in the last decade (Briffa et al., 2009). Duration of summer heat waves has doubled and frequency has tripled within the period of 1880 to 2005 in western Europe. Analyses of ca. 200 monthly precipitation series for the greater region of the Alps revealed a wetting trend (since 1860) in the north-western parts of the Alps and a drying trend in the south east (European Environment Agency, 2009). In a study about the probabilities of drought occurrences in the Alps, Calanca (2007) estimated a decrease of 20% in the frequency of wet days in the summer growing season (April to August) for the period 2071-2100. Concurrently, the frequency of droughts is predicted to increase from 15% to 50%, and their severity is predicted to increase by 20%.

Analyses of climatic time series data and climate change scenario models agree that high precipitation events will increasingly mass in winter and spring (Schmidli & Frei, 2005; Frei et al., 2006; Fuhrer et al., 2006; Moberg et al., 2006; Schmidli et al., 2007; Briffa et al., 2009; Smiatek et al., 2009), whereas precipitation will decrease in summer. According to predictions of climate change models particularly the south-western Alps will face a significant decrease (-41%) in summer precipitation till the end of the 21st century with according impacts on the hydrological cycle and water supply (European Environment Agency, 2009). However, analyses of Trnka et al. (2010) revealed no pronounced decrease of the water balance between April and June for the Alps. Lorz et al. (2010) assessed the probability of three major natural hazards – windthrow, drought and forest fire – for central and south-eastern European forests and found some increased vulnerability of the northern Alps for storms, but only marginal probability of droughts within the European Alps.

Agriculture

Worldwide trends

Generally, rising temperatures intensify chemical processes and prolong the vegetation period. Together with higher CO_2 levels, elevated temperature potentially increases primary production of plants as long as other factors (water, nutrients, etc.) are not limited (e.g. Maracchi et al., 2005; Trnka et al., 2010). Consequently, increasing temperature and solar radiation allowed an upward trend in net primary production (NPP) from 1982 through 1999 (Ciais et al., 2005; Trnka et al., 2010). However, for the last decade (2000 to 2009) increased droughts in the southern hemisphere inverted the trend and NPP decreased globally (Zhao & Running, 2010). While long-term mean climate change affect overall food production, changes in year-to-year variability have strong impact on food security due to increased inter annual yield variability and risk (Torriani et al., 2007; Gornall et al., 2010; Moriondo et al., 2010; Trnka et al., 2010).

Insect pests will be affected by rising temperatures since insects will adapt their distribution to the changed climate. Particularly regions on the cold limits of species occurrences (boreal zone and higher Alps) are likely to be affected by more stable and dense populations of pest insects (Virtanen et al. 1996; Ayres & Lombardero, 2000; Maracchi et al., 2005; Veteli et al., 2005; Battisti et al., 2006; Vanhanen et al., 2007; Seidl et al., 2009; Netherer & Schopf, 2010; Robinet & Roques, 2010). Beside a widening of the species ranges, simulation studies predict an increase in the number of generations per year for the Colorado potato beetle and the European corn borer (Kocmánková et al., 2011). Contrary, temperature increase and droughts may depress heat susceptible species in southern and continental parts of Europe as well as in low lying parts of the Alps. However, studies do not allow to clearly isolate the effect of droughts on pest insects. Although droughts may also negatively affect pest insects, they are predominately R-strategists which can easily recover even sharp depressions. Especially, forest pests show a time lag in population growth as drought stressed trees are infested in the consecutive years and pests populations increase (Wermelinger et al., 2008). Increasing drought frequency and duration will increase stress to plants and make them more vulnerable to pests, and droughts are frequently followed by pest outbreaks (Okland & Bjornstad, 2003; Rouault et al., 2006). Rising temperatures are shown to facilitate invasion of alien (pest) species which are adapted to warmer climates (Pautasso et al., 2010; Robinet & Roques, 2010; Moraal & Jagers Op Akkerhuis, 2011). However, the effect of droughts on the invasibility of a region is still unknown. It may slow down invasion as it will stress invasive species, but it may also accelerate invasion when indigenous species are even more stressed.

Europe

Ciais et al. (2005) showed a Europe-wide reduction of 30% in productivity due to heat and drought in 2003, particularly in the crop and grassland dominated parts of central western Europe (Hlavinka et al., 2009; Wreford & Adger, 2010). Temperate ecosystems converted to carbon sources which reversed the effect of four years of net ecosystem carbon sequestration (Reichstein et al., 2007), thereby intensifying a carbon feedback that is already predicted for the tropics and higher latitudes.

Nevertheless, particularly the northern parts of Europe are predicted to profit from climate change by increased productivity of agricultural crops (Falloon & Betts, 2010; Trnka et al., 2010; Olesen et al., 2011). Due to the assumed increase of the duration of the growing season, grassland productivity is likely to increase in the boreal regions, a trend which can also be anticipated for the Alps. However, early snow melt may also exacerbate water shortage in summer, even in such regions as the Alps.

At the same time, increasing problems in water supply, increasing drought risk, increased demands for irrigation and high temperatures will decrease productivity and suitability for agricultural crops and will increase production vulnerability in southern Europe. An analysis of the impact of climatic extremes on sunflower and winter wheat in Mediterranean countries (Moriondo et al., 2011) showed different vulnerability of crop species, which will limit their use in some regions but concurrently will offer new options for other regions. Sunflowers are more prone to the direct effect of heat stress at anthesis and drought during its growing cycle than winter wheat. Hence, yield of Sunflowers is predicted to decrease in southern parts of Europe, while winter wheat crop will gain importance for the Mediterranean region (Moriondo et al., 2011). Potatoes are specifically sensitive to reduced precipitation at tuber formation (Peltonen-Sainio et al., 2010). Hence, needs for adaptation will be high in this region (Wreford & Adger, 2010).

The most negative effects are predicted for the continental region of south-eastern Europe (e.g. Hungary, Serbia, Bulgaria and Romania) which will suffer most from heat waves and droughts without possibilities for effectively shifting crop cultivation to other time periods of the year (Olesen et al., 2011).

Alps

Shortage of summer irrigation may result from an earlier spring runoff peak in some regions of the Alps like South Tirol or Valais (Falloon & Betts, 2010), but increasing duration of the vegetation period together with higher temperatures and CO_2, a prolonged period for sowing and harvesting and increasing nitrogen deposition will generally enhance the potential for crop production in the Alps (Trnka et al., 2010). Particularly, the suitability for grape is predicted to increase substantially within the Alps.

Adaptation

Particularly in regions where crops are already cultivated near key thresholds (e.g. water stress) adaptation options are limited. Moreover, prolonged droughts may overstrain local water depots and may pose problems for irrigation. Despite its comparable low surface (about 1/50 of the global arable land), irrigated agricultural land accounts for about 40-45% of the global food production (Olesen, 2006; European Environment Agency, 2009). Currently, irrigation is not very dominant in the Alps, but it can be expected to increase in the future. However, an analysis of the efficiency of past adaptation strategies to heat waves and drought in the UK showed that there has been a considerable reduction in damages during the past four decades which indicates that the agricultural sector is increasingly well adapted to the current climate change and its extreme events (Wreford & Adger, 2010).

Adaptation options for the agricultural sector
(based on Maracchi et al., 2005; Olesen, 2006; Moriondo et al., 2010; Reidsma et al., 2010; Ceccarelli et al., 2010; O'Neill & Dobrowolski, 2011; Olesen et al., 2011)

- Cultivation timing: Earlier sowing dates will help to escape or avoid hot and dry periods during summer and use as much of the winter precipitation as possible. There will be some need to adapt harvest time, too. Generally, a more accurate matching between phenology of crop species and moisture availability and adaptation to changing vegetation periods will be necessary.
- Tillage practices: Change in tillage practices (e.g. mulching and minimum tillage) can help to reduce transpiration loss and soil erosion, both by water and wind.
- Changes in water management and water conservation: There is a bundle of options for a more efficient disposal of water: e.g. change of irrigation systems, underground irrigation or the re-use of (waste) water.
- Crop protection: There will be higher need for pest and disease monitoring and crop protection, as pest species are anticipated to follow rising temperature and drier conditions and expand their distribution to the north and to higher altitudes.
- New cultivars: Climate change will force the replacement of traditional crops. The use of drought tolerant crops or cultivars (from conventional plant breeding and genetically modification) with longer or shorter growing cycles will help to avoid drought periods and to utilize prolonged vegetation periods, respectively. Parallel, a re-emphasize on plant breeding will be inevitable to cope with climate change.
- Shift from rain-fed crops to irrigation: Irrigation will be an option in regions with sufficient ground water supply even in the driest periods. Irrigation, however, will compete with demands from other sectors like households, tourism, hydropower or industry.

Forestry

Beside timber production forests also serve as a multiple supplier of other services such as water purification, erosion protection, carbon sink/sources, recreation areas, etc. Hence, climate change impacts on forests will influence multiple interconnected services.

Worldwide trends

Several studies analysed the effects of past extreme droughts on the mortality of trees in the United States. In many temperate forests of the south-western USA, intense droughts, insect outbreaks, and wildfires have led to decreasing tree growth and increasing mortality during the recent decades, a trend which will probably even amplify in the future (Williams et al., 2010; Ganey & Vojta, 2011). Mueller et al. (2005) documented increased mortality of Pinyon Pine (*Pinus edulis*) in the south-western USA due to drought events. Mortality of Pine was found to be 6.5 fold higher than that of One-seed Juniper (*Juniperus monosperma*) which has already resulted in a vegetation shift as Juniper has started to invade Pine forests after drought periods. Similarly, van Mantgem et al. (2009) documented increased mortality rates of trees in the western USA within the past decades which was co-attributed to regional warming and increased water deficits. Drought induced tree mortality in mixed conifer forest in Arizona was found to be 200% higher between 2002 and 2007 than in the period 1997-2002. In Ponderosa Pine (*Pinus ponderosa*) forest tree mortality increased to 74%. Quaking aspen (*Populus tremuloides*) und White Fir (*Abies concolor*) were found particularly sensitive to droughts. Ganey & Vojta (2011) concluded, that the extraordinary increase in mortality is a strong indication for the very limited resilience of these forests to climate change. Adams et al. (2009) found that experimentally increased temperature accelerated the drought-induced mortality of *Pinus edulis*. They suppose that an interaction of temperature sensitive carbon starvation due to water stress and temperature insensitive sudden hydraulic failure under extreme water stress accounts for the observed higher mortality. They concluded that more severe and frequent drought periods will accelerate replacement of sensitive tree species and will result in vegetation shifts (see also Fuhrer et al., 2006). However, drought induced tree mortality is not limited to the USA. Worldwide the forests face, at least potentially, an amplified tree mortality due to drought and heat (Allen et al., 2011; Hartmann, 2011). Thereby, other services like carbon sequestration are affected and trigger a negative climatic feedback due to increased carbon release (Ciais et al., 2005; Fuhrer et al., 2006; Reichstein et al., 2007; Zhao & Running, 2010; Carnicer et al., 2011).

Europe

Mediterranean forests will face decreasing productivity due to droughts. An analysis of crown defoliation data showed a significant increase of tree mortality in southern European forests between 1987 and 2007 as response to increased water deficit (Carnicer et al., 2011). Similarly, Sarris et al. (2007) found that recent drought events in the eastern Mediterranean resulted in decreasing productivity, expressed as reduced tree-ring width, of Turkish Pine (*Pinus brutia*). An additionally effect are the more frequent wild fires. On a global scale, wild fire is predicted to increase especially in the United States, South America, central Asia, southern Europe, southern Africa, and Australia, but relative changes will be the largest in southern Europe (Liu et al., 2010).

Although drought directly affects tree physiology and growth, the impact of secondary factors like insect pests, pathogens and fire is usually greater than the primary stress and can lead to increased tree mortality. In the 2003 heat wave, western and central Europe experienced a serious drought leading to extensive forest damage (Rouault et al., 2006). Water stress in the vegetation period will particularly affect productivity and mortality of Norway Spruce (*Picea abies*) at lower altitudes. Hanewinkel et al. (2010) predict a loss of suitable area between 21 and 93% for the lower parts of Baden Württemberg in Germany. In case of sufficient precipitation, however, elevated temperature is supposed to positively effect productivity of Norway Spruce (Albert & Schmidt, 2010).

However, climate change does not only pose a threat to forestry. Latta et al. (2010) predicted increasing productivity (between 2 and 23%, depending on the climatic scenario) for forests of the more humid Pacific part of the United States. This is supported by Lindner et al. (2010) who anticipated positive effects of higher CO_2, increasing temperature, prolonged vegetation period and increased decomposition of soil organic matter on the productivity of northern and western European forests. Garcia-Gonzalo et al. (2007) predicted an increase of 8-22% in timber yield for Finnland. Similarly, Albert & Schmidt (2010) predicted higher productivity for beech forests in higher altitudes of Germany. However, increased precipitation, more rainy days and reduced duration of snow cover and soil frost may negatively affect forest work and timber logging (Maracchi et al., 2005; Lindner et al., 2010) which will offset some of the positive effects for the forest industry. Lower winter temperatures may reduce winter hardening in trees and result in an increased vulnerability to frosts (Hanninen, 2006). Moreover, the stimulating effects predicted for northern Europe will be outweighed by drought effects and higher disturbance in southern and eastern Europe.

Generally, increased frequency and magnitude of extreme events like heavy droughts, storms, wild fires and drought induced pathogen (pest and fungi) attacks will affect forests more than the average climatic trend (Schröter et al., 2005; Fuhrer et al., 2006; Bolte et al., 2009; Albert & Schmidt, 2010; Williams et al., 2010; Ganey & Vojta, 2011).

Alps

Studies of forests in dry alpine valleys suggest that particularly Scots Pine (*Pinus sylvestris*) is highly sensitive to drought periods and has already suffered a loss (Rebetez & Dobbertin, 2004; Bigler et al., 2006; Weber et al., 2007). Particularly, pine trees suffer from intensified pest infestation during dry years (Wermelinger et al., 2008). On the other hand, oak species are supposed to benefit especially in dry years (Friedrichs et al., 2009). This findings are partly supported by Gimmi et al. (2010) who also documented a higher mortality of Scots Pine after drought periods, but the increase of deciduous trees was primarily attributed to succession on abandoned pastures. Analogous, the increase of European Larch (*Larix decidua*) could not be attributed to climate change but to changes in forest management. An assessment of the vulnerability of Swiss Pine (*Pinus cembra*) in the Alps and the Carpathian mountains revealed a predicted habitat loss between 53 and 72%, depending on the climatic scenario (Casalegno et al., 2010). However, general increase of temperature will elevate the tree belts and increase the area of suitable habitats for forest species (Camarero & Gutierrez, 2004; Bolli et al., 2007), thereby providing a refuge for drought sensitive species in higher altitudes. Forest fires are likely to increase also in the Alps (Schumacher & Bugmann, 2006).

Adaptation

Forests are particularly effected by climate change and long-lived trees do not allow for rapid adaptation (Bolte & Degen, 2010; Lindner et al., 2010). Hence, adaptation should be well-considered and should not fail. The adaptive capacity in the forest sector is supposed to be relatively large in the boreal and temperate oceanic region of Europe, more constrained by socio-economic factors in the temperate continental, and largely limited in the mediterranean regions (Lindner et al., 2010).

Adaptation options for the forest sector
(based on Bolte et al., 2009; Seppälä, 2009; Albert & Schmidt, 2010; Bolte & Degen, 2010)

- Active adaptation: This includes the replacement of drought-sensitive tree species by less sensitive provenances of native and non-native tree species (e. g. Douglas fir) from regions with a climate corresponding to the expected one. However, active adaptation needs specific knowledge about the regional adaptation of species and easily runs the risk of selecting the wrong species, introducing highly invasive species degrading local species communities and local food-webs which would even decrease the resilience of forest ecosystems.
- Passive adaptation: This means the use of spontaneous adaptation processes (natural succession and species migration) which is the lowest-risk option, but may conflict with specific forest management targets.
- Pest and fire protection: Thinning of overstocked stands can reduce vulnerability against insect pests and fire.

Availability and quality of water resources

Availability of water resources

General: Climate change will cause a general intensification of the global hydrological cycle, and the pressure to freshwater resources will increase in the future (Jackson et al., 2001). Increased intra-annual variation in precipitation, together with shrinkage of glaciers and snow cover will severely effect the security of water supply in mountain regions (Schröter et al., 2005). Particularly, springs in karst regions react most rapidly to changes in precipitation (OcCC/ProClim, 2007) and are most sensitive to changes in precipitation patterns.
Alps: In the Alps, stream flow is predominantly snowmelt dominated. Climatic models predict a decrease of the snow fraction in winter precipitation, and the melting of snow will occur earlier in spring (Barnett et al., 2005) which results in a temporal shift in peak river runoff to winter and early spring where much water gets lost directly in the oceans. Decrease of winter snow, rising temperatures and earlier melting will increasingly exhaust the water depot fixed in snow and ice and will exacerbate water shortage in summer when demands for e.g. agriculture, tourism or households (e.g. swimming pools) is the highest. Studies from Switzerland showed a significantly reduced discharge for alpine regions during the heat wave in 2003, except for watersheds fed by glaciers which showed an increased runoff (Zappa & Kan, 2007). Even in regions with high precipitation like the Kitzbühler Alps, local groundwater recharge was reduced by 20 to 70%, resulting in local deficits (Vanham et al., 2009).

Water quality, water purification and waste water

General: Higher water temperatures will rise biochemical processes, increase the occurrence of algal blooms as well as the abundance of bacteria and fungi, and reduce oxygen levels (Anderson et al. 2008, Whitehead et al., 2009). Lower flows and reduced velocities resulting in higher water residence times in rivers and lakes will have negative effects on water quality (Whitehead et al., 2009). Lower flow conditions and higher temperatures might cause the release of heavy metals and nutrients from sediments (Eisenreich et al., 2005). Lower flows will decrease the dilution of waste water (Whitehead et al., 2009). On the landscape level, large scale disturbances due to drought or wind throw and subsequent pest outbreaks may change runoff and percolation of water with consequences to water quality.
Alps: There are only few scientific studies focusing on climate change effects on water quality in the Alps. Jandl et al. (2008) gave an indication that intensified decomposition due to heat and drought might negatively affect water quality in a dolomitic area in the eastern Alps.

Energy production

General: Climate change may lead to a shortage in energy supply during drought periods when river water level falls below a critical limit (European Environment Agency 2009). Changes in discharge regimes may reduce hydropower potentials by 25% and more for southern and southeastern European countries (Lehner et al., 2005). Using a combined eco-hydrologic and climatic model for a central European low mountain range it was predicted that the groundwater recharge and streamflow will be reduced by up to 50% (Eckhardt & Ulbrich, 2003).

Alps: In some regions of the Alps, the reduction of water flow during summer months may cause problems. In Piedmont (northwestern Italy) the drought of 2003 had strong effects on electric production due to minimal water run-off (Cassardo et al., 2007). In Switzerland the nuclear power plant had to reduce its production during two months in summer 2003 because of higher water temperatures of the reduced river water (OcCC/Proclim, 2007). For Switzerland it is also estimated that there is a 7% reduction of the production of hydropower electricity in the year 2050 due to increasing temperatures and drought effects (OcCC/Proclim, 2007). If the drought is temporarily limited, power stations with reservoirs should be less affected than river power plants.

Ecological integrity of running fresh water

Palmer et al. (2009) pointed out that increasing droughts and hence decreasing water bodies combined with elevated water temperatures and decreasing oxygen saturation will affect many freshwater species and will accelerate current habitat fragmentation. Heavy droughts in streams are disturbances which can disrupt hydrological connectivity (Lake, 2003). They can have strong effects on the densities and age-structure of freshwater species populations, can alter community composition and diversity and hence have negative effects on ecosystem services. Resistance of species against drought effects strongly depends on the availability and accessibility of refugia, and potential recovery relies on the hydrological continuum of a stream system that allows for recolonisation. Recovery of species from extreme (supra-seasonal) droughts are frequently characterised by dense populations of transient species and a depletion of resident biota. The severity of drought effects depends on whether certain thresholds are exceeded or not (Boulton, 2003).

Adaptation options for the water sector
(based on European Environment Agency, 2009)

- Establishment of an integrative and proactive adaptive water resource management on a regional scale.
- Ensuring and strengthening of cross-sectoral cooperation and management of water resources on a catchment scale beyond administrative borders.
- Development of drought emergency plans.
- Improved methods to reduce anthropogenic water use and to make the use more efficient.
- Strengthening the use of renewable energy production, especially solar and wind energy.
- Supporting the autonomous adaptation of species and ecosystems to drought, e.g. by removing migration barriers, re-establishing migration corridors, and decreasing other stress factors like intense land use or pollution.

Tourism

Some effects of climate change on tourism are already apparent. For example, the reduction in frost frequency and duration have a negative impact on low altitude skiing areas (Auer et al., 2005). Some trekking routes have become dangerous because of changing permafrost conditions, rock falls and landslides.

Nevertheless, drought effects on tourism are less obvious. One possible aspect is a reduction of summer precipitation that will positively affect most sectors of summer tourism (Kromp-Kolb & Schwarzl, 2007). Tourists may change their travel destinations from the Mediterranean to the Alps. Increasing summer tourism in the Alps due to warmer and drier summers, however, may increase the demand for water and may cause local problems (European Environment Agency, 2009). Conflicts between different types of water usage can be expected to increase. Water consumption by tourists may lead to serious problems in dry summers with low water regimes (Leipprand et al., 2007; European Environment Agency, 2009).

Particularly spring habitats and wetlands could be severely threatened since natural spring habitats might be destroyed by anthropogenic water consumption. Especially the construction of water reservoirs for snow cannons cause ecological problems. For artificial snow-making, water is taken in a time period when the water level is already low (European Environment Agency, 2009). It was estimated that 17-43 million m^3 of additional water supply would be needed per year to serve all the ski areas in the Alps (Teich et al., 2007).

In some cases drought may affect ecotourism. For instance, a touristic waterfall may run out of water or a mire may dry up. The 2003 heat wave changed sensible habitats, which are partly subject to ecotourism. In the southern Alps mires suffered severe drought damages that could be still noticed four years after the drought (Bragazza, 2008).

Adaptation options for the tourism sector
(based on Leipprand et al., 2007; European Environment Agency, 2009)

In general, tourism is more flexible than forestry or water resources management. Some possible adaptation options are:

- Mitigating negative impacts on water resources.
- Altering tourism products towards activities that are less dependent on water use.
- Reducing water consumption (behavioural and technological adaptations).
- Promoting sustainable tourism.

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