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Mountain ecosystems in a changing environment

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Abstract

This essey summarizes some of the major drivers of environmental change in mountain ecosystems, highlights a few examples of plant and ecosystem responses to these changes, and will place these findings, the land use aspects in particular, in a longer term context. First, I will summarize a few basic characteristics of the world's mountains.

In a strikt sense, when rated by their ruggedness, the mountains of the world cover ca. 16 Mio km² or 12.5 % of the terrestrial surface outside Antarctica (Körner et al. 2011). Of that area, a global fraction of 2.6 % falls in the life zone above the climatic treeline, the alpine and nival belt. These highest elevation biota are overproportionally rich in species, with an estimated 4 % of all angiosperm taxa above the treeline, largely as a result of topographic diversity (Körner 2004). The treeline that separates the alpine from the montane belt is one of the most prominent **biogeographic boundaries** globally, and is defined by a minimum warmth during the growing season (a ca. 6 °C isotherm of the seasonal mean temperature), with the length of the growing season at treeline varying between 90 days at the polar circle and 365 at the equator (Körner 2012). Its almost exclusive setting by temperature makes it a prime candidate for responses to climatic warming.

One of the often overlooked key features of any mountain is the trivial fact that the land area is gradualy shrinking upslope with increasing elevation. Given the gradual reduction of temperature by ca. 0.55 K/100 m, mountains offer an exceptional diversity of thermal life conditions over very short geographical distances. For that reason, mountains are often considered an 'experiment by nature'. The close proximity of bioclimatic zones that might otherwise be found across several thousands of kilometers of latitude, is one of the main reasons why mountains accumulate more biodiversity per unit land area than their surroundings. Not surprisingly, mountains are hotspots of biological richness worldwide and thus, **prime target regions for conservation**. These aspects have to be kept in mind when discussing the likely consequences of global environmental changes in mountains.

What is subsumed under **global change** includes a broad variety of changes of global dimension, of which 5 major changes are particulary relevant for high elevation ecosystems: (1) the rise in mean temperature, (2) associated changes in water (and snow) relations, (3) atmospheric CO_2 enrichment as a direct influence on vegetation, (4) nitrogen deposition, and (5) changes in land use. In the following, I will briefly comment each with a focus on the European Alps, and will than address land use changes in more detail.

Climatic warming in the Alps is evident by meteorological records (a 1.5 K warming during the last century), the massive retreat of glaciers, and the lengthening of the snow free season, at least below 2000 m of elevation. Given that mountain climates are considered generally cold, climatic warming is thus, viewed as the central and most impacting facet of global change in mountains. However, this is a too simplistic view. What weather stations measure is not necessarily what all organisms experience. While trees operate very close to ambient temperatures, and are indeed experiencing better growth conditions than they might have faced during the last 500 years (Paulsen et al. 2000), low stature vegetation produces its own microenvironment. Using infrared thermography and hundreds of in situ sensors, it could be shown that topography (shelter and exposure to the sun) creates a multitude of climatic niches that may differ more on a single alpine slope than any worst case climatic warming scenario for the next 100 years (Scherrer & Körner 2010, Graham et al. 2012). As a consequence, these low stature plants and their animal and microbial partners are living in a mosaic of life conditions that offers microclimatic alternatives over the distance of a few meters. In fact, it was estimated that a 2 K warming on such a slope would remove merely 3 % of the coldest habitat types, which are inhabited by organisms that are abundant at higher elevations. It may be speculated that the richness in topography-driven climate variation over short distances is one of the reasons, why mountains were always **refugia** when climatic conditions changed. From that it may be expected that the relative proportion of the area of climatic microhabitats will change, but the taxa confined to such habitats are unlikely to go extinct or have to migrate over long distances to find suitable survival conditions. Hence, warming is largely an issue for trees and large animals. Trees have clearly responded to the warmer conditions as evidenced by treering data (Paulsen et al. 2000), and it is only a question of time for the treeline to expand upslope into the lower alpine belt.

Water relations will be affected by climatic change in several ways. A warmer air exerts more evaporative forcing. More precipitation will fall as rain than snow at lower elevations, snow duration will be reduced at lower than treeline elevation, but since a warmer air also carries more moisture to mountains, the winter snow pack may actually increase at high elevation, with the net balance difficult to predict. What is termed heat waves at low elevation, commonly translates into particularly 'good' summers at high elevation, given that moisture is not commonly limiting in the upper montane and alpine belt. Hence periodic drought will exert minor impacts on high elevation biota. The regional water balance will on average become more positive as annual precipitation increases, but regional differences may be substantial. A direct water stress-related impact on alpine biota and the treeline are highly unlikely in the Alps.

Direct influences of **elevated atmospheric CO_2**, the prime food of plants absorbed during photosynthesis, had been expected to be particularly influencial in high elevation terrain because of the low atmospheric pressure and thus, partial pressure of CO_2. However the evidence to date suggests no or even negative effects on alpine vegetation, that is aparently not carbon limited at current atmospheric concentrations (INAUEN et al. 2012). The negative effects that were observed may be transitory, and most likely relate to excess carbohydrate exudation by roots, that stimulates rhizosphere organisms, which become competitors for soil nutrients. Responses of high elevation forest trees were explored in two projects, with one study in montane *Picea abies* showing absolutely no growth effect of elevated CO_2, but rather a negative effect on tree nutrition for the reasons as described above (HÄTTENSCHWILER & KÖRNER 1998), and the others at the treeline, again showing no effect, in this case on *Pinus cembra*, but a stimulation of growth in isolated saplings of *Larix decidua*, that was tied to particularly warm summers, with a tendency to decline with time. Differential effects were seen in dwarf shrubs, with the montane *Vaccinium myrtillus* showing a stimulation, but the alpine *Empetrum hermaphroditum* and *Vaccinium uliginosum* remaining unresponsive (DAWES et al. 2013). So, while alpine grassland and glacier forfield vegetation is clearly not taking any advantage from elevated CO_2, some species in the montane belt may profit, potentially causing some abundance changes. As a caveat, it needs to be recalled that all these experiments are exposing vegetation to a step-change in CO_2 at a time in the recent history at which CO_2 concentration has already increased by 40% compared to pre-industrial levels.

Nitrogen deposition in the form of NO_x or NH_4 is often considered a lowland problem, closer to industrial/urban areas and intense agriculture. Indeed mountains receive much less N-deposition than lowlands, but the vegetation is much more sensitive, given its selection for coping with poor nutrition. HILTBRUNNER et al. (2005) assessed N deposition accumulating in snow in the Swiss Central Alps and arrived at an estimated overall current deposition of 5 kg N per hectare and year. Alpine plants have been shown to respond sensitively to rates of nitrogen deposition as low as 5-10 kg of N per hectare and year, with species exhibiting differential responses (sedges particularly responsive; E. Hiltbrunner pers. comm.). Hence, N deposition is clearly more likely to induce changes in alpine vegetation than elevated CO_2.

Mountain biota are under **landuse pressure** worldwide (SPEHN et al. 2006). The Alps are a region known for its sustainable landuse practices at high elevation. Millennia of traditional landuse have in fact ‚produced' highly diverse, stable ecosystems of high conservation value (high biodiversity, no soil erosion). Undesired changes go in several directions: (1) destructive over-utilization followed by soil erosion, a problem of over-populated mountain regions mainly in developing countries, (2) a rapid under-utilization or abandonment leading to unstable transition stages that neither exert the benefit of the former cultural landscape nor the advantage of the original montane forests (avalanche protection, slope stabilization; TASSER et al. 2003). (3) Easily accessible (valley) terrain gets converted to species-poor, intensively used farmland with high fertilizer input. (4) under humid conditions many high elevation pastures become overgrown by native, but invasive species such as *Rhododendron ferrugineum*, *Calluna vulgaris* and other types of small as well as tall shrubs such as *Alnus viridis* (with accompanying *Salix* and *Sorbus*). These novel and extensive shrublands are unwanted for several reasons. First, they ruin the former grassland. Second, they slow or even prevent forest succession. Third, in the case of *Alnus*, N-fixing symbionts cause ecosystem N eutrophication, with a lush herb layer effectively suppressing tree seedling establishment, and polluting runoff water with excess nitrate. These thickets are most effectively battled against by specialized browsers such as goats or an old breed of sheep, the Engadine sheep (Bühlmann et al. in press).

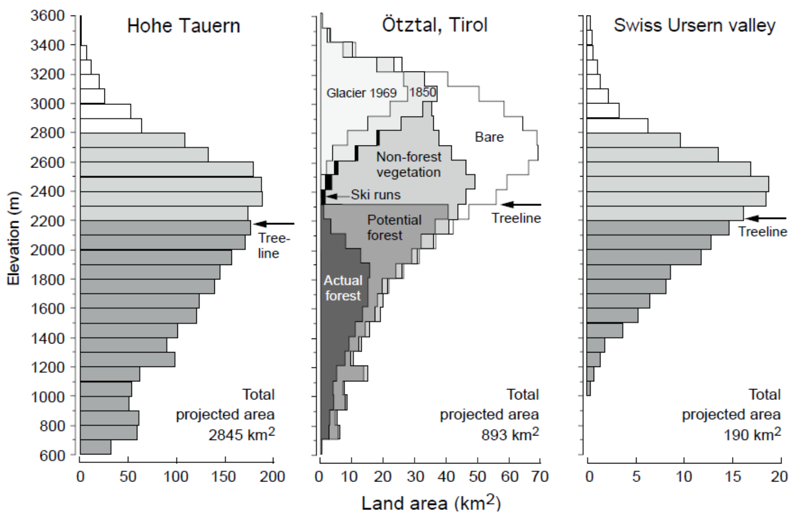

Figure 1: The elevational stratification of land area in three high mountain regions. (a) The Hohe Tauern region across a N-S transect from the Salzach to the Drau Valley; (b) the Ötztal region in Tirol, illustrating land cover categories, including ‚new land' released by glacier retreat (from Patzelt 1996 as modified in KÖRNER 2003); (c) for the Swiss Ursern Valley in the upper Reuss catchment. Note the climatic treeline in each area, separating the montane from the alpine belt.

The potential land area likely to undergo such successional stages is large. Geostatistics of land area per elevation evidences that the largest fraction of land area in the Alps is situated in the upper montane and lower alpine belt, the areas most likely facing declining landuse within the coming decades (Fig. 1).

Such statistics are best not confined by political boundaries (such as boundaries of countries, districts or national parks) but cover defined transects as set by geology and rivers (Fig. 2) as exemplified for the Hohe Tauern region. Using coarse **land cover statistics** for this area as assessed in the 1960s and 1970s, illustrates the situation close to the starting conditions before the most rapid phase of land abandonment is likely to have taken place (Fig. 3). As shown by the grid-specific land cover categories, 23% of the landscape was under extensive agricultural use below the treeline ba that time. A large fraction of this terrain will undergo successional land cover changes toward shrubland and montane forest. During the census in the area in the 1960s and 1970s (total selected area 2845 km² = 100%), 14.8% were covered by glaciers, rock and scree, 22.9% by alpine vegetation, 7.8% by lower alpine dwarf shrub heath, 2.7% by tall shrubs such as *Alnus* bush, 23.7% by coniferous forest, 2% by deciduous broad-leaved forest, 16.3% by pastures, and 6.7% by hay meadows. Agricultural cropland and settlements cover 3% of this area. If the trends are similar to those in the Swiss Alps, the tall shrub fraction should have doubled at least since then, and the area covered with forest will approach 30% at the cost of grassland.

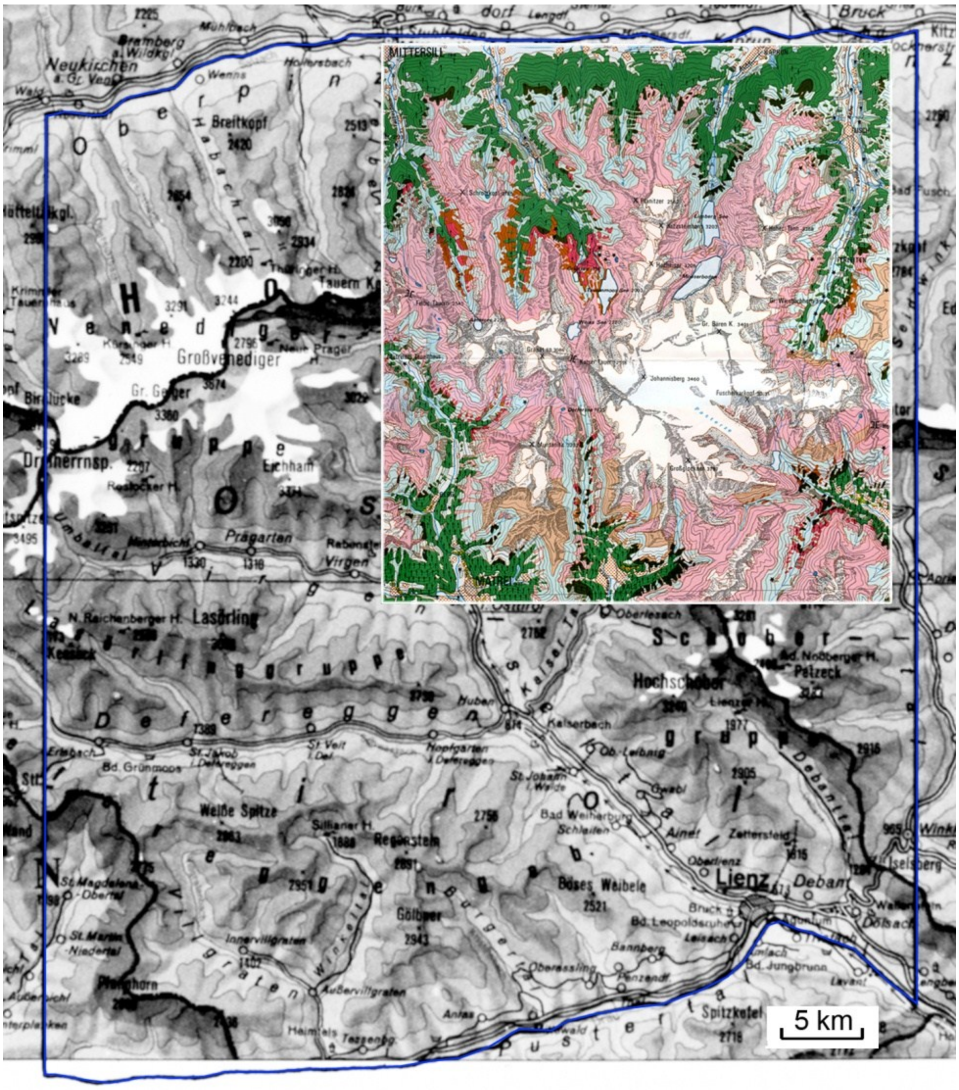

Figure 2 Geostatistical analysis of mountain terrain should be based on tectonic/geomorphological units (inset showing a transect from the Salzach to the Drau line (see Fig. 1a). The colored map shows the land cover categories as assessed by Ozenda (1975, 1984; see KÖRNER 1989).

The policy against such practically near to irreversible land cover changes takes its motivation largely from preserving a cultural heritage, maintaining farming activities for their own sake, or from a conservation point of view (biodiversity). There is evidence that such landuse changes have negative **hydrological implications** that so far are not accounted for in a more holistic consideration. First assessed in a pilot study in the Hohe Tauern region (KÖRNER et al. 1989, KÖRNER 2003), it is now confirmed across elevations that land abandoment causes evapotranspiration to increase by about 12% in the alpine belt, corresponding to similar reductions in runoff and thus hydroelectrical potential (INAUEN et al. 2013, T. van den Berg et al. unpublished). These losses of hydroelectrical potential need to be considered in management decisions for the maintenance of high elevation grassland. Overall, landuse changes are likely to exert the greatest impacts on high elevation biota in the Alps compared to all before-mentioned facets of global change.

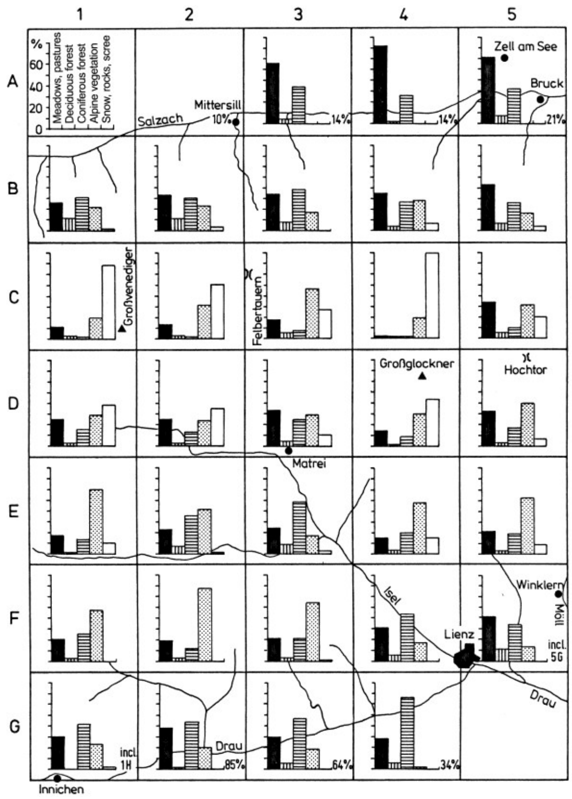

Figure 3: Land cover statistics for the Hohe Tauern region (area as in the inset of Fig. 2) using maps as shown in Fig. 2 (KÖRNER 1989).

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