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# Climate change and timber line in the European mountains – current knowledge and perspectives

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High mountain ecosystems are considered particularly vulnerable to climate change because productivity, composition, and diversity are directly limited by temperature. The European Alps experienced a 2° C increase in annual minimum temperatures during the twentieth century, with a marked rise since the early 1980s. Alpine plants have moved upward, community composition has changed at high alpine sites, and tree line species have responded to climate warming by invading the alpine zone and increasing growth rates during the last decades (Dirnböck *et al.* 2003). Some invasive species was introduced in multiple sites and subsequently dispersed to many other locations. On the other side severe declines of several rare plant species have been documented in the Western Swiss Alps. In this paper, I provide a brief synthesis of the current knowledge and perspectives regarding climate change and timber line in the European mountains.

The high altitude limit of forests, commonly referred to as tree line, timber line or forest line represents one of the most obvious vegetation ecotones. Most authors define tree line as the connecting line between the uppermost forest patches in an area, with trees upright, growing in groups, and at least 3m in height (Körner and Paulsen 2004). The upper limit of timber line is conditional on the cumulative effects of several factors. The factor that primarily determines timber line can be used to define types of timber line. Plesník (1971) recognized four types of upper timber line: climatic, orographic, avalanche and edaphic. More recently, Jodłowski (2007) has distinguished five boundary types using the example of dwarf pine (*Pinus mugo*). These include: orographic, morphological, edaphic, mechanically lowered and anthropogenic dwarf pine line. An orographic timber line is located in the valley bottoms or on the watershed ridges and is controlled by climatic factors (e.g. solar radiation and wind). An edaphic timber line results from lack of soil cover on talus slopes with block covers. A morphological line corresponds with slope-breaks or footsteps of rockfaces. A mechanically lowered timber line is controlled by avalanches or debris flows. Finally, an anthropogenic timber line exists where sites with intensive mountain-pine reconstruction have moved trees several hundred meters upslope and there is an abrupt transition between mountain-pine thickets and alpine meadows.

Tree lines are primarily considered to be thermally controlled, so increases in temperature should result in their upslope expansion (Moen 2006). Although forest composition and geographic distributions of canopy trees are expected to shift with global warming, it is not clear what level of inertia, or time lag, forests will display to climatic forcing nor how strong the relationship will be between warming and tree line rise (Beckage *et al.* 2008). Grace *et al.* (2002) considered the possible effects of climate change on the advance of the tree line. As temperature, elevated $CO^2$ and nitrogen deposition covary, it is impossible to disentangle their impacts without performing experiments. However, it does seem very unlikely that photosynthesis per se and, by implication, factors that directly influence photosynthesis, such as elevated $CO^2$, will be as important as those factors which influence the capacity of the tree to use the products of photosynthesis, such as temperature. Despite over a century of research, our understanding of how tree line is determined by environmental variables remains limited. Currently, there is much interest in the rate at which the tree line may advance in response to environmental change, especially global warming. There are at least three aspects of environmental change to which plants are generally thought to respond: increasing temperature, rising concentration of carbon dioxide, and increasing deposition of nitrogen. Models designed to predict the impact of climate change on tree lines need to incorporate these complexities and an understanding of energy balance, physiology and reproductive biology. Even then, there is evidence that tree lines in mountains may be more influenced by the grazing of seedlings and saplings than most people have supposed.

Casty *et al.* (2005) remarks that in the European Alps the years 1994, 2000, 2002, and particularly 2003 were the warmest since 1500. Lapin *et al.* (2005) detected similar climate changes in the Slovak mountains. The results showed a very significant increase in temperature and a decrease in relative humidity in the April to August season after 1990. From 1901-2005 air temperature increased (annual mean) moderately and precipitation decreased (Melo 2007). This trend of warming is expected to continue in the Slovak mountains. Results of three general circulation models show at the end of the 21st Century additional warming on this territory. In Slovakia, we expect annual average air temperature to increase by about 2-4° C by 2075

(Minďáš and Škvarenina 2003). Minďáš *et al.* (2004) predict the following changes in an area of dwarf-pine zone timber line: an increase in the abundance of tree species, dominant representation of spruce, a decrease of dwarf pine and an increase of general production and biomass of about 200-300%.

In addition to climate change, human land use may drive changes in tree line. Land use in sub-alpine and alpine areas (grazing, extraction) affects distribution of flora as well as climate. Since the 13-14$^{th}$ Century, anthropogenic degradation has involved clearing mountain-pine thickets to obtain new pastures for sheep and cattle grazing, for extensive charcoal and oil production, and for cooper and iron ore mining. Jodłowski (2007) described that establishing national parks in the Tatra, Babia Góra and Giant Mts. enabled secondary succession, which has led to colonization of previously abandoned habitats. However, these processes have been hampered by harsh edaphic and climatic conditions as well as by avalanches and debris flows. Extensive planting of mountain-pine in former Czechoslovakia significantly facilitated the renovation of dwarf pine thickets. After the absolute restriction of grazing in some national parks we have observed progressive long-term trends in secondary succession and patterns of plant establishment driven by climate. Closed mountain-pine thickets stretch up to 300m above timber line reaching approximately 1,600-1,750m a.s.l. in the Tatras. Encompassing the upper part of the forest alpine tundra ecotone. Mountain pine plays a significant role in the functioning of the natural environment – it protects the soil and stabilizes the snow cover, thus restricting the release of avalanches and provides habitat for many species of flora and fauna (Jodłowski 2006).

Clearly, it is important to consider climate in concert with land-use when predicting how tree line may change in the future. A wide array of models has been developed to cover aspects as diverse as biogeography, conservation biology, climate change research, and habitat or species management (Guisan and Zimmermann 2000). Potential response of alpine plant species distribution to different future climatic and land-use scenarios were assessed by Dirnböck *et al.* (2003). They used ordinal regression models of 85 alpine plant species based on environmental constraints and land use to determine their abundance in the north-eastern Calcareous Alps. Site conditions were simulated spatially using GIS, a Digital Terrain Model, meteorological station data and existing maps. Historical records were used to assess land-use impacts on vegetation patterns in combination with climatic changes. Their applied modeling approach was based on three major assumptions: the abiotic environment is a major agent controlling species distribution and abundance together with post-grazing succession; the models are calibrated using field data and thus comprise any competitive constraint a species may force upon or experience from its neighbour; the speed of plant migration is consistent with that of climate changes so that plant communities are in a permanent equilibrium with their environment. The result of this study supported earlier hypotheses that alpine plant species on mountain ranges with restricted habitat availability above tree line will experience severe fragmentation and habitat loss, but only if the mean annual temperature increases by 2˚ C or more. Even in temperate alpine regions it is important to consider precipitation in addition to temperature when climate impacts are to be assessed. Land-use, in particular logging and grazing in the high mountain areas, influences a plant´ s distribution as climate does. The maintenance of large summer farms may contribute to preventing the expected loss of non-forest habitats for alpine plant species.

In addition to land use factors, the ability of vegetation to disperse and resist invasion may strongly influence patterns of tree line. Global warming will likely shift tree lines upslope in alpine areas and towards the pole in arctic environments. However, responses of regional tree lines to climatic trends over the last century do not show any clear trends. Dullinger *et al.* (2004) hypothesizes that these equivocal responses may partly be caused by limitation of dispersal and/or recruitment that is species-specific to particular trees with potentially expanding ranges. To test this hypothesis a temporally and spatially explicit model of plant spread was created and its sensitivity to variation in predicted climatic trends was analyzed. Data from a high mountain landscape of the Northern Calcareous Alps in Austria where the tree line is dominated by Pinus mugo were used. They found that variation in the spatial distribution of recruits around a seed source and variation in the resistance of resident non-woody vegetation to invasion. Low growth rates and long generation times, together with considerable dispersal and recruitment limitation, resulted in an overall slow range expansion under various climate warming scenarios. Running the model for 1000 years predicted that the area covered by pines will increase from 10% to between 24% and 59% of the study landscape. The shape of the dispersal curve and spatial patterns of competitively controlled recruitment suppression affect range size dynamics at least as severely as does variation in assumed future mean annual temperature (between 0˚ C and 2˚ C above the current mean). Moreover, invasibility and the shape of the dispersal curve interact with each other due to the spatial patterns of vegetation cover in the region. Ambiguous transient responses of individual tree line systems may thus originate not only from variation in regional climatic trends but also from differences in species' dispersal and recruitment behaviour and in the intensity and pattern of resistance of resident alpine vegetation to invasion.

Understanding the relative impacts of biotic, land-use, and climate changes on tree line is critical for predicting future changes. Gehrig-Fasel *et al.* (2007) analyzed forest regeneration in the tree line ecotone in the Swiss Alps between 1985 and 1997. Forest expansion was quantified using data from the repeated Swiss land use statistics GEOSTAT. A moving window algorithm was developed to distinguish between forest ingrowth and upward shift. To test for a possible climate change influence, the identified upward shifts were compared to the potential regional tree line by calculating the difference in elevation of the respective pixels. The altitude of the potential regional tree line was thereby considered as a reference. Upward shifts above the potential regional tree line were considered to be influenced primarily by climate change, while upward shifts below the potential regional tree line were interpreted as primarily influenced by land abandonment. A significant increase of forest cover was found between 1,650m and 2,450m. Above 1,650m, 10% of the new forest areas were identified as true upward shifts whereas 90% represented ingrowth, where both land use and climate change were likely drivers. Most upward shift activities were found to occur within a band of 300m below the potential regional tree line, indicating land use as the most likely driver. Only 4% of the upward shifts were identified to rise above the potential regional tree line, thus indicating climate change. Land abandonment was the most dominant driver for the establishment of new forest areas, even at the tree line ecotone. However, a small fraction of upwards shift can be attributed to the recent climate warming, a fraction that is likely to increase further if climate continues to warm, and with a longer time-span between warming and measurement of forest cover.

Nicolussi and Patzelt (2006) describe that alpine timber line zone is very sensitive to climate variability. They conducted tree - ring analyses (dendrochronology) in the Tyrolean Central Alps and found that the rise of temperatures during the vegetation period over long periods induces also a rise of the tree line with higher forest stand density. Temperature reductions, however, led to less dense forests and a drop of the timber line. For the assessment and classification of present conditions it would be reasonable to refer not only to the last centuries (being well documented) but to the whole post glacial period, which means the last 11,000 years. Timber line migration during the post glacial period can be determined now by dendrochronological analyses of tree remnants, some of them dating back thousands of years. A comparison of the migration of alpine timber line with glacial variations during the last 11,000 years confirms the picture of a climatically favourable early and mid-post glacial period. Today's average temperatures have not yet reached the average maxima of this period even if the current level is clearly below the average of the past millennium.

Oberhuber (2008) states that effects of climate change should be seen first at boundaries of tree existence. He examined growth response of *Pinus cembra* and *Pinus sylvestris*, which form widespread forest ecosystems at the timber line of the Central Alps. Growth-climate relationships revealed that mean July temperature is the major and temporal stable driving force of *Pinus cembra* growth within the timber line ecotone. Körner and Paulsen (2004) present the results of a data-logging campaign at 46 tree line sites between 68° N and 42° S. They measured root-zone temperatures with an hourly resolution over 1-3 years per site between 1996 and 2003. The data support the hypothesis of a common thermal threshold for forest growth at high elevation but also reflect a moderate region and substantial taxonomic influence. Heiri *et al.* (2006) used the forest succession model ForClim to simulate Holocene tree line dynamics along an elevational transect in the Central European Alps, in order to explore the extent and cause of changes in tree line altitude and composition. Results indicate that changes in temperature alone can account for changes in tree line elevation for the first half of the Holocene and strong human influence on the Alpine tree line during the late Holocene. Esper and Schweingruber (2004) using the example of Siberia state that both tree line changes and growth increases correspond with decadal-scale periods of temperatures that are warmer than in any other period since observations started, suggesting the sensitivity of large-scale tree line changes for this climatic forcing. Vescovi *et al.* (2007) suggest that tree line ascended by ca 800-1,000m in a few centuries at most, probably as a consequence of climatic warming. The climate-driven tree line in the Tatra Mountains is situated around 1,550m a.s.l. and includes partly natural ecotones with individual conifers reaching ages of 350-450 years (Büntgen *et al.* 2007). Recent changes of climate and land-use are often regarded to affect the European Alpine region substantially and to trigger an increase in the elevation of the upper tree line (Bolli *et al.* 2007). Wieser (2008) warns that changes may have important implications on biogeochemical cycles and probably also on biodiversity within the timber line ecotone. Such orientated research brings not only concrete statistical-spatial information about the landscape structure and its changes but it is also important from point of view of further prediction about human influence on a high-mountain landscape and its management.

## References

Beckage, B., Osborne, B., Gavin, D.G., Pucko, C., Siccama, T. and Perkins, T. 2008: A rapid upward shift of a forest ecotone during 40 years of warming in the Green Mountains of Vermont. *Proceedings of the National Academy of Sciences of the USA*, **105**: 4197-4202.

Bolli, J.C., Rigling, A. and Bugmann, H. 2007: The influence of changes in climate and land-use on regeneration dynamics of Norway spruce at the tree line in the Swiss Alps. *Silva Fennica*, **41**(**1**): 55-70.

Büntgen, U., Frank, D.C., Kaczka, R.J., Verstege, A., Zwijacz-Kozica, T. and Esper, J. 2007: Growth responses to climate in a multi-species tree-ring network in the Western Carpathian Tatra Mountains, Poland and Slovakia. *Tree Physiology*, **27**: 689-702.

Casty, C., Wanner, H., Luterbacher, J., Esper, J. and Böhm, R. 2005: Temperature and Precipitation variability in the European Alps since 1500. *International Journal of Climatology*, **25**: 1855-1880.

Dirnböck, T., Dullinger, S. and Grabherr, G. 2003: A regional impact assessment of climate and land-use change on alpine vegetation. *Journal of Biogeography*, **30**: 401–417.

Dullinger, S., Dirnböck, T. and Grabherr, G. 2004: Modelling climate change-driven tree line shifts: relative effects of temperature increase, dispersal and invasibility. *Journal of ecology*, **92**: 241-252.

Esper, J. and Schweingruber, F.H. 2004: Large-scale tree line changes recorded in Siberia. *Geophysical Research Letters*, **31**, L06202, doi:10.1029/2003GL019178.

Gehrig-Fasel, J., Guisan, A. and Zimmermann, N.E. 2007: Tree line shifts in the Swiss Alps: Climate change or land abandonment? *Journal of Vegetation Science*, **18**: 571-582.

Grace, J., Berninger, F. and Nagy, L. 2002: Impacts of climate change on the tree line. *Annals of Botany*, **90**: 537-544.

Guisan, A. and Zimmermann, N.E. 2000: Predictive habitat distribution models in ecology. *Ecological Modelling*, **135**: 147–186.

Heiri, C., Bugmann, H., Tinner, W., Heiri, O. and Lischke, H. 2006: A model-based reconstruction of Holocene tree line dynamics in the Central Swiss Alps. *Journal of Ecology*, **94**: 206-216.

Jodłowski, M. 2006: Anthropogenic transformation of the krummholz-line in some mountain ranges in Central Europe. In *Global change in mountain regions.* pp. 186-187. Sapiens Publishing, UK.

Jodłowski, M. 2007: Krummholz-line in the Tatra Mts. Babia Góra and the Giant Mts. Ecotone structure and dynamics. The Institute of Geography and Spatial Management of the Jagiellonian University, Kraków.

Körner, Ch. and Paulsen, J. 2004: A world-wide study of high altitude tree line temperatures. *Journal of Biogeography,* **31**: 713-732.

Lapin, M., Šťastný, P. and Chmelík, M. 2005: Detection of climate change in the Slovak mountains. *Croatian Meteorological Journal*, **40**: 101-104.

Melo, M. 2007: Regional climatic scenarios for Slovak mountain region based on three global GCMs. *29$^{th}$ International Conference on Alpine Meteorology, 4-8 June, 2007 Chambéry, France: Extended Abstracts. Poster Sessions* **2:** 437-440.

Minďáš, J. and Škvarenina J. (eds.) 2003: Lesy Slovenska a globálne klimatické zmeny. EFRA Zvolen, Lesnícky výskumný ústav Zvolen.

Minďáš, J., Čaboun, V. and Priwitzer, T. 2004: Horná hranica lesa a očakávané klimatické zmeny. In *Zborník Turiec a Fatra*, Vrútky, p. 17-23.

Moen, J. 2006: Tree line dynamics in a changing climate. In *Global change in mountain regions.* pp. 187-188. Sapiens Publishing, UK.

Nicolussi, K. and Patzelt, G. 2006: Klimawandel und Veränderungen an der alpinen Waldgrenze - aktuelle Entwicklungen im Vergleich zur Nacheiszeit. BFW-Praxisinformation 10, April 2006, Wien, p. 3-5.

Oberhuber, W. 2008: Tree growth response to recent climate warming at boundaries of tree existence in the Alps. *Proceedings from COST strategic workshop: global change and sustainable development in mountain regions, 7 – 9 April, 2008, Innsbruck:* 32-33.

Plesník, P. 1971: Horná hranica lesa vo Vysokých a v Belanských Tatrách. Vydavateľstvo SAV, Bratislava.

Vescovi, E., Ravazzi, C., Arpenti, E., Finsinger, W., Pini, R., Valsecchi, V., Wick, L., Ammann, B. and Tinner, W. 2007: Interactions between climate and vegetation during the Lateglacial period as recorded by lake and mire sediment archives in Northern Italy and Southern Switzerland. *Quaternary Science Reviews*, **26**: 1650-1669.

Wieser, G. 2008: Risks of climate change on high elevation forests in Central Europe? *Proceedings from COST strategic workshop: global change and sustainable development in mountain regions, 7 – 9 April, 2008, Innsbruck:* 44.