Dwarf Pine (*Pinus mugo*) and Selected Abiotic Habitat Conditions in the Western Tatra Mountains

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The present paper focuses on the distribution of *Pinus mugo* in the Carpathians, in an area on the border between Slovakia and Poland. We analyze the response of *P. mugo* distribution to abiotic habitat conditions in the western Tatra Mountains and discuss possible implications for research. The source data for this study were aerial photographs from 3 periods (1965, 1986, and 2002). Mountain areas covered by dwarf pine were identified and analyzed by ArcGIS 9.2, and pine fields were classified with the help of the gray scale mode. A strip of dwarf pine above the upper limit of the forest represents a well-identifiable boundary on the aerial photographs: 25 well-recognized localities were selected to examine the changes in the tree line in the western Tatras. The distribution of dwarf pine systematically increased in the western Tatra Mountains from 1965 to 2002 on all monitored sites. The percentage of total surface area covered in *P. mugo* increased from 41.8% in 1965 to 51.8% in 1986 and to 58.2% in 2002. The study also analyzes the dispersal of dwarf pine over 40 years in relation with slope and elevation. The results of this study explain ongoing and future vegetation changes and can be used as an important contribution to monitoring of climate change in the mid-European mountain areas.

**Keywords:** Abiotic habitat conditions; climate change; land use change; *Pinus mugo*; principal component analysis (PCA); Carpathians; Slovakia; Poland.

Introduction

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 20th century, with a marked rise since the early 1980s (Beniston et al 1997). Alpine plants have moved upward, community composition has changed at high alpine sites, and tree line species have responded to climate warming by invasion of the alpine zone or increased growth rates during the last decades (Dirnbock et al 2003; Węzyk and Guzik 2004). The coniferous forest zone has a general tendency to increase in elevation (Mihai et al 2007; Sitko and Troll 2008). Recent changes of climate and land use are often considered to affect the European alpine region substantially and to trigger an increase in the elevation of the upper tree line (Bolli et al 2007). 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) have considered the possible effects of climate change on the advance of the tree line. Nicolussi and Patzelt (2006) describe the alpine timberline zone as very sensitive to climate variability. The rise of temperatures during the vegetation period over long periods also induces a rise of the tree line, with higher forest stand density. Vescovi et al (2007) suggest that the tree line ascended by about 800–1000 m in a few centuries at most, probably as a consequence of climatic warming.

Both forest management and pasture abandonment have also caused dramatic vegetation changes (Baur et al 2007). The historical effect of human use on vegetation in mountain areas greatly limits approaches based only on an assessment of current climatic change. The subalpine *Pinus mugo* quickly establishes itself on areas modified by human use and transforms the vegetation cover from former pastureland to a 2-m-high “forest” (Dirnbock and Grabherr 2000). Among others, this has hydrological effects, as the strong root system of *P. mugo* increases soil pores and consequently increases water drainage (Dirnbock and Grabherr 2000). Becker et al (2007) have stated that human-driven land use and land cover changes affect important ecosystem services (vegetation shifts, biodiversity, phytomass production, carbon sequestration, and water relationships). Wieser (2008) warns that changes may have important implications on biogeochemical cycles and probably on biodiversity within the timberline ecotone. Climate change will impact rare and invasive species (Randin et al 2009). On the one hand, some invasive species have been...
introduced in multiple sites and subsequently dispersed to many other locations (Eliáš 2009). On the other hand, severe declines of several rare plant species have been documented in the western Swiss Alps (Parisod 2008). Therefore, priority in research has been given to monitoring activities for understanding processes and for modeling and validating concepts of natural and socioeconomic developments (Bugmann et al. 2007). Such orientated research not only brings concrete statistical–spatial information about the structure of landscapes and changes in landscapes but also helps further predict human influence on a high-mountain landscape and its management (Kellerer-Pirkbauer 2002).

Clearly, it is important to consider climate in concert with land use when predicting vegetation change in the future. An 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 responses of alpine plant species distribution to different future climatic and land use scenarios is a subject of much research. Dirnbock et al (2003) used ordinal regression models of 85 alpine plant species based on environmental constraints and land use to determine their abundance in the northeastern Calcareous Alps. Dullinger et al (2004) used a temporally and spatially explicit model of plant spread, parameterized and analyzed its sensitivity to variation in predicted climatic trends, and described the spatial distribution of vegetation in the northern Calcareous Alps. The tree line is dominated by P. mugo. Gehrig-Fasel et al (2007) analyzed forest regeneration in the tree line ecotone in the Swiss Alps between 1985 and 1997, including possible drivers.

The approach presented in our study aimed to analyze the response—in terms of spatial distribution—of P. mugo influenced by abiotic habitat conditions in the western Tatra Mountains and to describe possible implications for research in the context of human and natural environmental change. As the highest mountain range in the Carpathians, the Tatra Mountains were selected as the study site. The strip of dwarf pine above the upper limit of the forest represents a well-identifiable boundary in aerial photographs. Jodkowski (2007) used the example of the dwarf pine line as a type of boundary timberline. Growth of dwarf pine (P. mugo) is affected by internal and external conditions; external conditions are climate, soil, height above sea level (asl), and historical human impact (Somora 1981). The appearance of dwarf pine is connected with site conditions, especially with soil, which segregates competition of shadow trees, mostly spruce (Picea abies). Another important factor is the intensity of light.

Apart from climatic effects, it is necessary to take into consideration factors including land use. The historical human effect on vegetation in the Tatra Mountains (Plesník 1978) greatly limits approaches toward trying to find equivalent indications of current climatic change. In the western Tatra Mountains, human use consisted mainly of grazing, which from the 16th century influenced the subalpine and alpine vegetal zones (Harvan 1965). Grazing was prohibited as of the early 1950s, when the Tatras became a national park. After this absolute restriction on grazing, we can observe a progressive long-term trend of secondary succession and climatic-related interaction of vegetal societies. This paper tries to verify trends in the spread of P. mugo and uses other variables to specify the method of expansion.

**Study area and study species**

The Tatra Mountains are situated at the Slovak–Polish border (20°10’E, 49°10’N) and constitute the highest mountain massif within the Carpathian Range of Central Europe. The highest summit reaches 2656 m; the massif is classified as a high-mountain landscape. The study area (Figure 1) is situated in the western Tatra Mountains and covers the subalpine and alpine zones. The geology of the investigated area is based on crystalline bedrock. The western Tatra Mountains contain a significant amount of metamorphics (gneiss and mica schist), in addition to granodiorite (Nemčok et al 1993). The vegetation of the alpine zone is dominated by alpine meadows (dry tundra with mostly Festuca picturata, Luzula alpino-pilosa, Calamagrostis villosa, and Juncus trifidus), with patches of dwarf pine (P. mugo) and an increasing percentage of rocks (bare or covered with lichens—commonly Rhizocarpon, Acaeospora oxytona, and Dermatocarpon luridum) above the upper tree line of 1800 masl (Voľoščuk 1994).

The average annual air temperature decreases with elevation by 0.6°C per 100 m, being 1.6 and −3.8°C at elevations of 1778 and 2635 m, respectively (Konček and Orlicz 1974). The amount of precipitation increases with the rise in elevation, varying from ~1.0 to ~1.6 m yr⁻¹ between 1330 and 2635 masl but reaching >2.00 m yr⁻¹ in some valleys (Chomitz and Samaj 1974). Precipitation is generally higher in the northern part than in the southern part of the mountains, as is runoff, which averages 1.42 and 1.57 m yr⁻¹ for the south and north, respectively (Lajczak 1996). Snow cover usually lasts from October to June at elevations > 2000 masl.

The relationship between climatic conditions of the environment (microclimate and vertical climate) and phytocenosis is expressed in different altitudinal zones in the forest. Climatic conditions definitively influenced the natural distribution of forest species; they were constant from the sub-Atlantic period (around 2000 years ago), when the current altitudinal zones were formed. Significant changes in structure also have been conditioned by intense human activity since the 13th century. Ecologically, forest altitudinal zones represent vertical classification of vegetation. Horizontal classification is determined by growth condition of forest societies, differentiated especially according to soil
conditions, ecological rows, interrows, and hydric files of forest type groups. The climate-driven tree line in the Tatra Mountains is situated around 1550 masl and partly includes natural ecotones with individual conifers reaching ages of 350–450 years (Büntgen et al 2007).

*P. mugo* is an obligatory prostrate pine with adult canopy height varying between 0.3 and 2.5 m in the study area. The typical dwarf pine altitudinal (subalpine) zone extends from 1500 to between 1850 and 1900 masl; it developed especially in the western Tatras with glacial-meadow relief, with great antierosion and water retention potential. Closed mountain-pine thickets stretch up to 300 m above timberline, reaching approximately 1600–1750 masl in the Tatras and 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 it provides habitat for many species of flora and fauna (Jodłowski 2006).

**Material and methods**

Aerial images from 2002 were acquired and georeferenced by Eurosense Ltd. and Geodis Slovakia on the basis of contour lines at a scale 1:10,000 (digital elevation model); we georeferenced aerial photographs from 1986 and 1965 on the basis of orthophotos (Table 1).

Dwarf pine fields were extracted as vectors. The orthophotos in gray scale and panchromatic aerial photos were reclassified according to the gray scale range that represented dwarf pine occurrence in the study area. Each photo was examined separately. If dwarf pine on the slide was gray, with a value from 75 to 110, all such values in the range were reclassified as 1. The remaining values from 0 to 75 and 110 to 256 were reclassified as 0. We created a grid where each pixel contained either the value 1 or the value 0. Then the grid was automatically vectorized on the basis of the 2 values. Histogram transformation because of misrepresentation of values

**FIGURE 1** Western Tatra Mountains in Slovakia and detailed view of the 25 localities in the study area (from west to east: Roháč, Baníkov, Baranec, Bystrá, Jamnická, Račkova, Kamenistá, Ticha, Kôprová, and Špania valleys). (Map by Jaroslav Solár)

**TABLE 1** Quality and resolution of data features (aerial imagery).

| Year | Source                  | Type            | Resolution   | Width | Height | Format |
|------|-------------------------|-----------------|--------------|-------|--------|--------|
| 2002 | Eurosense Slovakia      | Orthophoto      | RBG 72 DPI   | 2500  | 2000   | .jpg   |
| 1986 | Topographical Institute | Aerial photo    | Gray 2400 DPI| 21,829| 21,924 | .tiff  |
| 1965 | Kňazovický              | Aerial photo    | Gray 300 DPI | 2164  | 2175   | .jpg   |

DPI, dots per inch; RBG, red green blue.
was not realized. The size of the pixels’ (cell) grid was equivalent, because each image was adjusted to the same size cell size in the transformation of the grid, as well as in the georeferencing; thus, all images and the grids had the same pixels (Figure 2).

Selection of the appropriate areas, which represented 25 localities from the study area, and analysis of imagery were realized in ArcGIS 9.2. Differences in the *P. mugo* surface cover between the 2 periods were calculated using Statistica 8. The increments in dwarf pine were reported as means and standard deviations for potential comparison with other studies, but the values showed a highly skewed distribution in most sample groups. Therefore, a nonparametric approach to the analysis of the data was necessary. The significance of difference between groups was tested using the Kruskal–Wallis nonparametric test. When *P* < 0.05, the data were considered as significantly different.

A digital elevation model served as the main input for the representation of a selection of abiotic habitat conditions. One matrix was analyzed. Intersecting of study areas with 3 parameters (slope, aspect, and height asl) created 325 small localities with characteristics related to pine increase. Two localities (nos. 5 and 9; Table 2) were excluded due to lack of data from 1986. A multivariate technique, principal component analysis (PCA)–correlation matrix, was used to extract the potential interdependence among mentioned variables. Principal components are linear combinations of original variables (slope, height asl, and relative increase of pine during observed periods), each axis being statistically orthogonal to the others. Integration of the variables slope and height asl to increase of pine in different periods enabled us to follow different processes of mountain colonization by pine during the different periods. Because the technique produces statistically orthogonal axes, we were able to examine potentially independent biological phenomena. We use 4 variables; consequently, we evaluated 4 principal components. We tabulated the proportion of the total variance accounted for by each component.

**Results**

Dwarf pine permanently increased in the western Tatra Mountains in the period 1965–2002 on all monitored sites. The total surface area covered by dwarf pine increased from 8,173,812 m² in 1965 to 10,141,505 m² in 1986 and 11,394,461 m² in 2002. The percentage of total surface area covered thus increased from 41.8% in 1965 to 51.8% in 1986 and 58.2% in 2002. Only in 1 case (no. 25) did surface area covered by dwarf pine decrease.
In 2 cases (nos. 21 and 24) the area decreased in the first and increased in the second period (Figure 3; Table 2). This was probably due to influence by human activities or avalanches.

From 1965 to 1986, dwarf pine tended to grow rapidly at the lower elevations (Figure 4A; Table 3—PC1). This indicates ability of pine to recolonize sites from previous periods. In the period from 1986 to 2002, pine grew rapidly on steeper slopes (Table 3—PC2), mainly at elevations from 1500 to 1700 m (Figure 4B). In the first period measured, dwarf pine was able to densify to such a level at elevations between 1300–1400 masl that in the second period it further filled the area and increments were minimal. The third factor (Table 3—PC3) is less important for explaining pine increments: it shows a positive relationship between slope and elevation. PC4 (Table 3) is a unipolar vector indicating that pine grew more rapidly in the earlier period (1965–1986) than the later period (1986–2002). In the earlier period it grew intensely at all locations (Figure 4C), whereas in the period 1986–2002 it mainly preferred northwest and northeast aspects on steeper slopes, probably the most suitable locations for plant development in the Tatra Mountains. In both periods, the increments in the areas covered by dwarf pine were very low at the elevation of 1900 m, reflecting its natural upper line of occurrence. In

### TABLE 2  Overview of evaluated localities with differences in P. mugo cover in the period.

| Site number | Average altitude (masl) | Average slope (%) | Covered with *Pinus* (%) | Difference (+/−) |
|-------------|-------------------------|-------------------|---------------------------|-----------------|
| 1           | 1674                    | 34                | 27                        | +1/+20          |
| 2           | 1670                    | 46                | 7                         | +9/+11          |
| 3           | 1614                    | 44                | 29                        | +9/+23          |
| 4           | 1675                    | 36                | 24                        | +31/+41         |
| 5 (excluded)| 1686                    | 42                | −                         | −               |
| 6           | 1614                    | 33                | 35                        | +8/+10          |
| 7           | 1733                    | 28                | 28                        | +4/+9           |
| 8           | 1604                    | 40                | 53                        | +11/+13         |
| 9 (excluded)| 1807                    | 34                | −                         | −               |
| 10          | 1825                    | 22                | 16                        | +6/+16          |
| 11          | 1511                    | 47                | 61                        | +14/+14         |
| 12          | 1533                    | 43                | 68                        | +12/+16         |
| 13          | 1493                    | 33                | 47                        | +8/+10          |
| 14          | 1684                    | 40                | 19                        | +4/+12          |
| 15          | 1617                    | 46                | 21                        | +11/+13         |
| 16          | 1561                    | 43                | 62                        | +3/+10          |
| 17          | 1640                    | 45                | 48                        | +18/+28         |
| 18          | 1777                    | 35                | 34                        | +6/+11          |
| 19          | 1595                    | 55                | 45                        | +10/+12         |
| 20          | 1627                    | 30                | 42                        | +6/+23          |
| 21          | 1449                    | 33                | 49                        | +21/+20         |
| 22          | 1632                    | 45                | 42                        | +11/+31         |
| 23          | 1599                    | 36                | 68                        | +11/+20         |
| 24          | 1428                    | 31                | 59                        | +20/+16         |
| 25          | 1533                    | 38                | 65                        | −2/+2           |
the earlier monitored period the increments at 1900 m were 0%, whereas between 1986 and 2002 they were approximately 3% (Figure 4A, B). The trend is probably connected to warming in the region.

**Discussion and conclusions**

A multivariate technique, PCA, was used to extract the variability of real pine growth increment from the
variability caused by geographic information system processing of samples. The main results of our case study confirm the results of previous research on mountain vegetation zones in the Slovak Tatras. Boltižiar (2007) analyzed spatiotemporal landscape structure change in the alpine environment of the Tatra Mountains. The landscape structure in 1949 in the study area showed dominant grass, which resulted mainly from human activity. Statistical analysis of thematic maps from 2003 suggests extension of dwarf pine surface, advance growth of forest, and reduction of grass areas.

However, there are interesting comparisons with research in other European mountains. Examples from the Alps in Austria (Dullinger et al 2004), after running a 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 and 2°C above the current mean). Moreover, invasibility and shape of the dispersal curve interacted with each other due to the spatial patterns of vegetation cover in the region. In their study of alpine, subalpine, and forest landscapes in the Iezer Mountains (southern Carpathians), Mihai et al (2007) describe how dwarf pine–subalpine associations developed and increased in elevation. This is largely a feature of the study conducted by Dirnböck et al (2003) support earlier hypotheses that alpine plant species on mountain ranges with restricted habitat availability above the 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.

In addition to climate change, human land use may drive changes in tree line. Land use in subalpine and alpine areas (grazing and extraction) affects the distribution of flora just as much as climate. Since the 13th–14th century, anthropogenic land cover change has involved clearing mountain-pine thickets to obtain new pastures for sheep and cattle grazing, for extensive charcoal and oil production, and for copper and iron-ore mining, sometimes leading to degradation. Jodłowski (2007) described how establishing national parks in the Tatras—Babia Góra and Giant Mountains—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 regeneration

| Variable                  | PC1  | PC2  | PC3  | PC4  |
|---------------------------|------|------|------|------|
| Slope                     | 0.51 | -0.64| -0.50| 0.26 |
| Elevation                 | -0.71| 0.11 | -0.63| -0.27|
| Pine increment (1965–1986)| 0.73 | 0.14 | -0.10| -0.64|
| Pine increment (1986–2002)| -0.38| -0.78| 0.30 | -0.37|
| Variability (%)           | 36.5 | 26.8 | 18.9 | 17.8 |

PC, principal component.
of dwarf pine thickets. After the absolute restriction of grazing in some national parks, we observed progressive long-term trends in secondary succession and patterns of plant establishment driven by climate. Closed mountain-pine thickets stretch up to 300 m above timberline, reaching approximately 1600–1750 masl in the Tatras and encompassing the upper part of the forest–alpine tundra ecotone. The maintenance of large summer farms may contribute to preventing the expected loss of nonforest habitats for alpine plant species (Dirnbock et al. 2003).

Gehrig-Fasel et al. (2007) compared upward shifts 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 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 in forest cover was found between 1650 and 2450 m. Above 1650 m, 10% of the new forest areas were identified as true upward shifts, whereas 90% represented ingrowth, and the authors identified both land use and climate change as likely drivers. Most upward shift activities were found to occur within a band that ran to 300 m 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 thus considered to be the most dominant driver for the establishment of new forest areas, even at the tree line ecotone (Gehrig-Fasel et al. 2007).

More research on vegetation dynamics in Slovakia’s mountain areas is needed in light of the significance of vegetation in the context of global change. The results of our study can be used not only as a baseline for future research to test possible climate change influences (resulting upward shifts compared to a potential surface size and trends in approach of dwarf pine extension) but also to compare trends in other mountainous areas. Further understanding of dispersal, persistence, and survival strategies of dwarf pine in the western Carpathians is also required. We will continue to monitor dispersal of P. mugo in Slovakia and extend our studies to the central Tatras. This work will help to characterize and evaluate the total tree surface area as a basis for the State Nature Conservancy’s management of mountain national parks and protected areas in Slovakia.

FIGURE 5 Trends in annual average temperature (in degrees Celsius) and annual total precipitation (in millimeters) from 1965 to 2002 at the meteorological station of Skalnaté pleso (1751 masl), Slovak Institute of Hydrometeorology.
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