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ORIGINAL PAPER

Biodiversity and climate change: consequences for upper tree line in Slovakia

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Abstract

Study of the effects of climate change on upper tree limit has mainly focused on the diversity of tree species as a result of the ability of species to tolerate temperature and moisture changes as well as some effects of disturbance regime changes. The tree species diversity changes due to climate change has been analysed via gap model and biodiversity indices. Gap models are individually based on simulations of establishment, growth, and mortality of each tree on the forest plot. Input ecological data for model calculations have been taken from the permanent research plots located in primeval forests in mountainous regions in Slovakia. The results of regional scenarios of the climatic change for the territory of Slovakia have been used, from which the values according to the CGCM3.1 (global) model, KNMI and MPI (regional) models. Model results for conditions of the climate change scenarios suggest a shift of the upper forest limit to the region of the present subalpine zone, in supramontane zone. The most significant tree species diversity changes have been identified for the upper tree line and current belt of dwarf pine (*Pinus mugo*) occurrence. Hill's index of biodiversity in the upper forest line increased by 30 – 35% for horizon of 2050, resp. by 45 – 50% modeled for the horizon of 2075. Calculated values of Shannon's index show an even higher increase due to climate change. For horizon 2050 is a roughly of three fold increase and horizon for 2075 by almost fivefold increase in the value of the index. Results from the gap model indicate the increase of tree species diversity 2 – 2,5 times.

Key words: tree species diversity; climatic factors; upper tree line; forest management, Slovakia

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1. Introduction

Understanding how species and ecosystems respond to climate change has become a major focus of ecology and conservation biology. Modelling approaches provide important tools for making future projections, but current models of the climate-biosphere interface remain overly simplistic, undermining the credibility of projections (McMahon et al. 2011). Global circulation models of climate change predict an increase in mean annual temperature between 2.1 and 4.6 °C by 2080 in the northern temperate zone. The associated changes in the ratio of extinctions and colonizations at the boundaries of species ranges are expected to result in northward range shifts for a lot of species. However, net species colonization at northern boundary ranges, necessary for a northward shift and for range conservation, may be hampered because of habitat fragmentation (Honnay et al. 2002). Climate change can also affect forests and their diversity through disturbances. Disturbances are a natural and integral part of forest ecosystems, and climate change would alter these natural interactions. When disturbances exceed their natural range of variation, the change in forest structure and function may be extreme. Each disturbance affects forests differently. Some disturbances have tight interactions with the species and forest communities which can be disrupted by climate change (Dalea et al. 2000; Mezei et al. 2014).

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 3 m in height (Švajda 2008). 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 (ex Švajda 2008) 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 (Švajda 2008).

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The aim of this work is to analyze possible changes in the biodiversity of the upper forest line due to climate change through a range of methodological approaches. Potential changes of selected indices of biodiversity (Hill index, Shannon index) was assessed on the basis of current knowledge derived from actual diversity of trees in mountain forests and the forest line and their relation to climatic parameters (air temperature). Rating changes in tree species composition by Forest Gap Model to add information about changes in the potential range of species diversity, with special emphasis on woody component of ecosystems.

2. Material and methods

2.1. Biodiversity indices

Biodiversity analysis was performed based on model calculations for two diversity indices: Shannon's index and Hill index, which proved to be the most appropriate for assessing the diversity of mountain forests in Slovakia (see work of Minďáš et al. 2000 for more details).

Shannon index is defined as follows

$$H = -\sum_{i=1}^{n} x_1 * log_2 x_i \qquad [1]$$

where:

n – number of species identified on site,

x_i – ecological importance of species identified on site.

On the other hand, Hill index is defined as follows:
where:

$$N_2 = \frac{(\sum_{i=1}^{n} x_i)^2}{\sum_{i=1}^{n} x_i^2} \qquad [2]$$

n – number of species identified on site,

x_i – ecological importance of species identified on site.

Both indices can be calculated separately for tree species, shrub species, and herb species located at the explored plots.

2.2. Forest Gap Model

Forest gap models are included into a group of dynamic models which are able to calculate various characteristics of forest trees in time series. Gap models are individually based in that they simulate establishment, growth, and mortality of each tree on the forest plot. The response of an individual tree to ecological conditions on the plot are defined by a number of environmental response functions, generally expressed as a portion of optimal growth, ranging from 0.0 to 1.0. These environmental response functions have been defined by using various methods. The model requires the following input data for individual trees: maximum tree age, maximum diameter, maximum height, and maximum yearly seedling establishment scaled to plot. This model contains several „response functions" including light, water balance, and climate responses of individual trees, which are described in Minďáš et al. (2000).

2.3. Climate change scenarios for Slovakia

Four general circulation models of the atmosphere (GCMs), two of which are global (Canadian CGCM3.1, German ECHAM5) and two regional (KNMI Dutch and German MPI) have been used for the analyses. All models feature the outcomes of the daily values of a number of meteorological variables from 1951 to 2100. These models belong to the newest category of linked atmospheric-oceanic models with more than 10 atmospheric height levels and more than 20 oceanic depths calculating variables in the network nodes. CGCM3.1 model is close to Slovakia 9 nodes, a model ECHAM5 near Slovakia 12 square grid nodes (about 200 × 200 km) in proportion to smoothed orography. Regional models KNMI and MPI are more detailed integration of dynamic equations of atmospheric and oceanic circulation in the network nodes at a distance of 25 × 25 km, and boundary conditions solving equations taken from the global model outputs ECHAM5. In the area of Slovakia have models KNMI and MPI to 19 × 10 nodes (190) and of real orography with well defined all the mountains with a larger horizontal dimension than 25 km.

Table 1. Rise of mean annual air temperature according to the selected climate change models – Central Slovakia.

Climate Change scenario (SRES)	2050*	2075**
KNMI (A1B)	+ 1.65	+ 2.62
MPI (A1B)	+1.69	+2.58
CGCM3.1 (A2)	+ 2.1	+ 3.29

*Mean value from the period 2025–2075.

** Mean value from the period 2050–2100.

The main outputs from these scenarios are as follows (Table 1):

1) Average air temperature should be gradually increased by 2 – 4 °C compared with the average period from 1961 to 1990, while maintaining the same annual and inter seasonal temporal variability. The scenarios do not foresee significant changes in the annual running of air temperature in the autumn months, but would be smaller than the temperature rise in the rest of the year.

2) Annual precipitation should not change significantly, but rather assumes a slight increase (about 10%), mainly in the north of Slovakia. Major changes should occur in the annual running and temporal modes of precipitation. In the summer, it is widely expected slight decrease in rainfall (especially in southern Slovakia) and in the rest of the year, mild to moderate increase in rainfall (especially in winter and in northern Slovakia). In the warm part of the year it is expected to increase the variability of rainfall, probably will be extended and more frequent drought periods on the one hand and more intensive rainfalls on the other. Snow cover is likely to be higher on average only amounting to over 1200 m a.s.l., but these locations covered in Slovakia less than 5% of the area, which cannot significantly affect drainage conditions. Detailed description of climate change scenarios for Slovakia can be found in the paper of Lapin & Melo (2004).

3. Results

3.1. Influence of climatic factors on biodiversity

Globally, climate factors are crucial for the diversity of the world's biomes (Holdridge 1967), therefore, as a first step in the analysis of the relationship between species diversity and climate change, we performed an analysis of the frequency dependence of indigenous trees in the central region of Slovakia (Fig. 1) from the mean annual air temperature. We got out while data on natural extension of woody species in Slovakia (Minďáš 1998) and vertical change in mean annual air temperature. Maximum abundance of woody species is achieved at a mean annual temperature of around 7 °C from this value drops gradually (inflection point is reached at around 3 degrees, which is about the limit of the 6th altitudinal forest zone) and drops to zero in negative values of mean annual air temperature.

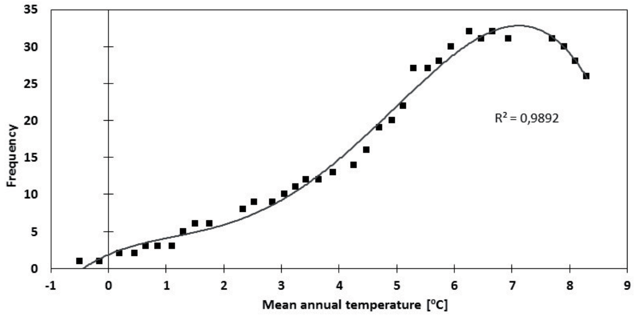

Fig. 1. Frequency changes of original tree species in the central part of Slovakia in relation to mean annual temperature.

Based on knowledge of the vertical distribution of tree species according to the mean annual air temperature and selected climate change scenarios we have implemented the model calculations to changes in the frequency potential of tree species in terms of climate change for the time horizon of 2075 (average period 2050–2100). The results are presented in Fig. 2. For the area of the upper limit of the forest, we can state a significant increase in the potential range of woody plants in the conditions of climate change, and the order of 400 – 500%. The truth must not forget that this bioclimatic potential occurrence of these species may not (and can not be) fulfilled by a number of reasons. In particular, the actual prevalence of trees in a circle from which these plants can spread in a natural way to the forest line. Other limiting factors may be the current protection system, actual management of forests at the upper limit of the forest, the occurrence of natural disturbancies, etc. Nevertheless, the results clearly indicate the growth potential of the diversity of tree species due to climate change within the area of current upper forest line.

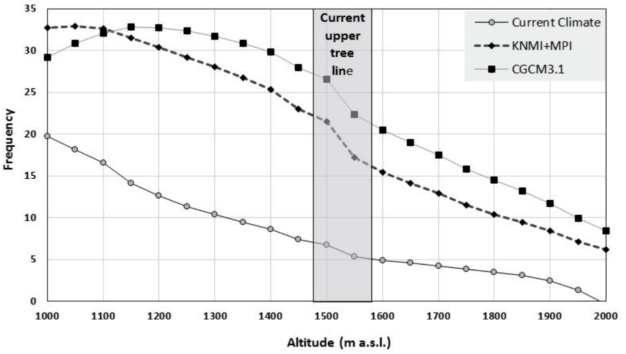

Fig. 2. Changes of original tree species occurrence in the central part of Slovakia in relation to the mean annual temperature for current climate and climate change scenarios.

3.2. Changes of biodiversity indices

As part of research on biodiversity of forest ecosystems were analyzed depending on selected indices of biodiversity and climatic parameters for the model area of the Low Tatras (Minďáš et al. 2000). Thus derived regression dependence of the two indices (Shannon, Hill) diversity of plant species we have used to calculate possible changes in those biodiversity indices for the selected scenarios of climate change.

Hill's index of biodiversity in the upper forest line increased by 30 – 35% for horizon of 2050, resp. by 45 – 50% modeled for the horizon of 2075 (Fig. 3). As regards the derived regression of the realistic assessment of forest ecosystems in this area, we can expect a real increase in the level of biodiversity in the forest line in the Low Tatras in the range of 30 – 50%.

Calculated values of Shannon's index show an even higher increase due to climate change. For horizon 2050 is a roughly of three fold increase and horizon for 2075 by almost fivefold increase in the value of the index. It should be noted that in the case of Shannon diversity index is a component of woody species of forest ecosystems.

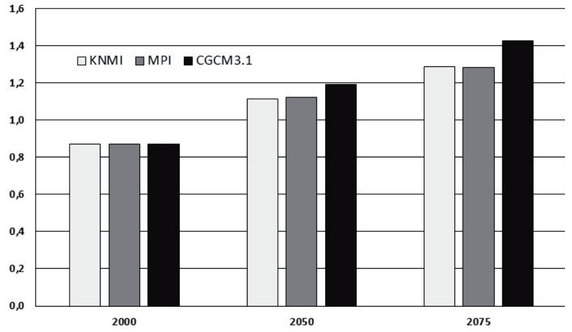

Fig. 3. Results of the calculation of Hill biodiversity index for upper tree line in Low Tatras region for current climate conditions and climate change scenarios.

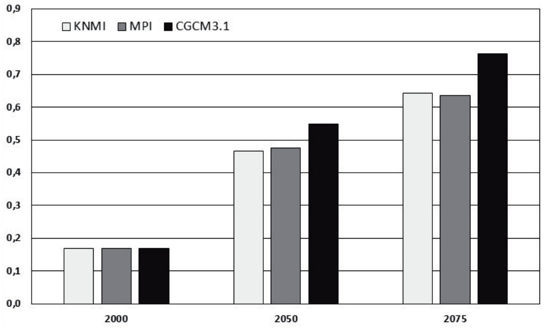

Fig. 4. Results of the calculation of Shannon (tree) biodiversity index for upper tree line in Low Tatras region for current climate conditions and climate change scenarios.

3.3. Forest Gap model

The consequences of climate change on forest ecosystems by Forest Gap model were analyzed for a number of forest ecosystems in Slovakia. For the purposes of this paper, we focused on the issue of changes in abundance (species diversity) of the occurrence of forest trees in the current upper forest limit. Model calculations were carried out for four locations in Slovakia with the appearance of the upper limit of the forest. The results are summarized in Table 2 and we could see from the results presented in each case increase in the number of species of tree to approximately double, being the plants with the occurrence of 5% (within the model calculations). Lower percentage of occurrence in the model does not guarantee real incidence of tree species in the unit. The highest potential increase in the number of trees we identified in the Low Tatras region, at least in the north of Slovakia (Pilsko).

Table 2. Number of tree species with frequency higher than 5 percent – Results from Forest Gap Model (four sites on the upper tree line).

		Climate change scenarios	
Location	Current Climate	KNMI, MPI	CGCM3.1(A2)
Pilsko (Oravske Beskydy)	3	6	7
High Tatras	4	7	7
Low Tatras	4	8	9
Low Fatra	3	7	8

4. Discussion

Many studies in recent years have investigated the effects of climate change on the future of biodiversity. According to the review of Bellard et al. (2012) the majority of models indicate alarming consequences for biodiversity, with the worst-case scenarios leading to extinction rates that would qualify as the sixth mass extinction in the history of the earth. Several works analyzed the current situation and last decades changes of upper forest line in Europe. By comparing the altitudinal distribution of 171 forest plant species between 1905 and 1985 and 1986 and 2005 along the entire elevation range (from 0 to 2600 meters above sea level) in Western Europe, we show that climate warming has resulted in a significant upward shift in species optimum elevation averaging 29 meters per decade. The shift is larger for species restricted to mountain habitats and for grassy species, which are characterized by faster population turnover. Our study shows that climate change affects the spatial core of the distributional range of plant species, in addition to their distributional margins, as previously reported (Lenoir et al. 2008).

Forest expansion was also 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 a possible climate change influence, the resulting upward shifts were compared to a potential regional tree line. A significant increase of forest cover was found between 1650 m and 2450 m. Above 1650 m, 10% of the new forest areas were identified as true upward shifts whereas 90% represented ingrowth, and both land use and climate change as likely drivers have been identified. Most upward shift activities were found to occur within a band of 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 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.

Dirnböck & Dullinger (2004) evaluate the potential influence of disturbance on the predictability of alpine plant species distribution from equilibrium-based habitat distribution models. Firstly, abundance data of 71 plant species were correlated with a comprehensive set of environmental variables using ordinal regression models. Subsequently, the residual spatial autocorrelation (at distances of 40 to 320 m) in these models was explored. The additional amount of variance explained by spatial structuring was compared with a set of functional traits assumed to confer advantages in disturbed or undisturbed habitats. The mentioned authors found significant residual spatial autocorrelation in the habitat models of most of the species that were analysed. The amount of this autocorrelation was positively correlated with the dispersal capacity of the species, levelling off with increasing spatial scale. Both trends indicate that dispersal and colonization processes, whose frequency is enhanced by disturbance, influence the distribution of many alpine plant species. Since habitat distribution models commonly ignore such spatial processes they miss an important driver of local- to landscape-scale plant distribution (Dirnböck & Dullinger 2004).

The results support earlier hypotheses that alpine plant species on mountain ranges with restricted habitat availability above the treeline 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. The maintenance of large summer farms may contribute to preventing the expected loss of non-forest habitats for alpine plant species. Conceptual and technical shortcomings of static equilibrium modelling limit the mechanistic understanding of the processes involved (Dirnböck et al. 2003).

5. Conclusion

The results indicate significant potential for positive changes of ecosystems in the forest line. Our findings clearly indicate significant changes in the current upper limit of the forest, where in the next few decades we can expect further alterations in species composition of these ecosystems. The changes can be expected on tree, shrub and herbaceous species diversities. Important factors that can enhance or dampen growth trends of species diversity, are not only anthropogenic factors, in particular the management of these ecosystems, but also natural factors especially disturbances (e.g. wind, snow, insects).

Biodiversity of forest ecosystems is still open scientific problem, especially in terms of the complexity of the assessment. Most of the work on that topic is mainly focused on diversity of woody components, but this certainly is not sufficient for assessing biodiversity of forest ecosystems as a whole. The results suggest potential and vector direction of possible changes in diversity, particularly forest trees in the forest line impacts of climate change. However, we are aware that in the future we will have to resort to more complex model analysis on the basis of multifactorial models and assessments of biodiversity change (Acton 2013).

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