



# Climate change increases the drought risk in Central European forests: What are the options for adaptation?

Klimatická zmena zvyšuje riziko sucha v stredoeurópskych lesoch:  
Aké sú možnosti adaptácie?

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## Abstract

The paper presents information on the projected drought exposure of Central Europe, describes the anticipated dynamics of the regional forests, and identifies measures facilitating the adaptation of forests to climate change-induced drought risk. On the basis of an ensemble of climate change scenarios we expect substantial drying in southern Slovakia and Hungary, while such trends were found to be less pronounced for the Czech Republic and Austria. In response to these climate trajectories, a change in species composition towards a higher share of drought tolerant species as well as the use of drought resistant provenances are identified as paramount actions in forest adaptation in the region. Adaptation to aggravating climate change may need to use artificial regeneration to enrich local gene pools and increase the drought tolerance of stands. Increasing risks from pests, pathogens and other disturbances are expected as a result of more frequent and severe droughts, underlining the need to put a stronger focus on risk management principles rather than on indicators of productivity in silviculture and forest planning. A consolidation of disturbance monitoring systems and a broader use of pest dynamics and hazard rating models are paramount tools to facilitate this adaptation process in forest management. The effectiveness of all the suggested measures needs to be controlled by efficient forest monitoring systems, the consolidation of which seems to be a timely task. Systematic and long-term implementation of the presented measures should increase forest stability and resilience, and further secure the sustainable provision of ecosystem services under climate change.

**Key words:** drought stress; temperate forests; adaptation measures; species shift; forest disturbances

## Abstrakt

V článku sú prezentované informácie o očakávanom vývoji sucha v oblasti strednej Európy, je opísaná možná dynamika lesov v podmienkach zmeny klímy, a je vypracovaný systém opatrení umožňujúcich adaptáciu lesov na zmenu klímy. Na základe kolekcie scenárov zmeny klímy bol identifikovaný výrazný nárast intenzity sucha v oblastiach južného Slovenska a Maďarska, zatiaľ čo v oblasti Českej republiky a Rakúska bola zmena relatívne nevýrazná. S ohľadom na tento vývoj predstavuje úprava drevinového zloženia smerom k vyššiemu zastúpeniu suchu tolerujúcich drevín a širšiemu využívaniu proveniencií rezistentných voči suchu jedno zo základných adaptačných opatrení. V prípade výrazných zmien klímy narastá význam umelej obnovy, ktorá predstavuje nástroj na zlepšovanie druhej a genetickej diverzity porastov a zvyšovanie ich tolerancie voči suchu. Narastajúci vplyv škodcov súvisiaci s rastúcim vplyvom sucha a ďalších abiotických činiteľov naznačuje potrebu orientovať pestovanie a hospodársku úpravu lesa viac na manažment rizík ako na maximalizáciu produkcie. Konsolidácia systémov monitoringu škodlivých činiteľov a širšie využívanie modelov dynamiky škodcov a hodnotenia rizík patria medzi ďalšie dôležité opatrenia podporujúce adaptáciu lesov na zmenu klímy. Všetky uvedené opatrenia musia byť podporené informáciami získanými na základe dlhodobého monitoringu lesa, ktorý však vyžaduje urýchlenú konsolidáciu. Systematická a dlhodobá realizácia prezentovaných opatrení podporí stabilitu a rezilienciu lesov a vytvorí predpoklady pre udržateľné poskytovanie ekosystémových služieb a funkcií v podmienkach zmeny klímy.

## 1. Introduction

Climate change is expected to have a profound effect on Central European forests (Tatarinov & Cienciala 2009; Hlásny et al. 2011a, b), although this region has not received adequate attention in climate change research and adaptation thus far. Central Europe belongs to the temperate oceanic and tem-

perate continental bioclimatic zones (Rivas-Martínez et al. 2004), where drought, storms and related changes in biotic disturbance regimes are expected to be the main climate change related impacts (Bréda et al. 2006; Lindner et al. 2010). Research of drought effects on temperate forest ecosystems identified a range of possible responses, including a change in forest production and carbon accumulation (Ciais

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et al. 2005; Tatarinov & Cienciala 2009), a shift in species competitive capacity with potential risks to species and genetic diversity (Archaux & Wolters 2006; Borovics & Mátyás 2013; Cavin et al. 2013; Mette et al. 2013), drought induced forest dieback (Jump et al. 2009), as well as an increase in susceptibility to biotic disturbance agents (Desprez-Loustau et al. 2006; Rouault et al. 2006). In addition to increasing the susceptibility of trees, growing virulence of antagonists and an escalating number of newly invading pests have been observed (Csóka & Hirka 2011). Forest fires in regions where this agent has been of minor importance historically represent another potential threat to Central European forests (e.g. Reinhard et al. 2005). Although observations of critical drought effect in Central Europe have been relatively rare until now, effects such as drought-induced decline of tree species (Siwecki & Ufnalski 1998; Mátyás et al. 2010a) or changes in population dynamics of climate sensitive pests (Hlásny & Turčáni 2009; Lakatos & Molnár 2009) have already been reported. Furthermore, observations around the globe, such as climatically induced decline of diverse *Abies* and *Pinus* species in the temperate forests of North America (van Mantgem & Stephenson 2007) are also deemed possible for the future in Central Europe.

In addition to ecological impacts, the substantial economic losses expected in relation to climate change (Hanewinkel et al. 2012) may adversely affect regional economies, including impacts on rural communities. Apart from direct impact on timber production, the quality of non-productive forest services might also be compromised by a changing climate (Briner et al. 2013). Therefore, development of appropriate forest adaptation measures, their inclusion into national legislation, and implementation to practical forest management are urgently needed. A growing body of literature on forest adaptation points to possible actions as well as barriers to the implementation of adaptation measures in forestry (Spittlehouse & Stewart 2003; Bolte et al.

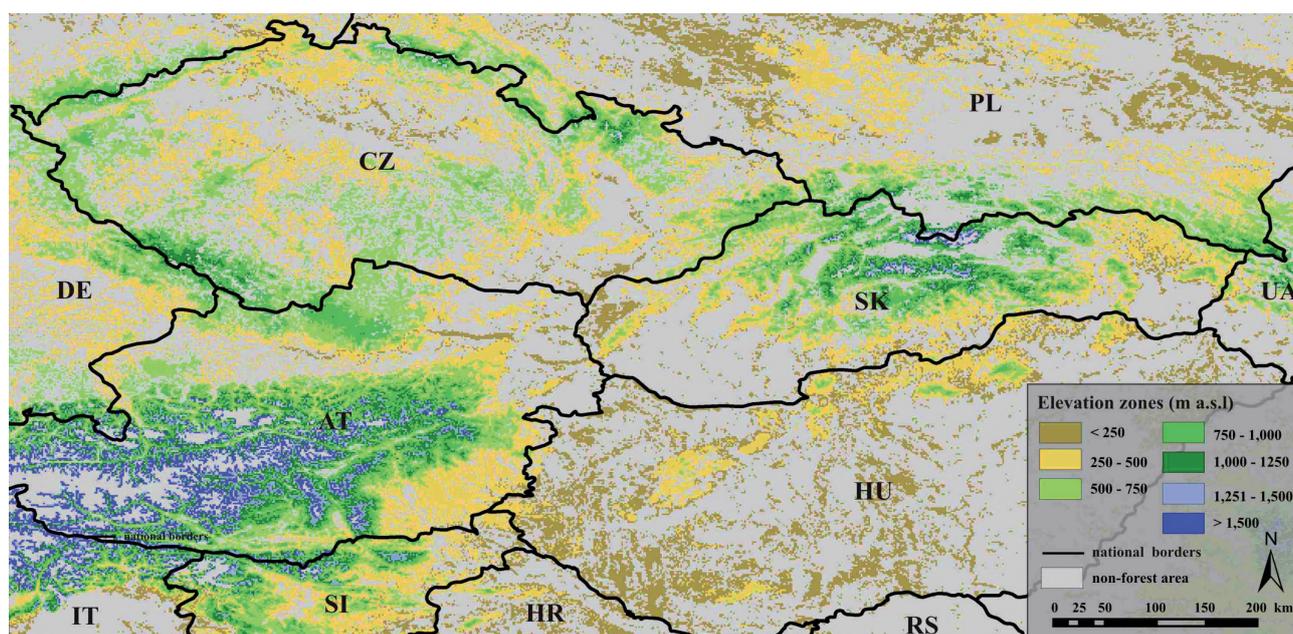
2009; Lindner et al. 2010; Kolström et al. 2011). Such measures need to be regionally adapted to address the regional climatic exposure and sensitivity of ecosystems, as well as to account for the current ecological and socio-economic conditions (Lindner et al. 2010). In this paper, we strive to provide essential information on the anticipated drought risks in Central European forests, and recommend forest adaptation measures specific to this region. In particular, our objectives are:

- to evaluate the projected climatic exposure of Central Europe with regard to drought;
- to review anticipated drought-related risks to Central European forests; and
- to compile possible adaptation measures to deal with drought-related climate change impacts in Central European forests.

## 2. Data and methods

### 2.1. Region of interest

We selected a rectangular area covering the entire Slovakia, Czech Republic and Hungary, as well as parts of Austria, Germany, Poland, Ukraine, Croatia, Slovenia, Italy, Serbia, and Romania as our study region, covering a total of 491,000 km<sup>2</sup> (Fig. 1). Forests cover 32% of the study region (Corine LandCover 2000, EEA 2006). The region encompasses a substantial climatic gradient, with diverse forest communities and land uses from the semiarid plains of Hungary to the highest peaks of the Carpathians and the Eastern Alps. Climatic continentality is increasing across the region from the West towards the East. The Southwest is under a sub-Mediterranean influence. A specific feature of the region is that most dominant, zonal tree species reach their low-elevation (xeric) distributional limits here. Therefore, increasing drought is important limiting factor and future threat to forests in this region.



**Fig. 1.** Forests of the study region classified by elevation zones.

The projected climatic exposure will be evaluated for the entire study region, while forest adaptation measures will primarily address the northern part, i.e. northern Hungary, the Czech Republic, Slovakia and Austria. This sub-region contains a gradient of zonal forests dominated by *Quercus* sp., *Fagus sylvatica*, *Abies alba* and *Picea abies*, with azonal occurrences of *Pinus sylvestris*.

## 2.2. Climate data – The FORESEE database

The FORESEE climatic database was developed to support climate change related research in Central Europe, and to ease the access to climate data (Dobor et al. 2013; <http://nimbus.elte.hu/FORESEE>). The database contains gridded daily observational data (1951–2009) based on the E-OBS and CRU TS datasets (Mitchell et al. 2004; Haylock et al. 2008), and an ensemble of climate projections (2010–2100). The future climate is represented by bias corrected meteorological data from 10 regional climate models (RCMs), driven by the A1B emission scenario (Source: the ENSEMBLES database, van der Linden et al. 2009). The database contains daily air temperature and precipitation data as well as numerous climate indices. The original ENSEMBLES and E-OBS data were interpolated to a uniform 1/6×1/6 degree horizontal resolution grid.

## 2.3. Assessment of the regional climatic exposure with respect to drought

To evaluate the climatic exposure of the study region, we produced high resolution (250×250 m) climatic maps for two time periods – 1961–1990 (reference period) and 2071–2100 (future period); the future climate data were calculated as the average of the 10 RCMs included in the FORESEE database. Kriging with External Drift, a spatial interpolation method which was previously found suitable for the interpolation of climate data, was used to derive the climatic maps (Hudson & Wackernagel 1994; Vizi et al. 2011). A digital elevation model with a spatial resolution of 250 metres was used to support the interpolation. The climatic exposure was calculated as the difference in climate between periods 1961–1990 and 2071–2100. As drought is of prime interest in the current study, we evaluated the change in precipitation totals during growing season (April–September) as well as in the Ellenberg climatic quotient. The Ellenberg climate quotient (EQ) expresses the coupled effect of temperature and precipitation. It is defined as the ratio of the mean air temperature of the long-term warmest month (MTWM) to the annual precipitation sum (AP):

$$EQ = MTWM / AP \times 1000$$

This quotient has been repeatedly used, for example to separate the areas dominated by beech from areas of boreal or thermophilic species (e.g. Jensen et al. 2004; Fang & Lechovicz 2006), as well as to evaluate anticipated changes in the beech distributional range (Mátyás et al. 2010a).

## 2.4. Proposed adaptation measures

We reviewed a body of literature to compile a list of possible adaptation measures and, where necessary, adopted measures reported in the literature to the specific conditions of Central Europe. The proposed measures address all aspects of forest management, and focus mainly on commercial and protective forests. Protected forests, with the main aim of conserving biodiversity, were not in the focus of this study. As we mainly address drought-related processes, some beneficial effects of climate change, which might be pronounced in mountain regions (e.g. Bergh & Linder 1999; Seidl et al. 2011a), and which thus present opportunities for forest management, have not been addressed here either. Hence, the suggested measures primarily concern lowland forests (except for floodplains), and zonal forests in the foothills and medium altitudes, except where stated otherwise.

## 3. Results and discussion

### 3.1. Future drought exposure of Central Europe

The pattern emerging for the study region is a decreasing gradient of growing-season precipitation from the North-West to the South-East (Annex 1). While projected precipitation remains more or less stable in the Czech Republic and Austria (i.e. comparable with the period 1961–1990), a decrease is projected for the entire area of Slovakia and Hungary. Though the decrease is moderate in absolute terms, ranging from –50 to –100 mm, it indicates a substantial drying of climate in southern Slovakia and throughout Hungary. When expressed in relative terms, these changes amount to reductions of up to 25% for southern Hungary, with most of Slovakia experiencing reductions by 10%. In the Czech Republic and Austria changes mostly remain within ±5% of the reference period. For Hungary and southern Slovakia, projections also indicate an increase in the frequency of consecutive drought extremes, which may be especially threatening to less drought tolerant species (Gálos et al. 2007).

The described precipitation change occurs concurrently with the increase in air temperature, which strengthens the atmospheric evaporative demand and thus amplifies the potential water deficit of plants. A multimodel projection of the mean annual air temperature indicates an increase ranging from ca. 1.4 °C in the North-West to 2.0 °C in the South-East of the region in the first half of the century, and an increase from ca. 3.1 °C to 3.8 °C by the end of the century (not presented in the Annexes).

The amplifying interaction between temperature and precipitation is captured by the Ellenberg climate quotient (Annex 2). While the main forested areas of Slovakia and the Czech Republic were in the range of Ellenberg quotient between 5 and 30 under the reference climate, future projections imply a potential decrease in water availability to plants over large areas by the end of the century (Annex 2). Critical drying of climate was projected to occur in Hungary, where values of up to 50 were projected across most of the country. It is noteworthy that value of 29 represents the approximate

limit of distribution for European beech-dominated forest types, while values above 40 have been associated with beech decline (Fang & Lechovicz 2006; Mátyás et al. 2010a). The difference map shows gradient of climatic drying from the North-West to the South-East of our study region. An increase in the Ellenberg quotient by up to 4 units is projected to occur in most of the uplands and mountain areas of the Czech Republic and Austria, while large areas of southern and eastern Slovakia are projected to face an increase by 4–10 units. The increase in large parts of Hungary was projected to be in the range 10–16 units. Thus the projected future conditions could represent critical conditions for the persistence of drought-sensitive species: For example, Mátyás et al. (2010a) suggested that beech forests may experience large-scale mortality if the Ellenberg quotient increases by more than 13 units compared to the long-term average.

### 3.2. Anticipated forest dynamics under climate change as a starting point for adaptation

We here address the anticipated response of three main Central European zonal tree species or species groups, i.e. oaks (*Quercus* sp.), European beech (*Fagus sylvatica*), and Norway spruce (*Picea abies*). These species constitute 71% of forest in Slovakia, 66% in the Czech Republic, 72% in Austria, and 42% in Hungary.

#### 3.2.1. Succession, colonisation and retreat

Oaks are known to be able to maintain their physiological performance under heat and drought (Dickson & Tomlinson 1996; Gallé et al. 2007), although inter-species differences are large (e.g. Acherar & Rambar 1992). Their drought resistance along with their low biotic and mechanical vulnerability implies that oak species might be increasingly successful under climate change in Central Europe. Climatic envelopes suitable for oaks were projected to expand substantially to higher elevations and latitudes (Peñuelas & Boada 2003; Hanewinkel et al. 2012). Hanewinkel et al. (2012) suggested that climates suitable for Mediterranean-type oaks may cover substantial proportions of Slovakia, Austria, the Czech Republic and all of Hungary by the end of the Century. In contrast, the area with climate conditions suitable for the present oak species is projected to shrink. Hlásny et al. (2011a) found, on the basis of growth simulations, that production of oaks could remain stable under climate change in the current distributional range of oaks in Slovakia, and climates suitable for oaks may extend to elevations up to 1,000 m a.s.l. Also in Austria, oaks are expected to substantially increase in their competitive strength and expand their range into the mountainous parts of the country (Lexer et al. 2002). Such facts support the potential importance of oak species under drier and warmer climates in Central Europe. Despite numerous evidence on the positive effects of climate change on oaks, and the proven capacity of oaks to sustain prolonged droughts, oak mortality following severe drought episodes was repeatedly observed in many European coun-

tries (Delatour 1983; Archaux & Wolters 2006; Massarutto et al. 2013). Such processes may result in loss of competitive strength and retreat of distribution in some oak species, as has been predicted, for instance, for sessile oak (*Q. petraea*) in Hungary (Czúcz et al. 2011).

As climate change may force a natural replacement of European beech by oaks in certain regions, the difference in climatic sensitivity between these two species can substantially shape the future of some European forests (Czúcz et al. 2011; Scharnweber et al. 2011). The climate sensitivity of European beech has recently been investigated by various authors (Leuzinger et al. 2005; Geßler et al. 2007; Mátyás et al. 2010a; Czúcz et al. 2011), suggesting the potential for decline of large proportions of current beech forests in the future. For example, extreme drought between 2000 and 2003 induced a decline of beech vitality accompanied by biotic damage, followed by large scale beech mortality in Hungary and Eastern Slovenia (Lakatos & Molnár 2009; Mátyás et al., 2010a). Growth simulations performed in Slovakia imply that beech production may decline in Central Europe up to elevations of ca. 500 m a.s.l. by the end of the century. Specifically, mortality may occur in up to 5% of current beech stands in the country, and 70% of stands lie in the area of declining production (Hlásny et al. 2011a). In areas of better water supply as well as in mid- to high elevation areas of the Eastern Alps beech has been reported to primarily respond positively to climatic changes (Seidl et al. 2008a; Seidl et al. 2011a). Yet, in low elevation areas potential increases in beech defoliation by gypsy moth (*Lymantria dispar*) (Csóka & Hirka 2006; Hlásny & Turčáni 2009) as well as potential damage by beech bark beetle (*Taphrorychus bicolor*) (Lakatos & Molnár 2009) may further reduce the vitality of trees and support the expansion of oaks and other drought tolerant species.

Norwayspruce has widely been planted in Central Europe at lower elevations for centuries, resulting in much higher shares of the species than its natural proportion (Ellenberg 1963; Spiecker et al. 2004; Hlásny & Sitková 2010). The current spruce shares are 26% in Slovakia, 52% in the Czech Republic, 60% in Austria and 1.5% in Hungary. Most of these forests are man-made and distributed largely outside the range of spruce natural distribution; these forests are prone to an array of pests and diseases, and outbreaks can be triggered by relatively minor climatic or other stressors (Seidl et al. 2008b; Wermelinger 2004). Progressive drought may adversely affect the species both directly as well as through an increase in biotic damages, especially at low to mid elevations, which may cause substantial forest decline over large areas (Hlásny & Turčáni 2013). Extensive decline of spruce forests may accelerate the expansion of broadleaved species, mainly of beech and pioneer tree species. The decline of secondary spruce forests may be accelerated in many regions by an increase in the number of bark beetle generations developed per year (Seidl et al. 2008b; Hlásny et al. 2011c) as well as by the influx of new pests, such as *Ips duplicatus* (Holuša et al. 2013). Thereby, spruce forests may be the most dynamically changing forest type in Central Europe under climate change.

### 3.2.2. Within-species genetic adaptation processes and their potential for adaptive forestry

Climate change forces the ecosystem to adapt at different levels – in species composition as well as at genetic level through selective pressure. Adaptation in the strict sense can be defined as the genetic adjustment of a population to actual abiotic and biotic environmental factors, leading to shifts in frequencies of gene variants (alleles) (Borovics & Mátyás 2013). Selective forces in different environments lead to diverse adaptive optima. This implies that differently adapted populations exist in all forest tree species of wide distribution, depending on local site and climate conditions.

Adaptive genetic variation created by natural selection provides an important option supporting the adaptation of trees to changing climates. It is assumed that populations growing in conditions analogous with expected future climates may better fulfill the expectations with regard to stability and growth performance. Provenance tests provide sufficient information about the response of progenies raised from reproductive material of non-local origin transferred into new environments, differing from their original habitat (Mátyás 1994). A common experience of these tests is the stability of performance across considerably changing climates. If the environmental change exceeds the level of genetically determined tolerance and stability, vitality starts to decline exponentially, finally leading to death and extinction (Mátyás et al. 2010b). The degree of stability<sup>1</sup>, i.e. the ability of populations to maintain productivity across changing conditions is inherited and may vary within species. For instance, Norway spruce populations from the Eastern Carpathians were found to perform better under changing environments than others. These stable (plastic) populations should be identified and preferred for artificial regeneration, as they are more tolerant and resilient to new environments (Mátyás & Borovics 2014).

## 3.3. Proposed adaptation measures

### 3.3.1. Change of tree species composition

Changing the prevailing tree species composition in response to increasing drought is a paramount measure in adapting forest ecosystems to climate change. The measure is primarily aimed at increasing the share of drought tolerant species, reduction of water demanding and drought vulnerable species, increasing stand diversity (which supports the inherent adaptive capacity of forests), and reducing the share of host trees within the outbreak range of biotic disturbance agents. The importance of such measures increase towards the lower range (xeric) limits of species, where adverse effects of drought might be more pronounced (Jump et al. 2009). It has to be noted, however, that such measures are associated with considerable lead times and will only gradually become effective (see e.g., Seidl et al. 2009), which underlines the importance for timely and anticipatory adaptation actions in forestry.

### Adaptation potential of oak species

A continuous increase of the share of oak species to the detriment of beech and some coniferous species in lower to medium elevations is a measure of high importance. In drought exposed sites, oaks that are currently at their northern distributional limit in Central Europe, such as *Q. cerris* – or even rare species such as *Q. pubescens* and *Q. frainetto* – appear to be sound options to adjust current species composition. An enrichment of the current beech-dominated forests by oaks should also be considered in the mid-elevation range (400–800 m a.s.l.). The share of *Q. petraea* and *Q. robur* could be increased in some intra-mountain valleys. *Q. robur*, which was found sensitive to ground water depletion (Friedrichs et al. 2009), should be used cautiously. Hornbeam-oak communities with conifers, containing *Carpinus betulus*, *Q. robur*, *Abies alba*, and *Picea abies*, which are considered native in some intra-mountain valleys in Slovakia (Michalko 1980), could in the future be used also on the adjacent slopes and higher elevations as well as in other regions in Central Europe. On some slopes, *Q. petraea* may replace *Q. robur*, and form mixed stands with beech and drought tolerant conifers such as *Pinus sylvestris* and *Larix decidua*. In the Eastern Alps of Austria, for instance, increasing the share of oak on selected sites was found to considerably lower the risk of bark beetle damage and reduce overall climate change vulnerability of forests (Seidl et al. 2008b; Seidl et al. 2011b).

### Risks and opportunities of using European beech in forest adaptation

Although the proportions of European beech in Central European forests vary among countries (Slovakia 31%, Czech Republic 7%, Austria 9.5%, Hungary 7%), the role of this species in forest adaptation seems indispensable (Tarp et al. 2000; Spiecker et al. 2004). In the future, current beech forests are expected to persist mainly in higher elevations (ca. above 800 m a.s.l.), and expand respectively. In some regions, beech is expected to be used as important surrogate species in the reconstruction of vulnerable spruce-dominated forests (e.g. Spiecker et al. 2004; Seidl et al. 2008b). The projected shift of the beech production optimum to elevations around 1,200 m a.s.l. (Hlásny et al. 2011a) by the end of the century implies that beech will be a key species for future forest management in mountainous regions. However, the climatic sensitivity of beech suggests the need of reducing the extent of present lower-elevation beech forests in Central Europe, and increase their diversity to lower climate vulnerability and risk. As the Ellenberg climatic quotient was found to be a powerful predictor of the distribution and vigour of beech (Fang & Lechovicz 2006; Mátyás et al. 2010a), the climate projections presented in the current study (Annex 2) can be used to identify the areas where beech is expected to suffer from drought in the future, and where more drought tolerant species should be introduced. While the need of such interventions seems marginal in the Czech Republic and Austria, it will be increasingly necessary in southern Slovakia and Hungary.

<sup>1</sup> stability of performance is quite often (in a strict sense, falsely) described as “phenotypic plasticity”. Stability or “plasticity” describes the extent to which growth and vitality of a population is maintained across a range of environments relative to other, e.g. local populations. Stability itself is also a genetically determined trait.

### Adjustment of species composition in secondary Norway spruce forests

A measure of paramount importance is the reduction of secondary spruce forests at elevations below ca. 800 m a.s.l., and their conversion to mixed and broadleaved forest types. This measure supports climate change adaptation, although the main driver of the currently ongoing conversion efforts are already observed extensive diebacks of spruce forests (Uniyal & Uniyal 2009; Hlásny & Sitková 2010; Hlásny & Turčáni 2013). The assessment of the urgency of conversion should strictly follow risk assessment principles (Netherer & Nopp-Mayr 2005; Kulla & Marušák 2011).

However, spruce will also retain a major role in Central European forests in the future as it can be particularly beneficial for biodiversity, stability and timber production as admixed species. The latter is particularly the case in higher elevation mountain forests, where longer vegetation periods are expected to result in improved growing conditions for spruce (Seidl et al. 2011a). Enrichment of spruce stands by broadleaves was found to significantly increase a probability that the stand reaches maturity, although the economic aspects of such interventions have not yet been sufficiently explored (Griess & Knoke 2013; Roessiger et al. 2013).

### Supporting biodiversity using enrichment species

In addition to the three main species discussed above there are number of species which may be used to enhance the diversity and drought tolerance of current forests. The proportion of species with climatic tolerance similar to oaks, such as *Fraxinus ornus*, *Acer campestre*, *Sorbus torminalis*, *Tilia cordata* and *T. argentea* could be increased in low to mid elevation beech and spruce forests. The share of these species can also be expected to increase spontaneously in response to climate drying. Scotch pine (*Pinus sylvestris*), European larch (*Larix decidua*) and even introduced conifers, such as Douglas fir (*Pseudotsuga menziesii*), could also be used as suitable enrichments in medium to higher elevation forests.

### Species translocation, assisted migration and introduction

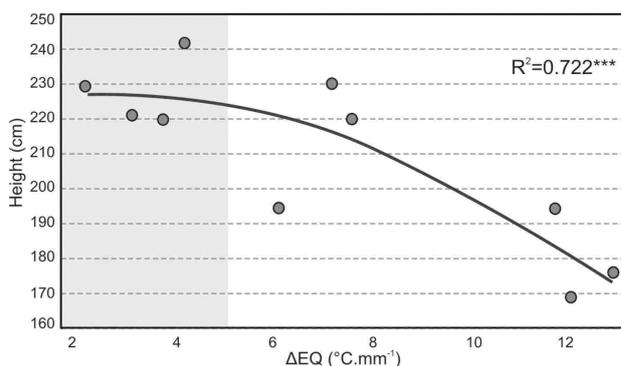
The anticipated increase in forest dynamics in Central Europe owing to climate change driven disturbances and potential species shifts suggest the need for non-traditional approaches supporting the change in tree species composition. Although the concept of assisted colonisation (Svenning et al. 2009) was originally intended as a proactive conservation strategy, it also seems to be effective as an adaptation measure. Man-assisted species translocation to environmentally suitable sites may support spontaneous succession after disturbances, as well as the shift of species for which the inherent migration capacity is insufficient to keep up with climate change. This option is primarily advisable in case of aggravating site and stand conditions.

Introduction of species which currently do not occur in Central Europe can be thought of as a questionable approach, mainly because of potential risks to biodiversity and unclear prospects of their long-term vitality. Substantial changes in climate may, however, favour southern species and provenances and they may become alternatives to the current species which may not be able to persist under a drier and warmer climate. For example, the above-mentioned expansion of climates favouring the Mediterranean oak types in

Central Europe emphasises the potential importance of the assisted migration.

### 3.3.2. A selection of preadapted populations and assisted transfer of reproductive material

Concerning the source of reproductive material the rule “local is always best” still finds the consent of both foresters and of environmentalists. Thereby, the idea of assisted migration through the planned transfer of reproductive material is still debated and not yet mainstreamed into forestry practice in the region, while already accepted, for example, in the American Northwest (Marris 2009). Reproductive material from local seed regions provides the reliability of being well-tested if site conditions do not change drastically. If the projected climatic changes are within the range of the expected stability potential of the provenance, adaptation may be achieved through exploiting phenotypic stability. In case of beech, for instance, field tests indicate that the increase of Ellenberg climatic quotient of up to 5 units can be buffered through phenotypic stability (plasticity) of the local population (Fig. 2). This buffering effect can, however, be diminished by adverse environmental and ecological factors (Mátyás et al. 2010a; Mátyás & Borovics 2014).



**Fig. 2.** Decline of 10-year height of 10 beech provenances in response to growing ecological (climatic) distance from the original habitat in the provenance test Bucsuta (Hungary). The transfer is expressed in terms of change of Ellenberg climatic quotient ( $\Delta EQ$ ,  $^{\circ}C \cdot mm^{-1}$ ). Positive  $\Delta EQ$  values indicate that all provenances were transferred into warmer/drier environment. The grey part shows the 5-unit “safety limit” of stability described in the text (Source: Mátyás et al. 2010a, modified).

For planning large-scale transfers of reproductive material from southern sources northward, and from low elevation populations upward, thorough understanding of anticipated changes in local site conditions and knowledge of suitable seed sources is needed. The difficulty of selecting such “preadapted” sources for artificial regeneration lies in the prudent compromise between an optimum match to changing climatic conditions and restraint due to the inherent uncertainty of both climatic projections and unforeseeable biotic risks.

When selecting a source region from which a provenance, which is considered preadapted for future conditions at a target location, is to be taken and transferred, both cur-

rent climate in source region and projected climate in target region need to be evaluated. Such assessment is needed to address the fact that any provenance will respond suboptimally during parts of its lifetime under transient climate change. Mátyás & Borovics (2014) suggested that the current climate in source region should correspond with the climate in the target location during approximately the first third of the expected felling cycle (i.e. for a stand planted in 2015 with a planned felling cycle of 90 years, the projected climate in ca. 2045 should be considered when selecting a source region). However, source regions with desired climates may likely occur outside the range of given species distribution. This fact implies the need for changing tree species composition in target location rather than trying to exploit intra-species adaptation mechanisms in facilitating the forest adaptation.

The selection of alternative provenances is essentially problematic at the xeric limits of the closed forest zone, such as those occurring at the edges of the Slovak and Hungarian plains, which are exposed to excessive summer heat and limited precipitation. There is growing evidence that populations at the xeric limits of a species contain less genetic diversity (Grivet et al. 2011; Borovics & Mátyás 2013) but accumulate alleles of drought tolerance. This, however, means lower adaptive potential (i.e. less phenotypic stability) to changing environmental conditions. These populations are apt to be used primarily as enrichment material or for creating provenance mixtures (“composite provenances”, Hubert & Cottrell 2007) to enhance the resilience of regeneration in problematic environments.

### 3.3.3. Regeneration, tending and thinning

Forest regeneration is especially susceptible to changes in climate (Spittlehouse & Stewart 2003), hence, changes in regeneration methods represent an opportunity to adapt tree species composition to climate change. In natural regenerations, long regeneration phases in small patches should be favoured. For instance, a shift to a fine-grained regeneration mosaic via group selection was found to increase the structural diversity of stands and help to lower the climate change vulnerability of forests in the Eastern Alps (Seidl et al. 2011b). In case of aggravating site conditions, enrichment planting (Lindner et al. 2008), i.e. the combination of natural and artificial regeneration, can be applied. The approach was found to positively influence genetic diversity and thus increase the inherent adaptive capacity of forests. Maintenance of the genetic diversity gains additional importance in climate change adaptation, as genetic diversity was found important in reducing the vulnerability of ecosystems (Seppälä et al. 2009).

Traditional thinning approaches usually lead to structurally and compositionally uniform stands (Nyland 2007), which often result in reduction of forest adaptive capacity (D’Amato et al. 2011). However, adaptation to climate change requires uneven-aged and mosaic forest structures that reduces the impact of disturbances and increase ecological stability. Adaptive silvicultural interventions should minimise the biotic risk after an intervention is performed, support species and structural diversity of stands, support

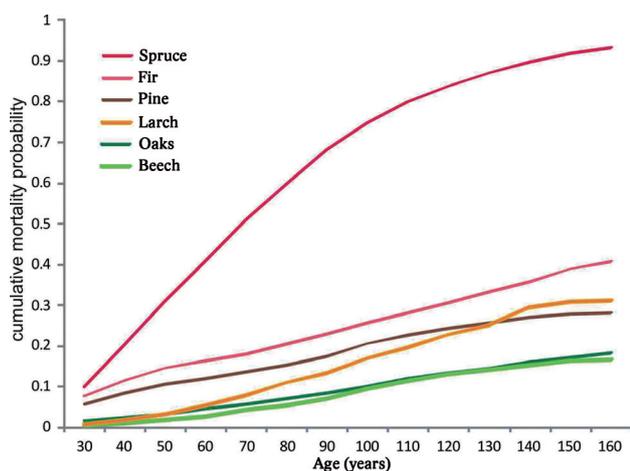
natural regeneration and facilitate water, carbon and nutrients cycling (Seidl et al. 2008a; Seidl et al. 2011b). Close-to-nature-forestry (Kruttsch & Weck 1935) and continuous-cover-forestry (Gadow et al. 2002; Kolström 2011) principles seem to be able to address the forest adaptation to climate change well. Thinning treatments can be applied to reduce the effect of disturbances (Running & Mills 2009). At drought prone sites, thinnings can reduce potential drought stress to trees (Sohn et al. 2013), because they reduce inter-tree competition (Allen et al. 2010), and can improve the recovery of growth after dry periods (Kolström et al. 2011). Intensive thinning was found to reduce the interception losses, and improve the water balance of stands (Slodičák et al. 2011). However, in the short-term, intensive thinnings can increase stand susceptibility to damage (Seppälä et al. 2009; Kolström et al. 2011). Therefore, introduction of risk assessment principles and tools for forest management optimisation seems important to guide the intensity, allocation and timing of silvicultural treatments. Thinning operations, if not systematically done, always contribute to a shift in the genetic variation of the population. Investigations show that medium intensity selective thinning alters genetic composition in an acceptable way, while extreme, vigorous interventions may strongly reduce within-stand genetic variation towards an undesirable, risky state of diminished adaptability (Mátyás & Borovics 2014).

### 3.3.4. Harvesting

Harvesting operations and harvest timing may substantially modulate forest vulnerability to climate change. In contrast to management under stable environmental conditions, where timber production-related indicators can be primarily used in harvest planning, risk management principles and flexibility of management should be of increased focus in forest management planning under climate change. Large openings should be avoided, as areas devoid of tree canopy may act as heat islands with adverse effects on the forest water cycle. Large clearings can increase the susceptibility of adjacent stands to biotic and abiotic damage (e.g. Lobinger & Skatulla 1996). Also the regeneration in large openings experiences higher exposure to drought and heat, often leading to tree mortality (Haeussler et al. 1995).

Shortening the rotation period can be used to shorten the stand development stage of high susceptibility to insects and diseases (Gottschalk 1995; Seidl et al. 2011b), and has the potential to accelerate the transition to a more suitable species composition (Bolte et al. 2009; Spittlehouse & Stewart 2003). However, a shortening of the rotation period should be considered in combination with all relevant site- and species-specific factors, and needs to balance positive effects on climate risk with effects on wood production, carbon storage, or biodiversity.

For example, an increase in the currently applied rotation period in oak stands in Slovakia was found to be beneficial in the context of timber production (Kulla & Petráš 2012). This potential benefit, however, needs to be balanced with an increasing disturbance risk with stand age. An analysis of species-specific survival probabilities under current climate, management and disturbance regimes (Fig. 3) indicates that



**Fig. 3.** Cumulative probabilities of main forest tree species to being critically damaged up to a given age. Data are based on sanitation felling records for entire Slovakia for the period 1990–2010, and include the combined effect of all relevant disturbance agents.

disturbance risk increases only moderately for oak and beech (with a survival probability of approximately 90% at age 100), supporting an application of extended rotation periods. The survival probability of Norway spruce, on the other hand, decreases to approximately 25% at age 100 already under current climate in Slovakia, and is likely to decrease further under climate change. This fact highlights the potential of shorter rotation periods for counteracting a climate-mediated increase in disturbance damage, particularly in the conifer-dominated stands in the region. Negative effects of reduced rotation length should also be considered, such as undesired overharvesting and a market surplus of timber supplies, which could potentially have a negative effect on timber economy (Lindner et al. 2008).

### 3.3.5. Forest protection and disturbance management

The high climatic sensitivity of most forest pests in combination with reduced tree resistance resulting from heat and drought pressure (Desprez-Loustau et al. 2006; Rouault et al. 2006), as well as the anticipated increase in the frequency of droughts and windstorms indicate an increased importance of forest protection and disturbance management under climate change. The currently applied procedures of pest control (e.g. removal of forest residues, wind throw clearings and sanitation felling, use of pesticides) can also be expected to remain effective in the future (Maroschek et al. 2009); intensity, extent, timing and spatial allocation of such measures should, however, be adapted to the changing environmental conditions. The following measures can help to improve current forest protection efforts in responding to climate change: (i) consolidation and harmonization of forest pests monitoring programmes, (ii) broader use of disturbance dynamics and hazard rating models in forest management planning (e.g. Netherer & Nopp-Mayr 2005; Seidl et al. 2014), (iii) broader implementation of principles of integrated pest management and risk management (Waters & Stark 1980; Blenow et al. 2013), and (iv) consolidation of human resources and infrastructure of national forest

protection services. A critical aspect for the enhancement of forest protection efficiency is integration of active pest control with silvicultural measures; for example planting pest and drought tolerant species, or reducing the shares of susceptible species and age classes. As seeds and nursery plants are important sources of pathogen dispersal, special care should be paid to aspects of disturbance management in early developmental stages. The fact that some pathogens can remain latent in reproductive material unless drought or other stressors trigger the infection should be considered (Desprez-Loustau et al. 2006).

### 3.3.6. Other actions

The importance of continuous and long-term forest monitoring increases under climate change as an early identification of development trends in the forest and environment is a prerequisite of adaptive management under changing environmental conditions. Since field monitoring is time and cost-demanding, the importance of remote sensing-based monitoring systems is expected to increase. The long-term evaluation of various biophysical forest indicators using satellite imagery will especially provide critical and near real-time information on the effect of environmental changes and support the adaptive forest management.

Adaptation of forest infrastructure includes the optimisation of forest road networks (Lindner et al. 2008). Increasing the density and improving the quality of forest roads provides accessibility to areas that require sanitation operations, stimulates small-scale management and reduces overharvesting in accessible locations (Kolström et al. 2011). However, this measure has to be applied with caution as there is strong evidence that improperly built road networks can negatively affect the water regime (Smerdon et al. 2009), and thus amplify the adverse effects of drought.

The forest planning infrastructure also needs to be improved, as many current planning tools such as yield tables and empirical models are not able to address the effects of a changing environment. In this regard it is increasingly important to consider climate sensitive processes explicitly in models used for planning (e.g., Seidl et al. 2011c), and to improve the linkages between process-based modelling and the decision support systems used in practical forest management (Wolfslehner & Seidl 2010).

Although most of the measures mentioned above addressed a forest stand scale and primarily concerned forest management, there is a range of cross-sectoral measures which focus on watershed or landscape scales. Adaptation measures at a landscape scale should mainly support the connectivity of ecosystems, create and/or maintain corridors between separated forested areas, and avoid forest fragmentation (Lindner et al. 2008; Running & Mills 2009; Seppälä et al. 2009). These measures should support the natural migration of species and gene flow, and thus enhance the effect of inherent adaptation mechanisms of forests. Forest adaptation can also aim at the enhancement of diverse forest regulation functions, which can be used to moderate the adverse effects of climate on landscape, including water regulation and flood prevention (Buttle 2011; Hlásny et al. 2013).

## 4. Conclusions

Forest responses to climate change are highly complex, and our understanding of potential impacts and sensitivities is still limited. Despite such limitations, it is possible and necessary to develop and implement climate change adaptation strategies already now (Spittlehouse & Stewart 2003). All forest management decisions are taken in face of uncertainty about the future, and delaying the implementation of adaptation measures in expectation of improved knowledge will likely lead to perpetual inaction. However, a thorough uncertainty assessment with regard to the expected climate change impacts can help to assess the need and likely success of adaptation measures. Both climatic uncertainty and societal uncertainty, for example that related to changing demands on ecosystems, need to be addressed (Seidl & Lexer 2013). Furthermore, an explicit consideration of the possible effects of adaptive management on a variety of locally important ecosystem services and an assessment of possible trade-offs with regard to their societal acceptance are needed.

Currently, climate change adaptation is often not addressed in forest management deliberately, but rather manifests itself in response to impending threats, such as pest epidemics or windthrows. In facing such threats, finer-grained and close-to-nature forest management systems are increasingly applied, while large-scale even-aged systems have been restricted to a narrow set of conditions in most of Central Europe. Accordingly, silvicultural approaches that promote a natural species composition, close-to-nature forest structure, and natural regeneration have gained traction in recent decades in all Central European countries. Such practices represent key starting points and opportunities for climate change adaptation. Yet, the profound changes expected for the future might require more systematic and targeted adaptation efforts going beyond what is currently implemented.

This paper stressed key processes and actions which need to be addressed to facilitate effective forest adaptation. First, an understanding of inherent adaptation mechanisms acting at species and genetic levels, and a thorough consideration of such mechanisms in forest management are critical prerequisites for effective adaptation. Second, the role of risk assessment in forest management planning for changing environmental conditions is becoming increasingly important. Thereby, the historically strong focus of planning on timber production will need to be broadened in many areas, not only to accommodate the concept of multifunctional forestry but also to ensure acceptable levels of risk in ecosystem services provisioning. Third, the information on long-term forest responses to climatic and other stressors needs to be improved. However, the technical and organisational frameworks of the current forest monitoring systems in the region as well as the ensuing utilisation of the collected data are not yet geared towards supporting adaptive forest management. Hence, a consolidation of monitoring systems and a strengthening of information transfer to management decision makers are required. Fourth, despite an increasing availability of climate projections and regional vulnerability studies, the application of such information in forest management decision making is still limited. To promote the use of this information, actions on increasing of the awareness of managers

and stakeholders need to be taken, and legislative support to adaptation processes need to be improved. Although forest adaptation is already included in many national forestry strategies, programmes and actions, these documents do not per se ensure an efficient and systematic implementation of such measures in forestry practice. Ultimately, successful adaptation decisions depend on skilled professionals, which is highlighting the importance of improved forest education. To conclude, we advocate a mainstreaming of climate change issues into all realms of forestry – from education to policy and from monitoring to management planning – in order to make the forests of Central Europe fit for a changing future.

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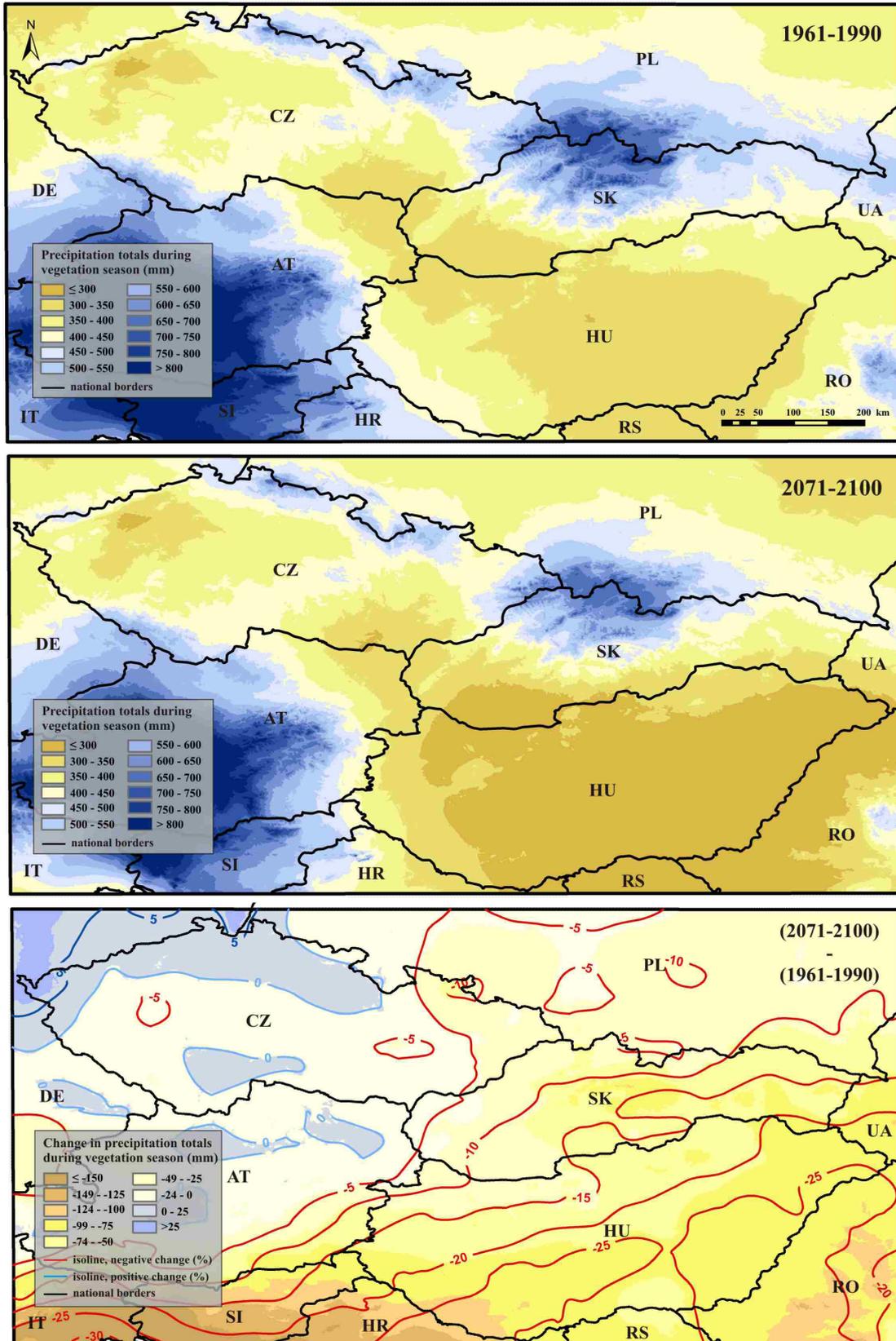
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**Annex 1:** Precipitation distribution (April–September) in Central Europe in the period 1961–1990 based on observed meteorological data, and calculated as an average of 10 regional climate models for the period 2071–2100. A difference and percentage change map is given as well.



**Annex 2:** Distribution of the Ellenberg climatic quotient in Central Europe in the period 1961–1990 based on observed meteorological data, and calculated as an average of 10 regional climate models for the period 2071–2100. A difference map is given as well.

