Expected impacts of climate change on forests: Czech Republic as a case study

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ABSTRACT: We provide fundamental information about the future development of selected climate elements in relation to anticipated threat to forests in the Czech Republic. All analyses were carried out in relation to four elevation zones with specific potential forest vegetation – up to 350 m a.s.l. (oak dominance), 350–600 m a.s.l. (beech dominance), 600–900 m a.s.l. (beech-fir dominance), 900–1,100 m a.s.l. (spruce dominance). We found out that while the projected increase in mean annual air temperature is almost constant over the Czech Republic (+3.25–3.5°C in the distant future), the frequency of heat spells at lower elevations is expected to increase dramatically compared to higher elevations. The precipitation totals during the vegetation season are projected to increase in the near future by up to 10% and to decrease in the distant future by up to 10% over all vegetation zones. In general, drought is presumed to become a key limiting factor at lower elevations, while increased temperature along with the prolonged vegetation season at higher elevations can be beneficial to forest vegetation. Consequently, northward progression of forest tree species and retraction of the species lower distribution range are a generic response pattern. Such impacts are presumed to be accompanied by changes in the distribution and population dynamics of pests and pathogens. Mainly the impacts on two key forest pests, *Ips typographus* and *Lymantria dispar*, are discussed.

Keywords: elevation zones; drought stress; heat spells; forest growth and distribution; forest pests and pathogens

Observed and projected changes in the Earth's climate are presumed to significantly influence most biological systems, including forests (Malcolm et al. 2001; Pielke et al. 2003). The nature and intensity of such impacts depend on the anticipated change of respective climate elements and sensitivity of receptors, such as forest trees, pests, pathogens or ground vegetation. Climate change is presumed to evoke a number of positive and negative responses in forests, such as increased productivity at higher elevations and latitudes, drought-induced increase of mortality and species range retraction in southern regions (van Mantgem, Stephenson 2007, Hlásny et al. 2011), increased risk of forest fires in the Mediterranean area (Schröter et al. 2005) or disruption of synchrony in multitrophic systems (e.g. Visser, Holleman 2001).

Climate change influences tree species either directly, through impacts on essential physiological processes (changes of air temperature, drought, solar radiation, chemical composition of the atmosphere) or indirectly, through alteration of intra- and inter-species relationships, changes in species competitiveness, introduction of new pests, or changes in the distribution and population dynamics of resident species. According to Lindner et al. (2009), the main impact factors are increased CO_2 concentration, increased air temperature, changes in precipitation patterns and related drought periods, floods and increased risk of forest fires.

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The knowledge of forest ecosystem responses remains low and regional impact studies are scarce (e.g. Hlásny, Turčáni 2009). The ways of validating such studies are limited as well, mainly because of forest longevity and complex responses of individual forest components. Therefore, solid scientific bases allowing for the development of region-specific forest management strategies aimed at building forests to resist climate change are insufficient.

The purpose of this paper is to describe the future climate development in the Czech Republic and to assess the anticipated impacts of projected changes on forests. We discuss mainly the impacts associated with gradual changes of climate, although the effects of extreme events can be critical (Führer et al. 2006). In particular, we:

– propose altitudinal zones corresponding with the vertical distribution of potential forest vegetation across the whole of the Czech Republic as a spatial framework for assessing climate change impacts;

– evaluate the expected development of selected climate elements in the respective zones; and, on the basis of the review of literature, we propose zone-specific impacts of climate change on potential dominant forest tree species and pests.

Data and methods

Forest composition data

Since forest management plans or other reliable information on the distribution of forest vegetation for the whole country were not available, we used CORINE land cover data describing the main land cover categories derived from the Landsat satellite imagery (European Environment Agency). Three out of 44 land cover categories were used: 311 broadleaved forest, 312 coniferous forest, and 313 mixed forest.

Climate change scenario used

The reference and future climate data were originally calculated using the global climate model (GCM) ARPEGE–Climat V4 (Déqué 2007) in an experiment performed by CNRM/Météo-France. Because of the GCM's rather coarse resolution (~ 50 km over Central Europe), the regional climate model (RCM) ALADIN-Climate/CZ (Farda et al. 2010) was used for an additional downscaling of the GCM data. The IPCC A1B emission scenario was adopted as the information regarding the future development of greenhouse gas emissions. The scenario represents a medium variant of greenhouse gas emissions. The scenario was developed as part of the CECILIA (Central and Eastern Europe Climate Change Impacts and Vulnerability Assessment, www.cecilia-eu.org) 6FP project. The RCM covers Central Europe with a resolution of 10 km. The data used in this study are a subset of ALADIN's overall integration domain covering the Czech Republic.

Design of elevation zones

The proposed elevation zones (EZs) embody a simplified scheme allowing for the assessment of climate change impacts within regions having specific potential forest vegetation and climate. While such a design can be used to investigate anticipated threats in the whole of the Czech Republic, any proposal for adaptation measures and climate-friendly forest management practices would need to downscale the knowledge thus obtained to a much finer spatial scale. EZs were primarily produced by classifying elevation within the Czech Republic (Table 1). The elevation thresholds were designed based upon the knowledge of vertical vegetation distribution according to Plíva (1971), Viewegh et al. (2003) and Holuša and Holuša (2008). Where appropriate, the elevation zones were split into several subzones, considering their geographical distribution in the country (Fig. 1).

Analysis of climate development and risk to forest

Daily climate data associated with grid points of the RCM used in the 10 × 10 km grids were divided into individual EZs. Subsequently, the average values of selected climate characteristics for the periods 1961–1990, 2021–2050 and 2071–2100 were compared between the zones. In particular, we analysed:
– mean annual air temperature,
– precipitation totals during the vegetation season,
– number of days with average air temperature exceeding 5°C,
– number of days with maximum air temperature exceeding 30°C,
– number of rainless periods with duration of 10 days at least during the vegetation season.

To describe the risk to forests of the Czech Republic induced by climate change, we carried out a review of literature and interpreted it in relation to projected changes of climate in the respective EZs.

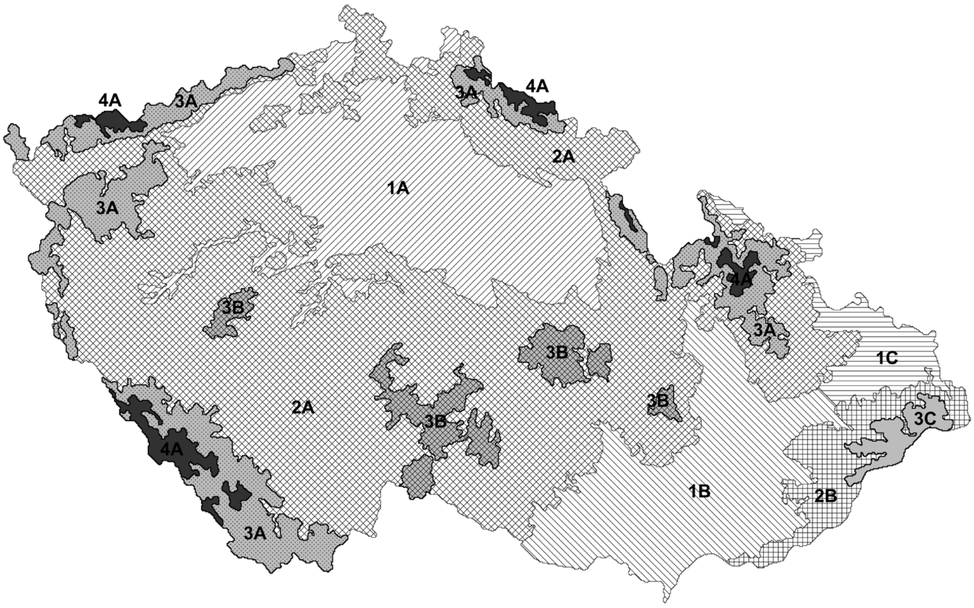


Fig. 1. Elevation zones used for analysing the anticipated climate change impacts on forests of the Czech Republic

1A, 1B, 1C – regions of the 1st elevation zone (oak); 2A, 2B – regions of the 2nd elevation zone (beech); 3A, 3B, 3C – regions of the 3rd elevation zone (beech-fir); 4A – 4th elevation zone (spruce)

RESULTS AND DISCUSSION

Design of elevation zones

We describe the climate change impacts on forests in the framework of EZs corresponding with the vertical distribution of natural vegetation. Although the present species composition reflects a dramatic change from the past, and mainly in favour of Norway spruce (44.7% of the total forests in the country; Vašíček 2007), we investigated the impacts on naturally dominating tree species in the zones. Such analysis can be useful for actual forest management that aims to achieve continuous forest transformation toward a species composition closer to the original composition. If appropriate, such knowledge can be extrapolated to the present species composition. Each zone (Fig. 1) is characterized by its proportion of the main forest composition types on the basis of the CORINE land cover classification (Table 1).

1st Elevation Zone represents elevations up to 350 m a.s.l. originally dominated by oak species (*Quercus* sp.). The ecological optimum of *Quercus robur* and *Quercus petraea* lies within this zone. The 1A subzone roughly corresponds with the zoogeo-

Table 1. Characteristics of the proposed elevation zones for the Czech Republic

EZ/elevation range (m a.s.l.)	Subzone	Size (ha)	Forest (ha)	TC (%)	TF (%)	Deciduous (%)	Coniferous (%)	Mixed (%)
1st (oak) < 350	1A	1,385,480	434,138	17.6	9.3	15.2	48.6	36.2
	1B	917,971	253,821	11.6	5.3	43.8	35.5	20.7
	1C	221,101	65,323	2.8	1.4	50.6	10.5	38.9
2nd (beech) 350–600	2A	3,832,590	206,871	48.6	44	4.1	77.6	18.4
	2B	255,293	236,253	3.2	5.4	19.4	52.4	28.1
3rd (beech-fir) 600–900	3A	772,018	959,711	9.8	20.4	2.3	86.6	11.6
	3B	273,412	224,069	3.5	4.7	1.3	94.7	4.0
	3C	78,742	97,709	1.0	2.1	5.7	72.2	22.1
4th (spruce) > 900	4A	150,495	350,776	1.9	7.4	1.0	88.8	10.2

EZ – elevation zone; TC – proportion in the total area of the country; TF – proportion in the total forested area (on the basis of the CORINE LandCover 2000) graphic district of the Central Bohemian Lowlands (Mařan 1958) and the warmest biogeographic regions (Culek 1996). The 1B zone is part of the Pannonian biogeographic province with markedly thermophilous vegetation. Marginal plains belong to the colline beech-oak vegetation zone with natural occurrence of *Carpinus betulus* and rarely with *Fagus sylvatica*. The 1C zone roughly corresponds with the Polonicum biogeographic province, being slightly colder and mainly moister compared to the 1B subzone (Fig. 2). Oak-beech (colline) and beech (submountain) vegetation zones dominate.

Scotch pine (*Pinus sylvestris*) accounts for a significant percentage of the present species composition. The pine proportion varies in the range of 30–60% in the 1A subzone and up to 20% (extraordinarily 60%) in the 1B and 1C subzones. The proportion of Norway spruce (*Picea abies*) varies in the range of 2–50% (Culek 1996).

2nd Elevation Zone represents elevations in the range of 350–600 m a.s.l. originally dominated by European beech (*Fagus sylvatica*). Silver fir (*Abies alba*) occurs at a co-dominant level, accounting for about 20%. *Quercus petraea* and *Quercus robur* occur only as interspersed species with their representation of up to 10% (Holuša, Holuša 2008). The 2A subzone is located in the western part of the country spreading over lower elevations of the Hercynicum biogeographic subprovince. The 2B subzone is located easterly, being a part of the West Carpathian biogeographic province. While the mean annual air temperature is almost the same in the two subzones, the 2B subzone is significantly moister during the vegetation period (Fig. 2). The present species composition reflects dramatic changes due to human activities. Coniferous forests composed of 30–70% spruce dominate. The percentage of Scotch pine often reaches 30% or 40% (Culek 1996).

3rd Elevation Zone represents elevations in the range of 600–900 m a.s.l. originally dominated by European beech (*Fagus sylvatica*) and silver fir (*Abies alba*) (Viewegh et al. 2003). The 3A subzone represents the middle parts of the country's highest mountains. The 3B subzone represents the inner mountains and is thoroughly surrounded by the 2nd elevation zone. The 3C subzone spreads over the highest elevations of the Beskids. The proportion of spruce in the present forests is higher than 60%. Scotch pine is planted only occasionally and its proportion is in the range of 1–15% (Culek 1996).

4th Elevation Zone represents the highest elevations of the country (above 900 m a.s.l.) distributed in four isolated ranges – Krkonoše Mts. and Jizerské hory Mts. in the north, Krušné hory Mts. in the northwest, Šumava Mts. in the south, and Orlické hory Mts. with Jeseníky Mts. in the east. Beech naturally dominates at lower altitudes, while Norway spruce with an admixture of *Acer* and *Sorbus* substitutes beech at higher elevations. *Pinus mugo* grows above the upper tree line at the highest elevation of the Hercynian Mts. (Culek 1996).

Anticipated risk to forests

We focused on impacts related to increasing air temperature and changing precipitation pattern, which are primarily presumed to influence forest growth, mortality and distribution. The alteration of disturbances such as rime damage or frost periods was not analysed, because they are not presumed to cause significant damage to forests in the future.

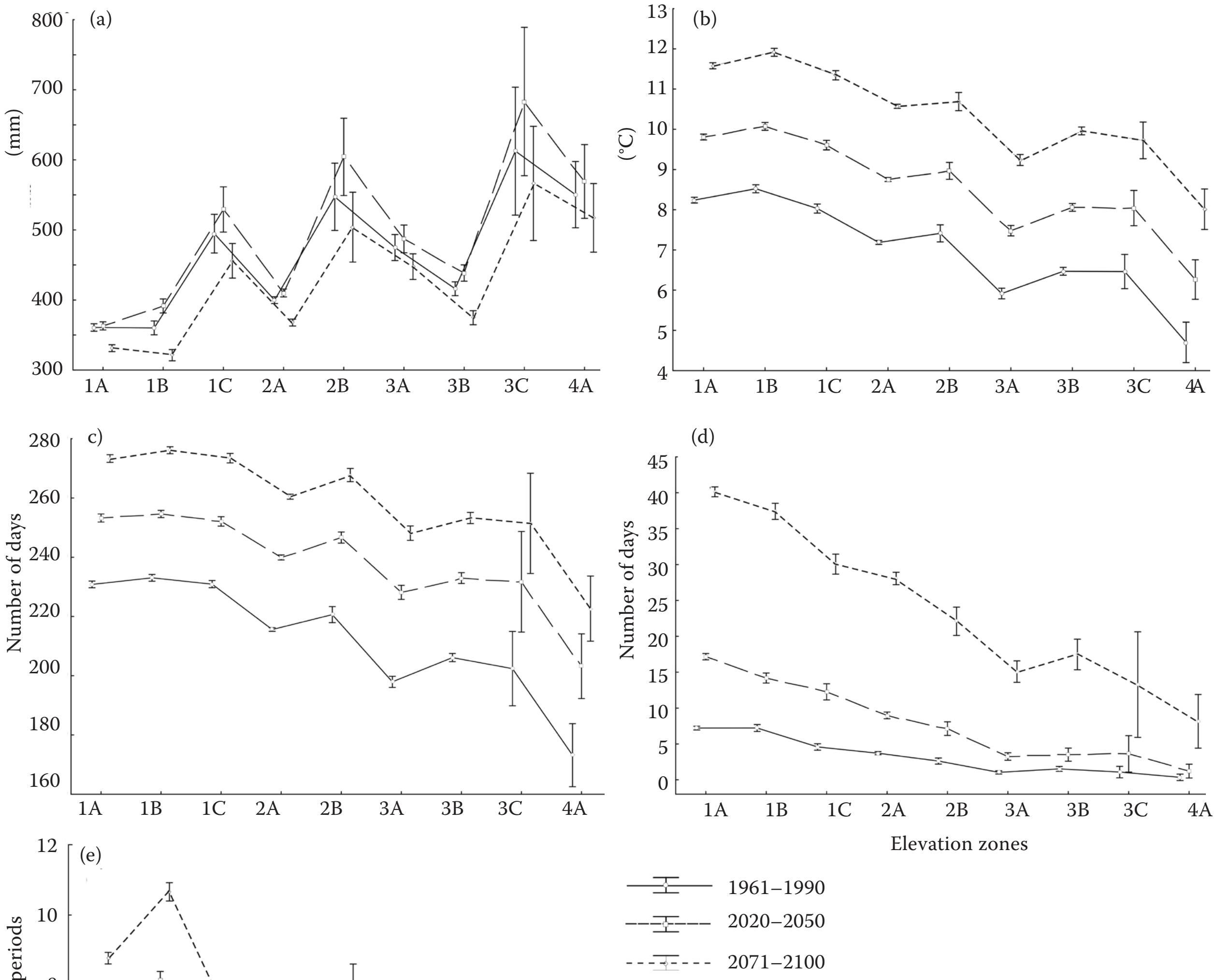
The climate change scenario used indicated that while air temperature increases more or less constantly over the whole of the Czech Republic, the frequency of heat spells significantly varies among the EZs (Fig. 2 and Table 2). Heat stress is certainly one of the most dangerous stresses for plants because of its direct effect on plant metabolism, and also due to a series of concurrent stress factors (Rennenberg et al. 2006). The occurrence of drought periods remains at the reference level in the near future, but it markedly increases in the distant future throughout the entire country. Schär et al. (2004) and Giorgi and Coppola (2007) projected that present storm tracks would shift northward, which might trigger droughts and heat spells in Central Europe with severe impact on forest vegetation.

The indicator used to represent growing season duration (annual number of days with mean air temperature above 5°C) suggests that the growing season will be prolonged by approximately 10–7% in the near future and by 18–28% in the distant future. This can positively influence mainly higher elevation forests where such a factor can be limiting. Further, we synthesized the projected changes of climate with the recent knowledge of climate change impacts on forests.

1st Elevation Zone

Direct impacts

An extremely increased number of hot days potentially causing heat stress to forest vegetation is the most notable feature for this zone. In the distant future, hot days are projected to amount to 30–40 per season compared to 5–7 days in the refer-



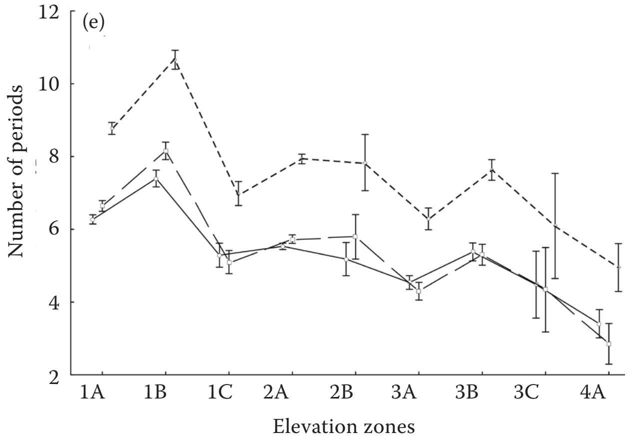


Fig. 2. Projected changes of selected climate elements within the elevation zones of the Czech Republic. (a) Average precipitation totals during the vegetation season; (b) mean annual air temperature; (c) number of days with average daily air temperature exceeding 5°C; (d) number of days with maximum daily air temperature exceeding 30°C; (e) number of rainless periods with duration of 10 days at least during the vegetation season

ence period. Heat waves occurring in summer result in increased evapotranspiration demand, which eventually results in concurrent drought stress for vegetation (Rennenberg et al. 2006). The highest increase of drought period occurrence was projected in the 1B subzone, while vegetation in the more northerly and moister 1C subzone will be less stressed by drought.

Drought-resistant oak species are presumed to suffer mainly from extreme temperatures, potentially increasing tree mortality and reducing the increment. The magnitude of predicted changes does not imply the occurrence of mass drought-induced oak mortality as reported from the oak southern distribution limit (Peñuelas, Boada 2003). Beech occurring in this zone is presumed to suffer mainly from drought, which can cause the retraction of the beech lower distribution range (Peñuelas et al. 2007).

Impact on pests and pathogens

Projected drought stress is presumed to predispose oak and beech forests to infestation by insect defoliators and fungal diseases, such as *Armillaria* spp. (Wargo, Harrington 1991). Tree dieback due to *Armillaria*, together with an assortment of fungal pathogens (e.g. *Phytophthora quercina*), was reported in association with oak decline during periods of soil water deficits (Balci, Halmschlager 2003). The ranges of Gypsy moth (*Lymantria dispar* L.) outbreak have been projected to significantly enlarge in Slovakia, reaching the upper distribu-

Table 2. Projected changes of selected climate elements within the elevation zones of the Czech Republic. Relative change in the future compared to the reference period is given for the variables NoD5, Precipitation, NRP10 and NoD30. Absolute increase is given for air temperature

EZ	N	NoD5 (%)		Precipitation (%)		Air temperature (°C)		NRP10 (%)		NoD30 (%)	
		2021–2050	2071–2100	2021–2050	2071–2100	2021–2050	2071–2100	2021–2050	2071–2100	2021–2050	2071–2100
1A	141	9.7	18.4	+0.6	–8.2	+1.57	+3.34	+5.9	+39.9	+137.9	+456.4
1B	95	9.3	18.5	+8.7	–10.8	+1.55	+3.39	+10.3	+44.1	+96.4	+418.2
1C	23	9.2	18.4	+7.0	–7.8	+1.58	+3.31	–3.6	+32.0	+167.4	+556.0
2A	373	11.3	20.8	+2.6	–8.0	+1.57	+3.39	+3.6	+43.4	142	+655.7
2B	23	11.8	21.4	+10.4	–7.9	+1.55	+3.28	+11.8	+51.2	+172.6	+743.5
3A	77	15.3	25.4	+2.6	–5.7	+1.56	+3.32	–5.3	+38.6	+211.1	+1345.8
3B	31	13	22.9	+5.4	–9.9	+1.59	+3.49	–1.4	+41.9	+130.1	+1044.4
3C	7	14.5	24.2	+11.6	–7.5	+1.58	+3.26	–3.1	+36.0	+233.7	+1122.4
4A	13	17.4	28.6	+3.4	–6.0	+1.56	+3.31	–16.2	+45.4	+246.8	+2221.5

EZ – elevation zone; N – number of ALADIN-Climate/CZ RCM grid points within the zone; NoD5 – number of days with average daily air temperature exceeding 5°C; precipitation – average precipitation totals during the vegetation season; air temperature – mean annual air temperature; NRP10 – number of rainless periods with duration of 10 days at least during the vegetation season; NoD30 – number of days with maximum daily air temperature exceeding 30°C

tion limit of the primary host, Turkey oak (*Quercus cerris*), in coming decades (Hlásny, Turčáni 2009). In fact, Turkey oak is a marginal species in the Czech Republic, but other oak species may suffer from defoliation as well – mainly *Q. robur*, *Q. pubescens*, and *Q. petraea* on drier sites. An altitudinal shift of pest outbreaks in warm years has already been reported from Hungary (Csóka, Hirka 2006). Outbreak periodicity is presumed to remain stable (8–11 years in Central Europe) (Johnson et al. 2006), but occasional appearance of inter-outbreak defoliation can appear in the future.

In contrast to Gypsy moth, outbreak ranges of Winter moth (*Operophtera brumata*) are presumed to diminish under increasing temperature (Turčáni et al. 2007). Another recently observed phenomenon is the climate change-induced disappearance of synchrony between the phenology of Winter moth (*Operophtera brumata*) and host oak (*Quercus robur*) reported from the Netherlands (Visser, Holleman 2001). Respective damage to oak stands and probability of the occurrence of such events in the Czech Republic are not known yet.

2nd Elevation Zone

Direct impacts

Increased frequency of heat spells and drought periods in the distant future is projected to occur over the most spacious beech-dominated elevation zone in the Czech Republic. The 2A subzone is projected to be significantly drier compared to the Carpathian 2B subzone (Fig. 2).

The presumed altitudinal shift of the leading (upper) range of oak could cause beech retraction in this zone in favour of oak species. Notably, the upward expansion of oak species having their northern distribution limit in Central-Eastern Europe (*Quercus pubescens* group, *Quercus cerris*, *Quercus frainetto*) can be expected in the future. This could be true especially of nutrient-poor and drier sites, where oak can successfully compete for resources with the resident species.

The growth and competitive ability of European beech will not necessarily respond positively to increasing CO_2 concentrations, but it may be strongly impacted by intensive drought that occurs during the growing season (Gessler et al. 2007). However, there remains a considerable uncertainty to what extent other environmental factors (e.g. soil properties, competitive interactions) may modify the drought response of beech, thus either enhancing susceptibility or increasing drought tolerance and resilience potential. Peñuelas et al. (2007) reported intensive climate warming-related responses of the beech forest structure in north-eastern Spain. Strong beech replacement by Holm oak (*Quercus ilex*) was observed at the beech lower range limit. In contrast, beech stands gained density and shifted altitudinally upwards, advancing with establishment of new, vigorous outpost trees in the beech upper distribution range. These two processes are presumed to dominate in shaping the future forest structure in this zone (Hlásny et al. 2011).

Impact on pests and pathogens

The occurrence of biotic agents causing direct mortality in beech has not been reported from the Czech Republic yet. Recent observations indicate that Gypsy moth (*Lymantria dispar*) can tend toward feeding on beech as an alternative host under climate change (Hlásny, Turčáni 2009). A 2006 outbreak in Hungary (Bakony Mts., Bükk Mts.) that spread over thousands of hectares of beech stands of different ages at 500–700 m and defoliated as much as 50–70% over large areas (Hirka 2006) suggests that such events can be expected in the future also in the Czech Republic. Although such defoliations are known to cause mortality in the trees only exceptionally, a synergistic effect of beech defoliation, *Nectria* spp. cancer and progressive drought stress could be fatal.

3rd Elevation Zone

Direct impacts

Climate change impacts on forests in this zone can be considered as overlapping between here and the adjacent zone, as this zone represents a transitional region between the colline and mountain regions. The expected climate change-induced progress of beech to a higher elevation implies an increase in the proportion of beech to the detriment of the resident species. Sykes and Prentice (1996) suggested that the climate change could induce a spread of beech and other temperate hardwoods to the north as well as an increased rate of beech establishment as a successional response after disturbances. Forests are expected to respond to such impacts by a change in species composition in favour of temperate broadleaved species. The knowledge of fir responses to climate change in Central and Eastern Europe is rather limited. Peguero-Pina et al. (2007) suggested that the increasing drought stress could result in decreased photosynthesis and growth in sites located near the ecological limits of the species. Impacts on pests and pathogens are comparable with the adjacent zones.

4th Elevation Zone

Direct impacts

Mountain ecosystems are generally considered highly vulnerable to climate change (Beniston 1994). Plant species responding to higher temperatures may migrate upwards and cause a serious competitive pressure within the narrow, primarily temperature determined vegetation belts in mountain regions (Pauli et al. 2003). While a more intensive temperature increase is projected for mountain regions, the projected precipitation pattern is subjected to great uncertainty. In contrast to the reference period, days with daily maximum temperature exceeding 30°C are projected to increase in the distant future. Drought periods are projected to be 16% less frequent in the near future but 45% more frequent in the distant future (Table 2).

Inasmuch as Norway spruce is generally recognized to be a highly vulnerable species, impacts acting through the alteration of forest disturbances are expected to be much more pronounced compared to direct impacts. In contrast to lower elevations, the projected increase of air temperature and heat spell frequency could be beneficial to forests in this zone, as the more temperate climate and longer vegetation season can cause the upper tree line to shift, increase recruitment rates, as well as increase production (Colwell et al. 2008). The fact that global warming induced a 130 m shift of the upper tree line during the last century underlines the importance of this issue (Walther 2004). Drought periods increasing tree mortality are anticipated to occur only exceptionally. On the other hand, drought impacts on forest vegetation observed during the heat wave in 2003 at higher elevations in the Alps (Jolly et al. 2005) suggest that such events should not be underrated.

Impact on pests and pathogens

While the moderation of climatic limitations at high elevations offers opportunities for forest management, increasing disturbances might be counterproductive and detrimental (Lindner et al. 2009). Outbreaks of bark beetles (e.g. *I. typographus* and *Pityogenes chalcographus*) will generally be fuelled by abiotic disturbances (Wermelinger 2004). The Kyrill windstorm in 2007 and a subsequent large-scale bark beetle outbreak in the Šumava Mts. are a recent example. Severe regional heat waves may become more frequent in a changing climate (Meehl, Tebaldi 2004), thereby increasing spruce susceptibility to bark beetle attacks. In addition, forest stands damaged by wind are especially important precursors to outbreaks as they quickly provide large quantities of optimal breeding material (e.g. Grodzki et al. 2006). Thus, the projected increase in the frequency of windstorms (Giorgi, Coppola 2007) could escalate bark beetle threat to forests.

The projection of *Ips typographus* development in Slovakia (Hlásny, Turčáni 2009) indicates that the area providing climatic conditions suitable for the full development of the second generation of *Ips typographus* within the present distribution range of Norway spruce will almost double by 2075. Significant areas (20% of the present range of spruce distribution) with a potential for the full development of the third generation are expected to appear around 2045. They will continue to increase to some 50% in 2075. The fourth and fifth generations are not expected to occur in the spruce present distribution range at all. Similar development can be expected in the Czech Republic. The longest flight season of *Ips typographus* since the beginning of regular observations, recorded in 2009 (starting by April 8th and ending by October 5th), documents the importance of this issue. Fungal diseases, such as *Armillaria* spp. are presumed to increase their virulence under climate change (e.g. Wargo, Harrington 1991) although the knowledge of this subject is rather incomplete.

CONCLUSION

In this paper we have addressed the anticipated impacts of climate change on forests of the Czech Republic. We designed four elevation zones with specific forest vegetation and used them to provide a simplified framework for describing the future climate development and assessing the impacts of climate change. A broad range of literature has been reviewed to compile the knowledge of climate change impacts on forests in individual elevation zones. Both direct impacts and impacts acting through alterations due to biotic disturbances have been addressed. Due to space limitations, the impacts on tree physiology, forest stand carbon balance, and forest management issues have not been addressed. A single high resolution climate change scenario was used to describe the future development of regional climate.

We found out that while the increase of mean annual air temperature is almost constant over the Czech Republic (+3.25–3.5°C in the distant future compared to the reference period), the frequency of heat spells (defined as days with daily maximum air temperature above 30°C) at lower elevations increases from 5–8 (reference period) to 30–40 (distant future). Such an increase is less intensive at higher elevations. The precipitation totals during the vegetation season are projected to increase in the near future by up to 10% and to decrease in the distant future by up to 10% over all the vegetation zones. This corresponds with an increase by up to 50% in the distant future in the number of drought periods of 10 days at least during the vegetation season.

In general, drought is anticipated to become a key limiting factor at lower elevations, while the increased temperature along with a longer vegetation season at higher elevations can be beneficial to forest vegetation. Consequently, northward progression of forest tree species and retraction of the species lower distribution range are a generic response pattern. Such impacts are expected to be accompanied by changes in the distribution of pests and pathogens and in population dynamics. Projected impacts on two key forest pests – *Ips typographus* and *Lymantria dispar* – have been described. In general, an increase in the number of annual generations of *I. typographus* as well as expansion of outbreak ranges of *L. dispar* can be expected. Despite the limited knowledge regarding the sensitivity of forest ecosystems to altered synchrony in multitrophic systems, such events could be a serious threat in the future.

The use of appropriate forest management techniques can help to mitigate a great part of climate change impacts on forests. Climate change-induced changes in trees growth will influence the competitive relations between species, the potential species composition, and the choice of species available in managed forests (Lindner 2000). Therefore, the knowledge concerning regional responses of forests to climate change is crucial for adapting forests to the forthcoming environmental conditions as well as for mitigating climate change through the forest capacity for carbon sequestration.

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