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The effects of climate warming on the growth of European beech forests depend critically on thinning strategy and site productivity

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ABSTRACT

Recent studies have revealed that European beech (*Fagus sylvatica* L.) has significantly increased its growth in Central Europe during the last century but recently started to decline at the edge of its southern distribution. Climate scenarios predict an increased frequency of severe drought events in the future, which is supposed to cause a decline of beech forests even towards the northern edge. Whether the management has the potential to mitigate the negative effects of climate warming has not been fully addressed yet. In order to fill the knowledge gap, we compiled data from 29 long-term research plots (LTRP) at 8 sites across the western Carpathian Mountains (Eastern Europe). The LTRP were established in 1958–84 and measured every 4–5 years till 2015. Development of forest stand attributes including top height (h_{top}), mean quadratic diameter (d_q), mean annual tree volume increment ($\bar{iv}$), periodic annual volume increment (PAIV), mean annual basal area increment (BAI), and total yield production (TY) was compared with the simulations by the Slovakian yield models developed in the 1980s based on data from the period before recent climate change. Results were additionally confronted with the growth of beech forests in a larger Central European region. Results showed an increase of TY since the 1960s compared to the simulated TY, starting from the same value, ranging from 5% to 40% and mainly depending on site quality and average annual temperature. The largest increase was found on less productive sites, which was in line with the previous findings in recent literature. Interestingly, beech TY in the Western Carpathians was found to be lower by −11% on average compared to beech forests in Central Europe (Germany). Moreover, while an increase in the BAI continues in unmanaged forests, it has recently slowed down in forests managed by "free crown thinning" and it even started to decrease in less productive forests where heavy thinning from below was applied. Finally, our results showed that the responses of beech BAI to climate variation significantly depended on tree class.

1. Introduction

The knowledge of the responses of forest ecosystems to climate warming has been expanding (Gazol et al., 2015; Hember et al., 2012; Pretzsch et al., 2014), but uncertainties due to a lack of long-term and well-replicated data at a regional and continental scale still remain. Furthermore, individual studies of climate change impact on tree growth greatly differ in the type of data used and statistical methods applied (Peters et al., 2015), which makes it difficult to compare and generalize. In addition, most of the studies use tree-ring width (TRW) data which is not able to account for changes in stand dynamics including tree mortality rates and changes in total yield (Pretzsch et al., 2014). To circumvent the costly and time-consuming field data collection, various models at a local to global scale have been used instead (Hlásny et al., 2011; Pretzsch et al., 2008). However, both process-based and empirical models will always have to be adequately supplemented with new empirical data (Pretzsch et al., 2014) to increase the reliability of the results. In addition, strategic decision making in forestry policy in Europe will have to rely on objective scientific knowledge with known uncertainty at a local, regional and continental level (O'Connor et al., 2015).

Now it is well documented that forests of central and northern Europe have experienced a growth increase in the last century (Pretzsch et al., 2014). On the other hand, recent studies have sug-

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gested that many species will likely suffer from drought stress at the southern edge of their current distribution in Europe and will probably shift their range northward (Rabasa et al., 2013; Saltré et al., 2014). European beech (hereinafter "beech"), as the dominant and economically and ecologically important tree species in Europe, has experienced divergent changes across the continent varying according to site quality and altitudinal environmental conditions (Aertsen et al., 2014; Di Filippo et al., 2007; Dittmar et al., 2003; Jump et al., 2006; Peñuelas et al., 2008; Piovesan et al., 2008). While the species has encountered a growth release in Central Europe (Pretzsch et al., 2014), it has recently turned to decline in the south of its distribution (Jump et al., 2006; Peñuelas et al., 2008; Piovesan et al., 2008). Surprisingly, there is also an evidence of a growth increase in Mediterranean beech populations (Tegel et al., 2014). On the contrary, some studies indicated that the species has recently experienced a growth decline even in Central Europe at higher altitudes (Charru et al., 2010; Dittmar et al., 2003; Zimmermann et al., 2015). Other studies demonstrated that due to climate changes (warming) the beech in Central Europe expanded above the tree line in the last decade (Vacek and Hejcman, 2012).

Recent studies have expectedly suggested that the response of wood production will likely depend on forest composition and structure (Coomes et al., 2014; Vacek et al., 2014) which are critically dependent on the forest management strategy applied during its lifespan (or rotation period). However, there is a lack of evidence on how and to what extent forest management can contribute to mitigating the impacts of climate change on forest ecosystems.

To contribute to the debate, we performed the synthesis of a unique long-term experiment in spontaneously developing beech forests and in those managed by different thinning methods. The long-term research plots were established across the Western Carpathians (Eastern Europe) and measured every five years during the period 1958–2015. The synthesis was carried out in order to fill the following methodological and knowledge gaps: i) Eastern Europe; ii) forest growth dynamics data instead of TRW series; iii) different thinning strategies compared to spontaneously developing forests. The research was conducted to answer the following questions: (1) Has there been an increase in wood production in Eastern European beech forests since 1958? (2) What have been the main drivers of the growth dynamics in these beech forests? (3) Can different thinning methods modify the growth responses to climate warming?

2. Material and methods

2.1. Study area

The study was conducted in the Western Carpathian Mountains (Slovakia) situated in Eastern Europe (Fig. 1). The Western Carpathians are a discrete morphostructural unit of the Alpine–Carpathian mountain chain (Minár et al., 2011). The area of the Western Carpathians comprises approximately 70,000 km^2 with the elevation ranging from 95 to 2655 m above sea level. A complicated geological structure and specific tectonic pattern are characteristic of these mountains (Minár et al., 2011). The geological and geomorphological complexity resulted in highly variable climatic and nutritional conditions in the region.

2.2. Long-term research plots and thinning treatments

Twenty-nine long-term research plots (LTRP) in eight localities across the Western Carpathians and western part of the Eastern Carpathians (Fig. 1a) were established in 1958–1984 (Table 1). The forests in which the plots were located were critically selected to meet the following criteria: (i) they were strictly established by natural regeneration, (ii) no thinning was applied to the forests prior to the LTRP establishment, (iii) beech was a dominant tree species (with the canopy cover over 90%), and (iv) they were not older than 30–60 years.

The LTRPs were established in order to study the effects of different thinning methods on wood production and timber quality. Each of the eight sets of LTRP included 3–5 subplots with the application of different thinning types as well as one control subplot ("0") where no management was applied at all. They were situated on the same site next to each other along the contour line on the slope to exclude a potential effect of the site. In addition, a 15-m wide buffer zone was left between the subplots to exclude potential between-subplot interactions. The area of the square-shaped subplot was 0.25 ha (50 × 50 m). The following thinning types were applied: 1) "C"—heavy thinning from below (following the principles defined by German forest research institutes released in 1902); 2) "H" or "H2"—free crown thinning (thinning from above) applied in 5- and 10-year intervals, respectively, as defined by Štefančík (1984). The principle of this thinning type lies in supporting the selected best-quality trees (so-called target trees) by removing their competitors. Here, an emphasis is put not only on stem quality but also on crown shape and spacing of target trees. In addition, a qualitative group selection thinning "H1" (Kató and Mülder, 1983; Kató, 1972) in the 5-year interval was applied on the Žalobín site. To make it simpler for further statistical analysis we grouped the H thinning types into one type and called it commonly thinning from above. The support to this approach was that all these H thinning types had the same principle – to support selected best-quality trees in the upper canopy layer.

Thinnings of different intensity were applied during the study period. The intensity ranged between 10 and 30% of the stand basal area at the first 2–3 thinning treatments. At the later treatments, it did not exceed 10%. In total, 7–12 treatments were carried out in the managed subplots.

All trees with diameter at breast height (*dbh*) over 3.6 cm were registered and measured at each inventory (in 5-year intervals) during the study period. All the trees were numbered and the place of *dbh* measurement was marked to avoid measurement errors. Trees that reached the *dbh* registration threshold during the study period were always included; they were numbered, marked and measured. All registered trees were measured for *dbh* using two perpendicular measurements and calculating the average. All the trees were classified into tree classes (vertical layers): 1—dominant, 2—co-dominant, 3—sub-dominant and 4—suppressed.

A transect of 10 m in width and 50 m in length was established on each subplot. Tree height, crown base and crown width were measured in all trees on the transect at each inventory (measurement) during the study period.

2.3. Derivation of stand growth and production attributes

Height-diameter models for each LTRP and each measurement (inventory) during the study period were developed using tree height and *dbh* measurements from the transects in order to estimate heights of all other trees in which the height was not measured.

Further, top stand height (h_{top}, m), mean quadratic diameter (d_q, cm), mean volume increment (iv, m^3 yr^{-1}), periodic annual volume increment (PAIV, m^3 yr^{-1} ha^{-1}), mean annual basal area increment (BAI, cm^2 yr^{-1}) and total yield production (TY, m^3 ha^{-1}) were derived. The hundred largest trees (with the largest *dbh*) per hectare were selected to calculate h_{top}. PAIV was calculated as a difference between growing stocks at the consecutive measurements (V_2–V_1) including natural loss and trees removed by thinning