



Stem and root diameter growth of European beech and Norway spruce under extreme drought



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ARTICLE INFO

Keywords:

Intra-specific competition
Interspecific competition
Rainfall exclusion
Mixed forest stand

ABSTRACT

Current and future climate change will be accompanied by more frequent and more severe drought events, with potential impacts on tree growth and forest stand productivity. Tree growth response may depend on its water status and on the competition or facilitation of the neighbouring trees. We analysed inter- and intra-annual diameter increments of European beech and Norway spruce trees within a mixed forest stand for two treatments, i.e., with and without rainfall exclusion and for two neighbourhood competition situations of the two climatically contrasting years 2014 and 2015. Rainfall exclusion by roofs at about 3 m height induced soil drought under 116 trees, particularly supported in the year 2015 by hot and dry weather conditions. The effects of extreme drought was examined at three levels, i.e. at two stem heights and at the main coarse root of 48 trees with inter- and intraspecific neighbourhood. We found species specific diameter growth performances during the year at all three levels. Compared to beech trees annual diameter increments of spruce trees were in most cases significantly higher in the year 2014, while in the drought year 2015 no significant differences between the two species were obvious. Under the heavy drought by the rainfall exclusion experiment and by the hot year 2015 diameter increments were significantly smaller for spruce trees at all three levels whereas for beech trees at all levels no significant differences were obvious. The diameter growth differences between inter- and intraspecific neighbourhood were in most cases small and not significant. In the drought year 2015 beech trees in intraspecific neighbourhood grew better at all levels compared to interspecific neighbourhood, with a significantly higher growth rate at the upper stem level. Reasons for the species specific reactions patterns on drought were discussed (phenology, water balance, species specific physiological reactions).

1. Introduction

Declining tree vitality and tree growth found in different European regions can be traced back to a severe reduction of the water availability (ICP-Forests, 2004). Tree mortality of forests at the edge of their bio-geographical distribution may rise if temperature is increased, particularly in Southern and Central Europe (e.g. Schröter et al., 2004; Camarero et al., 2015). On the other hand, climate and other environmental changes such as precipitation patterns, length of growing season, CO₂-concentration, or nitrogen deposition can stimulate forest growth (e.g. Pretzsch et al., 2014a), which is a major component of the forest biomass changes through time since recruitment and mortality also influence the turnover times of forest biomass (Körner, 2017). In recent years the number of studies increased which report an acceleration and a rise of tree and stand growth of temperate and boreal forests within the last 50 years (e.g. Innes, 1991; Spiecker et al., 1996; Pretzsch et al., 2014a; Kauppi et al., 2014; Fang et al., 2014; Aertsens et al., 2014). The higher growth rates of the last decades can be

explained by temperature increase (IPCC, 2007), by extended growing seasons (e.g. Chmielewski and Rötzer, 2001) and by the rise of N-depositions (e.g. Churkina et al., 2010) and of the atmospheric CO₂-concentration (e.g. Churkina et al., 2010) within the last century (Pretzsch et al., 2014a).

In future water availability which is an essential parameter for tree growth will become more and more critically with longer and more frequent drought periods (Leuschner, 2009; Allen et al., 2010). While drought adapted forest types show mortality during long-lasting water shortage, less drought adapted forest types like temperate broadleaved forests show highest mortality rates during short-term (seasonal) water shortage (Allen et al., 2010). The influence of water shortage on tree and stand growth is closely linked with the environment of the tree individuals and the forest stand as a whole (Rötzer et al. 2017), i.e. with tree age (e.g. Peterken and Mountford, 1996), social classes of the trees (e.g. Orwig and Abrams, 1997; Dohrenbusch et al., 2002), site and soil conditions (e.g. Orwig and Abrams, 1997; Modrzynski and Eriksson, 2002; Pichler and Oberhuber, 2007) but also tree species (e.g. Orwig

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and Abrams, 1997; Leuschner et al., 2001) and tree genotype (e.g. Hamanishi and Campbell, 2011). Further on, species mixing could change the stand water balance (e.g. Pretzsch et al., 2012).

For mixed stands of Norway spruce (*Picea abies* (L.) H. Karst.) and European beech (*Fagus sylvatica* L.) which are the most relevant mixture in Central Europe, actual evapotranspiration rates were found to be clearly different from the corresponding monospecific stands and thus also stand productivity and resource use efficiency (Pretzsch et al., 2012). And even forest mixing structure, i.e. the spatial distribution of the species within the stand, change the resource supply of water and light and in consequence tree growth (e.g. Rötzer, 2013). The responses of beech and spruce trees to the long and intensive drought of the exceptionally hot and dry summer of 2003 in Central Europe brought new knowledge in tree growth reactions on drought stress (Leuzinger et al., 2005; Breda et al., 2006; Löw et al., 2006; Nikolova et al., 2009; Pretzsch et al. 2012). Forest growth and primary production was reduced in this year which was closely linked to water availability (e.g. Ciais et al., 2005; Pichler and Oberhuber, 2007; Reichstein et al., 2007; Pretzsch et al. 2013). However, there is still a lack of knowledge how different tree species behave under extreme drought conditions, particularly in mixed forests, and what are the consequences for stand growth.

Many studies about mixed spruce beech stands in Central Europe showed a significant overyielding of mixed versus monospecific stands of 10–30% in terms of volume growth (Kennel, 1965; Pretzsch et al., 2010a; Rothe, 1997). Growth superiority of mixed versus monospecific stands, mostly referred to as overyielding, can amount to 10–30% in 2-species stands (Pretzsch et al., 2016a) and increases degressively with species richness (Liang et al., 2016). For the age series of a long term forest experiment (Pretzsch et al., 1998) which includes the Kranzberg Forest the long-term overyielding at the stand level amounts to 1.18 (Pretzsch et al., 2010a, Pretzsch and Schütze, 2009). Under normal conditions the mixed stand is by 18% more productive than the weighted mean of the two monocultures; both Norway spruce and European beech contribute approximately the same to this overyielding. The better below and above ground resource access of mixed stands as reasons for overyielding have been studied rather extensively, e.g., regarding the tree morphology (Kennel, 1965; Petri, 1966), canopy layering (Pretzsch, 2014), and root stratification (Wiedemann, 1942).

The higher growth stability of mixed-species stands compared with monocultures can be quantified by comparing the inter-annual growth oscillation of mixed stands with the monocultures at the stand or species level (Río et al., 2017). The main reason for their more stable growth is an asynchronous growth behaviour of the associated species (Jucker et al., 2014). Río et al. (2017) showed that asynchrony can closely correlate with stability and overyielding. The species' complementarity known from monocultures may even increase in mixture due to their phenotypical plasticity. E.g., crown extension and thereby light interception of European beech can exceed beyond its behaviour known from monocultures (Dieler and Pretzsch, 2013). Such temporal diversification was studied at the long-term inter-annual scale (von Lüpke and Spellmann, 1997; Pretzsch et al., 2010a; Rothe, 1997) but hardly at the intra-annual level (seasonal development).

Plant allocation theory states that biomass allocation to above-ground or belowground tree compartments follows the principle of maximizing the capture and minimizing the limitation of resources (e.g. Chapin, 1980). Consequently, decreasing water supply or increasing drought conditions may result in enhanced root growth. This is reported in numerous articles (e.g. Cienciala et al., 1994; Polomski and Kuhn, 1998; Leuschner et al., 2001; Frank, 2007; Noguchi et al., 2007) as well as shown by simulation studies (Rötzer et al., 2009; Rötzer et al., 2012). Thus, water uptake of trees in periods with low water availability can be ensured by carbon allocation to the roots (Leuschner et al., 2001). Extreme drought, however, may reduce root biomass, particularly for less drought adapted species like spruce (Polomski and Kuhn, 1998; Rötzer et al., 2009). Further, species mixing can change

share and distribution of roots in forests. For example spruce in inter-specific neighborhood or in mixed stands with beech showed lower root biomasses respectively lower fine root production compared to spruce trees in intra-specific neighborhood or in monospecific stands (Goisser et al., 2016; Bolte et al., 2013).

In this study we analyse any annual growth differences between Norway spruce and European beech. We examine whether stem diameter growth is equal in inter- and intra-specific neighborhood, i.e., whether it is modified by species mixing under normal and extremely dry conditions. We further scrutinize whether the diameter increments of the upper stem and of the main roots are similar to the increments at breast height under normal conditions and also under extremely dry conditions. Extreme drought conditions were induced by a rainfall exclusion experiment (Pretzsch et al., 2014b). This way, the following research questions arise

- (1) How do spruce and beech trees differ in their growth reaction on drought stress (2014 vs. 2015 and control vs. drought treatment)?
- (2) Are there differences in the stress reaction on drought between trees in intra- and inter-specific neighborhood?
- (3) To which extent do drought periods modify the growth development of the stem (diameter at breast height (1.3 m) and 50% height) and the main roots of spruce and beech trees?

2. Material and methods

2.1. Study area Kranzberg forest

Located in Southern Germany, about 35 km Northeast of Munich the study site Kranzberg Forest (longitude: 11°39'42"E, latitude: 48°25'12"N, elevation 490 m a.s.l.) has an average annual precipitation of 750–800 mm yr⁻¹ and of 460–500 mm during the growing season (May - September), both for the period 1971–2000. The average air temperature is at 7.8 °C on annual average and 13.8 °C on a seasonal basis (Hera et al., 2011). The forest stand has a size of 0.5 ha and stocks on a luvisol originating from loess over Tertiary sediments and providing high nutrient and water supply (Göttlein et al., 2012; Pretzsch et al., 1998). Depending on soil depth the water holding capacity for plant available water ranged between 17% and 28%, while soil pH pH_{H2O} varied between 4.1 and 5.1. The mixed stand comprises groups of beech trees surrounded by spruce trees. By coring each tree to the heart wood in a height of 30 cm tree age was assessed as 63 ± 2 years for spruce and 83 ± 4 years for beech for the year 2014.

2.2. The KROOF rainfall exclusion experiment

The Kranzberg Forest is part of the age series of a long term forest experiment (Pretzsch et al., 1998). Within the Kranzberg Forest site 12 experimental plots were established. Already in spring 2010 trenching was performed to avoid effects on tree growth in the study phase (Pretzsch et al., 2016b). Lined by a heavy-duty plastic tarp which is impermeable to water and root growth soil was trenched to about 1 m deep. Afterwards it was refilled with the original soil material. A dense clay layer of tertiary sediments prevented further downward-rooting at a depth of app. 1 m (Haberle et al., 2015).

Each plot as well as the entire site consist of intra-specific zones with only spruce and beech trees and a mixed transition zone with both spruce and beech trees. Six of the 12 plots are serving as control plots. At another six plots roofs were built underneath the stand canopy at about 3 m height to induce soil drought, with the first drying cycle being started in April 2014. To induce experimental drought the automated rain exclusion roofs only close during rainfall to exclude unintended micro-meteorological and physiological effects (Pretzsch et al., 2014b).

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