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Discerning environmental factors affecting current tree growth in Central Europe

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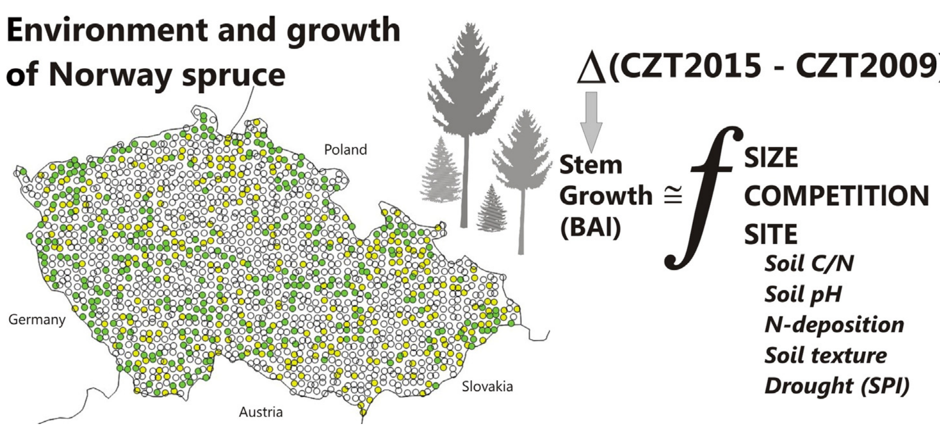
HIGHLIGHTS

- Promoted artificial spruce distribution makes Central-European forestry vulnerable.
- Observed tree growth available from a repeated national survey (2009–2015)
- Mixed linear model used to assess significant environmental variables for growth.
- Spruce tree growth linked to soil properties, N-deposition and moisture conditions
- Altitudinal range reflects indirect and direct limitation to tree growth.

GRAPHICAL ABSTRACT



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ABSTRACT

We examined the effect of individual environmental factors on the current spruce tree growth assessed from a repeated country-level statistical landscape (incl. forest) survey in the Czech Republic. An extensive set of variables related to tree size, competition, site characteristics including soil texture, chemistry, N deposition and climate was tested within a random-effect model to explain growth in the conditions of dominantly managed forest ecosystems. The current spruce basal area increment was assessed from two consecutive landscape surveys conducted in 2008/2009 and six years later in 2014/2015. Tree size, age and competition within forest stands were found to be the dominant explanatory variables, whereas the expression of site characteristics, environmental and climatic drives was weaker. The significant site variables affecting growth included soil C/N ratio and soil exchangeable acidity (pH KCl; positive response) reflecting soil chemistry, long-term N-deposition (averaged since 1975) in combination with soil texture (clay content) and Standardized Precipitation Index (SPI), a drought index expressing moisture conditions. Sensitivity of growth to N-deposition was positive, although weak. SPI

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N-deposition
Managed forest
Tree increment

was positively related to and significant in explaining tree growth when expressed for the growth season. Except SPI, no significant relation of growth was determined to altitude-related variables (temperature, growth season length). We identified the current spruce growth optimum at elevations about 800 m a.s.l. or higher in the conditions of the country. This suggests that at lower elevations, limitation by a more pronounced water deficit dominates, whereas direct temperature limitation may concern the less frequent higher elevations. The mixed linear model of spruce tree growth explained 55 and 65% of the variability with fixed and random effects included, respectively, and provided new insights on the current spruce tree growth and factors affecting it within the environmental gradients of the country.

1. Introduction

Tree growth depends on numerous factors including essential resources such as light, water, nutrients, which are accessible to individual trees according to their social position and actual physical dimension. All these factors interact and vary over space and time to be jointly expressed in observed growth rate changes. Discerning the effect of individual factors on growth is essential for assessing the effect of changing and/or disturbed growth environment. This is specifically important in the conditions of Central-European forestry, where the heavily altered tree species composition made the Norway spruce (*Picea abies (L.) H. Karst.*) dominated forestry vulnerable to both directly human-induced and environmental pressures. The former include effects of atmospheric acidification with direct damaging effect on foliage from the 1960s to 1990s in the last century (Ulrich, 1983, Purdon et al., 2004) and long-term impact on forest soils by acidification and nutrient degradation (Hruška and Cienciala, 2003). This was manifested by a notable forest dieback due to severe industrial air pollution already during the 1970s (Fanta, 1997), the pressure of which lasted until the early 1990s (Hůnová et al., 2014; Kopáček and Veselý, 2005). The environmental pressures include the observed conditions of changing climate that forest ecosystems face nowadays. The impacts such as more frequent and more severe drought, windstorm and biotic disturbances affect ecological stability and functioning of these forest ecosystems (Hlásny et al., 2014; Lindner et al., 2010). As a result, forest management is impaired by a high rate of sanitary felling, which must be prioritized over the planned interventions. Hence, increasing stability of Central-European managed forest stands with a heavily altered species composition is an issue that must be addressed by current forest adaptation strategies to climate change (Hlásny et al., 2011). Evidently, for this, elucidation of current tree-level responses to key environmental drivers is essential and needed.

The above applies specifically to the conditions of the Czech Republic, the spatial domain of the current study. Although the share of Norway spruce has been slowly declining during recent years in this country, spruce remains represented with above 52% by volume and 42% by area (Cerny et al., 2015, Cienciala et al., 2015), which is significantly higher than its natural distribution, which is assumed to be about 12% (Vokoun, 1997). This is no different than elsewhere in Central-Europe with production-oriented forestry based on spruce grown extensively at lower elevations (Spiecker et al., 1994).

This study seeks to analyze the observed current tree growth obtained from a repeated country-level statistical sampling, focusing on Norway spruce. This information has become available only very recently in the Czech Republic, when both the National forest inventory (Adolt et al., 2016) and the Landscape inventory CzechTerra (Cerny et al., 2015) conducted their repeated (second) survey cycle. This study utilized the data from the latter project. It shares a similar structure of data as commonly used in national statistical forest inventories (Tomppo et al., 2010), namely individual trees grouped within sample plots distributed across the country. Such a type of clustered data requires taking into account the mutual correlation among trees within a plot, which is effectively solved by a mixed model approach (Adame et al., 2008; Hökkä et al., 1997; Laubhann et al., 2009).

Interest in multi-variate forest tree and stand growth modelling in the recent two decades has been strongly driven by the puzzle of observed increasing growth rates in Europe, which became well documented already in the 1990s (Spiecker et al., 1996, Spiecker, 1999). Since then, several studies have attempted to disentangle the effects of key drivers on tree growth, focusing specifically, but not only, on changing temperature and nitrogen deposition. Added N has the potential to act as a fertilizer, stimulating plant growth (Townsend et al., 1996). However, a long term N deposition may also impair forest growth through acidification and nutrient degradation (Schulze, 1989). Our understanding of this topic remains incomplete, even though the quantitative contribution of N deposition to forest carbon sequestration has been intensively debated in recent years (Magnani et al., 2007, De Vries et al., 2008; Högberg, 2012). In this debate, however, Högberg (2012) convincingly documented that the contribution of ambient N-deposition on ecosystem production is relatively small fraction (13%) of the total N-supply (soil N, natural soil N fixation, historical and current deposition).

Soil eutrophication have been shown as important factors affecting tree growth in Europe (e.g., Wilson and Elling, 2004; Högberg et al., 2006; Schulze et al., 2012; Kolář et al., 2015). Consequently, mutual effects of climate and changed soil chemistry may alter tree growth rates. This, however, does not exclude a possible contribution of other factors on growth such as ozone (De Marco et al., 2013, Fares et al., 2013) or increased CO_2 (e.g, Norby et al., 2005) that are not considered in our study focusing on current tree growth and robust environmental gradients within Central Europe.

Based on evidence from both tree and stand level approaches, the European studies suggested that primarily nitrogen deposition was assessed as the main factor explaining the increased tree and forest growth (Kahle et al., 2008, Solberg et al., 2009), while other document a mostly temperature-driven increased growth, especially on fertile sites (Pretzsch et al., 2014). A tree-level study focusing on four tree species including Norway spruce showed, however, that tree level growth differed among tree species in responding to site variables such as soil chemistry and climate, although the positive effect of nitrogen deposition, apart from tree size and competition variables, was confirmed for all investigated species (Laubhann et al., 2009).

We have been specifically interested in identifying and assessing the strength of site and environmental variables, i.e. those related to soil properties, temperature, moisture and N deposition gradients, as the published experience with tree-level modelling suggested that tree size and competition variables would likely be dominant in explaining the observed tree growth patters (Laubhann et al., 2009). The nature of statistical sampling used in this study allows analyzing imprints of the environmental gradients on current tree growth and their interactions. Clearly, both temperature and N-deposition effects on tree growth vary with altitude, the former linked to moisture conditions, while the latter also to soil acidification, which is pronounced especially at high elevations (Kopáček et al., 2012).