



Original Article

Soil properties affect the drought susceptibility of Norway spruce

Romy Rehschuh^{a,b,*}, Tobias Mette^c, Annette Menzel^{a,d}, Allan Buras^a^a Technische Universität München, Professorship of Ecoclimatology, Freising, Germany^b Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research, Atmospheric Environmental Research (IMK-IFU), Garmisch-Partenkirchen, Germany^c Bavarian State Institute of Forestry (LWF), Soil and Climate Department, Freising, Germany^d Technische Universität München, Institute for Advanced Study, Garching, Germany

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ABSTRACT

Norway spruce (*Picea abies*) is considered to be one of the economically most important coniferous tree species in Europe. It is, however, susceptible to drought and there is concern that anticipated climate change may greatly influence its yield potential. In addition to the climate, soil characteristics are known to play a major role in tree growth rates. Detailed knowledge about the relationships between the soil and tree growth in the face of climate change has started to be generated only recently. As a contribution to this field we investigated the influence of soil on the drought susceptibility of Norway spruce by means of dendrochronology. Tree-ring data were acquired from two sites southwest of Munich, Germany, with rather similar climates but different soil textures. By combining multivariate statistics with climate correlation and pointer year analyses, we were able to show a clear differentiation between the two sites with respect to the growth performance of Norway spruce. That is, trees growing on a shallow, well-drained soil grew less and expressed a relatively higher drought sensitivity compared to trees from a site with a deep, silty soil as indicated by higher correlations with drought related indices and more intense droughts in negative pointer years compared to neutral years. Among the considered drought indices the soil water deficit index explained best the multivariate differentiation between the two sites, wherefore we interpret these findings as a significant impact of soil characteristics on Norway spruce performance. In the context of climate change and an increasing risk of extreme droughts during the 21st century, this finding has important implications for forest management activities since the risk of drought induced tree mortality appears to be affected by soil conditions.

1. Introduction

Norway spruce (*Picea abies* (L.) Karst) is among the economically most important coniferous tree species in Europe (Lu et al., 1996; Spiecker, 2000). Due to its high growth potential and timber quality as well as limited demands with respect to site conditions, it is planted far beyond its natural range and utilized for timber production (Spiecker, 2000; Roloff et al., 2010). The forest area of *P. abies* in Germany is currently about 2.76 million ha (i.e. 25.6% of the total forest area; Kroiher and Bolte, 2015). However, several studies have reported a high susceptibility of *P. abies* to drought stress in lower elevations (Dittmar and Elling, 1999; Spiecker, 2000; Spiecker, 2002). Thus, on these sites *P. abies* seems to be particularly prone to drought induced decline in the course of climate change (Kohler et al., 2010). Modeled

dynamics of the European spruce bark beetle (*Ips typographus*) project outbreaks with stronger drought and windthrows (Temperli et al., 2013), thus increasing the risk of tree mortality. Climate projections from global circulation models calculate temperatures to rise by 1–5 °C until the end of the 21st century in Europe (Jacob et al., 2014). If higher temperatures result in higher vapor pressure deficits, water conductance on canopy-scale will decrease according to Darcy's law (Park Williams et al., 2013; McDowell and Allen, 2015). Extreme heat and drought events impact the physiological functioning of trees which in combination with other stressors such as pests and diseases can result in growth decline and in the long-term in mortality (Bigler et al., 2006; Eilmann et al., 2009). Drought decreases carbon uptake due to stomatal closure, and the related water deficit often provokes a lack of nutrients, which decreases primary production and lowers plant growth (Lu et al.,

Abbreviations: AET, actual evapotranspiration; BAI, basal area increment; FP, Forstenrieder Park; NN, nearest neighbor; PAWC, plant available water capacity; PCGA, principal component gradient analysis; PET, potential evapotranspiration; SG, Schöngeising; SPI, standardized precipitation index; SPEI, standardized precipitation evapotranspiration index; SWDI, soil water deficit index

* Corresponding author at: Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research, Atmospheric Environmental Research (IMK-IFU), Garmisch-Partenkirchen, Germany.

E-mail address: romy.rehschuh@kit.edu (R. Rehschuh).

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1996; McDowell et al., 2008; Eilmann et al., 2009). Therefore, understanding the impacts of climate change on forests is of particular importance. Detailed information on forest growth and future trends is the foundation for projecting the resistance of tree species and for maintaining a sustainable wood production. Updated species-related and site-specific information is needed for economical, ecological, and social issues of forest management (Spiecker, 2002). The *iron law of location* expressed by Wilhelm Pfeil is a basic principle of silviculture which also remains valid under climate change (Falk et al., 2013). It means that for successful silviculture, site conditions must meet the demands of the tree species over the whole rotation period. The choice of tree species being able to cope with climate change should respect forest soil is a focal point (Leitgeb et al., 2013). Soil characteristics were shown to play a major role in plant performance, given that plant water availability not only depends on precipitation sums and temperatures, but also on the soil type (Jury et al., 1991; Lévesque et al., 2013). Soils influence tree growth intensively through their moisture and temperature regimes, physical properties (texture, skeleton, density, conductivity etc.), soil chemistry and accumulation of organic matter. The soil texture is an important variable for infiltration and water retention capacity and therefore has a significant impact on the supply of water and nutrients to the plant (Jury et al., 1991; Fisher and Binkley, 2000). Due to the projected longer and more intense drought periods for the future, there is a need to further study the interactions between soil characteristics and tree growth.

For this, dendrochronology appears to be a valuable tool. Several dendrochronological studies have shown growth decline by revealing narrower tree-rings during years with lower moisture availability for different tree species (e.g. Bigler et al., 2006; Weber et al., 2007; Eilmann et al., 2009; Kohler et al., 2010; Boden et al., 2014). However, few studies have analyzed the interactions between soil conditions and growth response to drought. Some studies have taken the plant water availability of the soil into account, e.g. by investigating the influences of thinning on *P. abies* stands (e.g. Misson et al., 2003; Kohler et al., 2010; Sohn et al., 2013). They found that a lower stand density increases soil water availability in the short-term, which favors tree growth and increases the resistance of the trees to drought but this could change in the long term due to increased water demand of the residual trees or the development of an understory. Fekedulegn et al. (2003) investigated with dendroecological methods the influence of the topographic aspect on different tree species in an Appalachian watershed. Most species exhibited lower growth rates and stronger drought responses at the southwest aspect compared to the northeast aspect for which higher solar radiation and thus more desiccated soils were found to be one of the reasons. Rigling et al. (2001) investigated tree growth on different soil substrates and found a low climatic response of Scots pine on dune sites, which was explained by the low available water capacity of the soils due to the large permeability of sandy soils. Furthermore, Weber et al. (2007) analyzed the effect of altitudinal gradients in the dry Valais valley, Switzerland, and revealed that sub-regional disparity was mainly driven by different responses to distinct climatic and soil conditions. On the other hand, Oberhuber et al. (1998) and Boden et al. (2014) reported that the impact of changing moisture conditions on tree-ring formation of Scots pine and Norway spruce does not depend on the specific study sites which differed in site characteristic including the soil type and depth.

Moreover, based on tree-ring parameters Lévesque et al. (2013) analyzed drought responses of five conifer species growing in a mixed stand (*P. abies* amongst others) at two ecologically contrasting sites, i.e. mesic and xeric. They reported trees at the mesic sites to be more sensitive to summer soil water deficits, whereas trees at the xeric site were more strongly affected by previous year and winter soil water deficits.

To clarify uncertainties and fill existing knowledge gaps with respect to the influence of soil characteristics on the drought susceptibility of *P. abies*, we here analyze tree-ring records of two mono-

specific *P. abies* stands situated in close proximity to each other but on soils with differing textures, i.e. a shallow sandy soil and a deep silty soil. We hypothesized that the drought response of *P. abies* differs between these two stands. That is, we expected that *P. abies* exhibits a higher productivity and a lower drought susceptibility on silty soils in comparison to shallow sandy soils due to the higher water retention capacity of the former compared to the latter. In our study, drought susceptibility refers to the response of a tree to drought events, i.e. extremely warm-dry years. Objectives were a) to investigate long-term growth differences between the two distinct sites, b) to determine pointer years in tree-ring series of Norway spruce at the two locations and clarify their association with climatic factors and soil characteristics, c) to identify the periods and duration of drought and soil water deficits during the year which revealed greatest impacts on Norway spruce growth at the two differing sites. Improving our knowledge about the impacts of the soil on tree growth will allow for optimizing species selection for long-term forest plantations and thus, a positive development in the productivity of the timber production industries.

2. Material and methods

2.1. Study sites

To test for the influence of soil conditions on the performance of *Picea abies*, we selected two sites southwest of Munich (Fig. 1, left), i.e. Forstenrieder Park (FP) and Schöngeising (SG). These sites were selected for their rather similar climate conditions and stand properties with respect to age and stand density, but differing soils, i.e. a deep silty soil (FP) and a shallow sandy soil (SG).

The climate is warm temperate; FP receives on average more precipitation than SG (annually 1068 mm and 906 mm, respectively) of which 592 mm in FP and 495 mm in SG occur during the vegetation period from May to September. Over the whole year, it is slightly colder in FP than in SG (mean annual temperature: 8.09 °C in FP and 8.45 °C in SG). The temperature difference between the warmest (July) and the coldest (January) month is 18.32 °C in FP and 18.70 °C in SG (interpolated climate station data from DWD weather stations for 1961–2013). The interannual climatic conditions at the two sites are depicted in Fig. 1, right panel.

The *Stagnic Cambisol* in FP has a field capacity of 422 mm and a permanent wilting point of 222 mm and the *Cambisol/Luvisol* in SG has a field capacity of 133 mm and a permanent wilting point of 59 mm (LWF, 2015). Thus, the plant available water capacity (PAWC, i.e. the amount of water held between field capacity and permanent wilting point) is 200 mm for FP and 74 mm for SG.

At each site we investigated 20 specimens using dendrochronological techniques. Mature, dominant trees were selected to lower influences of competition. From each tree two increment cores using Haglöfs increment borers were sampled in two perpendicular expositions, i.e. east and north. In addition for each tree we measured its diameter at breast height (DBH) as well as the distance to its nearest neighbor of similar size (NN).

2.2. Data acquisition and preparation

Increment cores were glued to wooden sample holders and polished using a belt sander to increase the visibility of annual rings. Subsequently, polished cores were scanned at a resolution of 1200 dpi. Tree-ring widths were measured from the scans using CooRecorder and measurements were cross-dated using CDendro (Cybis, 2017).

We used two different tree-growth proxies, i.e. basal area increments (BAI) and detrended ring-width indices (RWI). BAI was calculated using ring-width measurements and DBH. BAI better represent actual growth due to the successive narrowing of tree-rings with increasing stem size in spite of an increasing wood production. RWI was calculated using a cubic smoothing spline with a frequency response of

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