



Stability of tree increment in relation to episodic drought in uneven-structured, mixed stands in southwestern Germany

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ABSTRACT

Future increases in temperature and changes in precipitation patterns may negatively affect the growth performance of economically important tree species such as Norway spruce, which in the past have often been established and managed in monocultures. Structural diversity has been advocated as a silvicultural approach to increase resistance and resilience of forests to climate change extremes. Whether it promotes growth stability during and following drought years has not yet been analyzed.

We investigated stem growth reactions to the extreme drought of 2003 in 23 uneven-structured, mixed Norway spruce and Silver fir stands in southwestern Germany. Using linear mixed-effects models we analyzed the resistance and resilience of basal area increment in relation to species identity, drought intensity, tree size, competition, density and diversity.

Structural diversity, measured as variation in tree diameter at breast height, had no influence on increment stability during the extreme summer drought of 2003. Likewise, the effect of species diversity was weak and inconclusive. However, a higher presence of Silver fir in the mixture appeared to reduce increment stability in 2003 for both fir and spruce. Reducing competition through thinning counteracted this effect and promoted increment stability. Our findings indicate that the species identity of competitors in mixtures is a better predictor of stem growth reactions to drought than diversity. They support the conclusion that diversity does not generally increase stability to drought stress.

Silver fir consistently showed a substantially higher increment resistance and resilience than spruce. Its resistance increased with diminishing drought intensity, yet spruce reacted uniformly, manifesting a low resistance across the whole drought intensity gradient. Spruce did not regain pre-drought growth levels within the first three years after drought, whereas fir did. We conclude that fir may be able to act as a silvicultural alternative to spruce under changing climatic conditions, given appropriate sites and thinning regimes.

Considering the expected increase in drought intensity and frequency in the 21st century, understanding species interactions at the local scale emerges as an essential prerequisite for developing resilient forest stands.

1. Introduction

The late 20th and early 21st century represents probably the warmest period since 1500 or longer (Luterbacher et al., 2004). Looking ahead, the 21st century is expected to bring a rise in average temperatures, as well as an increase in the frequency and duration of drought events (IPCC, 2013). As a result, the adaptation potential of existing forests, as well as the risks of large-scale forest mortality and substantial shifts in species' distribution ranges have increasingly attracted the attention of the scientific community (Allen et al., 2010; McDowell and Allen, 2015). The long-term character of the expected

climatic changes has prompted discussions regarding silvicultural pathways towards more resistant and resilient forest ecosystems in the future (Puettmann, 2011; O'Hara and Ramage, 2013; Brang et al., 2014; Puettmann et al., 2015; Pretzsch et al., 2017).

In the context of climate change adaptation, it is essential to gauge the current drought vulnerability of different forest types and species. For example, given its fast growth and favorable wood properties, Norway spruce (*Picea abies* (L.) H. Karst.; “spruce”) is an economically important tree species in Europe which has often been managed in monocultures. In Germany spruce covers 25% of the forest area, represents 33% of the growing stock volume and is the staple species in

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forestry and the timber industry (BMEL, 2014). However, spruce has been found to be rather sensitive to drought (van der Maaten-Theunissen et al., 2012; Zang et al., 2012; Boden et al., 2014; Zang et al., 2014; Vitali et al., 2017) and drought-related pest risks such as bark beetles. Additionally, spruce has often been planted outside its natural distribution range, a factor which most likely increases its vulnerability to environmental stress (Boden et al., 2014). In consequence, future increases in temperature and changes in precipitation patterns may severely impact spruce stands by reducing growth and increasing mortality. It is expected that even under moderate climate change scenarios spruce may become unsuitable in large areas of its current, human-influenced distribution range (Hanewinkel et al., 2013).

There appears to be a relatively narrow range of silvicultural options that may help mitigate drought vulnerability of existing forests. Among them, heavy thinning has been found to reduce drought sensitivity in general – and in spruce stands in particular (Kohler et al., 2010; Sohn et al., 2013; Sohn et al., 2016b). Thinning appears to stabilize stem growth reactions especially by promoting increment recovery immediately after drought (Kohler et al., 2010; Sohn et al., 2013; Sohn et al., 2016b). Nevertheless, heavy thinning has been found to stabilize drought responses in the short-term, yet little is known about its long-term benefits and risks in relation to severe episodic droughts (D'Amato et al., 2013; Sohn et al., 2016a).

Mixing tree species with complementary traits has been suggested to promote ecological and economic resilience (Brang et al., 2014; Pretzsch et al., 2014). Both silvicultural approaches, reducing stand density through thinning and increasing species diversity, represent areas of active research, yet their track record for effectively mitigating drought sensitivity of trees and forests is rather inconsistent. In fact, there seems to be no general pattern for the interaction between tree species diversity and the drought response of trees and forests (Forrester et al., 2016; Bauhus et al., 2017). Empirical studies have found different results in this respect, with the mixing of species leading to positive (Lebourgeois et al., 2013; Pretzsch et al., 2013; Río et al., 2014; Gazol and Camarero, 2016), negative (Martínez-Vilalta et al., 2012; Grossiord et al., 2014; Jucker et al., 2014) or no effects (Klos et al., 2009; Merlin et al., 2015) on growth stability. Furthermore, many appraisals are based on experiments with a restricted spatial extent, which limits the transferability of observed patterns to a larger population (Bauhus et al., 2017).

While recognizing that compositional diversity and structural diversity are intertwined, increasing the latter has also been recommended as a potential long-term approach to promote ecological resilience (O'Hara and Ramage, 2013; Brang et al., 2014). In contrast to the steadily growing number of drought sensitivity assessments in mixed forests (Lebourgeois et al., 2013; Jucker et al., 2014; Forrester et al., 2016; Metz et al., 2016; Thurm et al., 2016; Vitali et al., 2017), few studies have tested the relationship between structural diversity and drought sensitivity so far (Gazol and Camarero, 2016).

In the current study, we used a data set displaying wide diversity gradients in managed, conifer-dominated mixed stands to investigate to which extent stem growth responses might be influenced by variations in structural diversity, species diversity and composition (i.e. the latter based on the relative representation of fir or spruce). Mainly admixed with spruce in these stands, Silver fir (*Abies alba* Mill.; “fir”) is a species known to be more tolerant to shade and drought than spruce (Hartl-Meier et al., 2014; Zang et al., 2014; Vitali et al., 2017). As a result, we expected different species responses to drought.

Recent studies revealed that when trees with different sizes co-occur within a stand, large trees tend to be more severely affected by drought in terms of stem growth and mortality than smaller trees (McDowell et al., 2011; Bennett et al., 2015; McDowell and Allen, 2015). Given the high variability of tree sizes in our study stands, we expected to also detect such a size-related sensitivity to drought.

Our leading hypothesis (i) was that diversity promotes stem growth

Table 1

General site and stand information for the experimental plots used in the current analysis. STS and GS stand for the single-tree selection and group shelterwood management treatments, respectively. Stand basal area values refer to residual basal area after the last thinning intervention preceding 2003. The attributes tree age in 2003 and tree diameter under bark in 2003 are based on a subset of tree ring chronologies originating from stem disks (N = 183).

Attribute	STS	GS
Number of sites/plots	2/2	6/21
Plot area (ha), Mean	0.8	0.25
Elevation (m), Min-Max	745–1003	518–1042
Mean annual temperature 1910–2010 (°C), Min-Max	5.4–6.2	4.9–7.8
Annual precipitation sum 1910–2010 (mm), Min-Max	1688–1755	922–1977
Mean annual temperature 2003 (°C), Min-Max	6.5–7.3	6.1–8.9
Annual precipitation sum 2003 (mm), Min-Max	1254–1262	728–1462
Stand basal area (m ² ·ha ⁻¹) preceding 2003, Min-Max	29–31	12–56
No. of tree ring chronologies from disks/cores	14/0	169/42
Tree age in 2003, Min-Max	62–156	93–155
Tree diameter under bark in 2003 (cm), Min-Max	22.0–71.4	24.2–73.8

stability during and following drought. In other words, with other things being equal, we expected higher structural diversity and species diversity to stabilize stem responses to drought. We also tested the following hypotheses: (ii) fir and spruce differ in their average stem growth sensitivity to drought, and their responses are mediated by drought intensity; (iii) larger trees show larger relative stem growth reductions during drought; (iv) diminishing competition through thinning reduces stem growth sensitivity to drought.

2. Material and methods

2.1. Study sites

Our study sites are located in southwestern Germany and are dominated by fir and spruce. Other species present in the stands are European beech (*Fagus sylvatica*), sycamore maple (*Acer pseudoplatanus*), and, less frequently, European ash, Norway maple, Scots pine and pioneer species. The eight study sites originate from two long-term experiments managed by the Forest Research Institute of Baden-Württemberg (Table 1): ‘single-tree selection’ and ‘group shelterwood’, which have already been described elsewhere (Puettmann et al., 2009; Forrester et al., 2013; Dănescu et al., 2016; Dănescu et al., 2017). Although the study sites are located along an elevational gradient, most stands can be classified as mixed-mountain forests. Across sites, annual precipitation sums range from 900 to 2000 mm, and a temperate to cool-temperate climate is characteristic.

Long-term programs for thinning interventions, with a large variation in thinning intensities across plots, have led to a wide range of growing conditions and structural heterogeneity. The plots have been surveyed repeatedly at intervals of usually five years and harvesting operations were always synchronized with the survey schedule in order to obtain accurate information about pre-harvest and post-harvest stand conditions. Tree diameter at breast height (*dbh*) was recorded on two perpendicular directions to the nearest 1 mm for all trees larger than 5 cm. Only trees with *dbh* > 6.5 cm were considered for variable calculation. If trees died or disappeared between subsequent surveys, only their last recorded living dimensions were taken into account. In summary, plots belonging to these particular experiments were selected for several reasons: (i) they offer an excellent information base owing to long-term monitoring; (ii) they cover a wide range of vertical and horizontal stand structures due to the application of different harvesting regimes; (iii) they cover a relatively wide environmental gradient.

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