Dendrochronologia 52 (2018) 123–130

Contents lists available at ScienceDirect

Dendrochronologia

journal homepage: www.elsevier.com/locate/dendro

Exploring the growth response of Norway spruce (*Picea abies*) along a small-scale gradient of soil water supply

Inken Rabbel[a,*], Burkhard Neuwirth[b], Heye Bogena[c], Bernd Diekkrüger[a]

[a] Department of Geography, University of Bonn, Meckenheimer Allee 166, 53115 Bonn, Germany
[b] Dendro-Labor Windeck, Tree-Ring-Analyses, 51570 Windeck, Germany
[c] Agrosphere Institute (IBG-3), Forschungszentrum Jülich, Wilhelm-Johnen-Straße, 52428 Jülich, Germany

ARTICLE INFO

Keywords:
Tree growth
Soil moisture
Soil properties
Soil nutrition
Planting density
Cluster analysis

ABSTRACT

The climate-growth response of specific sites and species is one of the main research subjects in classic tree ring studies. Traditional sampling approaches therefore aim at maximizing the climate signal of the analyzed tree ring series, which is typically achieved by focusing on dominant trees or on sites located in particularly temperature or moisture limited environments. However, there is increasing evidence that these selective sampling strategies cannot yield chronologies that are representative for entire populations. One promising approach to gain a deeper understanding of forest dynamics and climate-growth responsiveness is the analysis of climate signal ranges among trees. This individualistic approach requires random sampling and the integration of information on small-scale heterogeneities in site and tree characteristics. Here, we analyze the climate-growth response of 144 Norway spruce trees (*Picea abies* Karst.) on difference levels of data aggregation. The aim of our study is to investigate the relevance of small-scale heterogeneities in site conditions, particularly in soil water supply, for the detected climate-growth signal. We identify soil water supply and site characteristics, which indirectly modify the water availability for trees, as dominating growth factors across scales. The driest sites show the strongest climate-growth reaction, while the growth response of wetter sites is weak or even insignificant. Therefore, we conclude that integrating small-scale information on site characteristics, particularly on soil water supply, can help to gain a deeper understanding of species specific growth limitations.

1. Introduction

Investigating the climate-growth response of specific sites and species is one of the main research subjects in classic tree ring studies. Hence, site and tree selection typically aim at maximizing the climate signal in the inspected growth chronology (Nehrbass-Ahles et al., 2014; Primicia et al., 2015; Sullivan and Csank, 2016). Respectively, many researchers follow a selective sampling focusing either on “dominant, large and healthy trees” (Nehrbass-Ahles et al., 2014) or on sites located in particularly temperature or moisture limited environments (Esper et al., 2007; Sullivan and Csank, 2016).

However, even though selective sampling is acknowledged as appropriate approach for climate growth analysis and climate reconstructions (Nehrbass-Ahles et al., 2014), there is increased evidence that the resulting tree ring chronologies are likely to miss representativeness for the tree population (Carrer, 2011; Nehrbass-Ahles et al., 2014; Sullivan and Csank, 2016), because the climate sensitivity of individual trees largely depends on site and tree characteristics (Carrer, 2011; Galván et al., 2014; Primicia et al., 2015). Recent studies show that the growth responsiveness of trees to climate is related to forest management and composition (Pretzsch and Dieler, 2011; Primicia et al., 2015), physical and chemical soil properties (Braun et al., 2010; Pretzsch and Dieler, 2011; Tromp-van Meerveld and McDonnell, 2006; Ibáñez et al., 2018), soil water state (Ashiq and Anand, 2016; Helama et al., 2016; Jiang et al., 2016; Lévesque et al., 2014; Linares et al., 2010; Primicia et al., 2015; Zhang et al., 2018), canopy structure (Adams and Kolb, 2004; Linares et al., 2010; Martín-Benito et al., 2008; Primicia et al., 2015), tree to tree competition (Linares et al., 2010; Primicia et al., 2015; Gleason et al., 2017; Piutti and Cescatti, 1997), tree size (Carrer and Urbinati, 2004; Linares et al., 2010), and tree age as a proxy for other, size related effects (Carrer and Urbinati, 2004; Primicia et al., 2015).

Consequently, researchers increasingly seek for randomized sampling strategies that allow for both (1) the extraction of a mean climate-

---

[*] Corresponding author.

E-mail addresses: irabbel@uni-bonn.de (I. Rabbel), b.neuwirth@online.de (B. Neuwirth), h.bogena@fz-juelich.de (H. Bogena), b.diekkrueger@uni-bonn.de (B. Diekkrüger).

https://doi.org/10.1016/j.dendro.2018.10.007
Received 10 September 2018; Received in revised form 4 October 2018; Accepted 8 October 2018

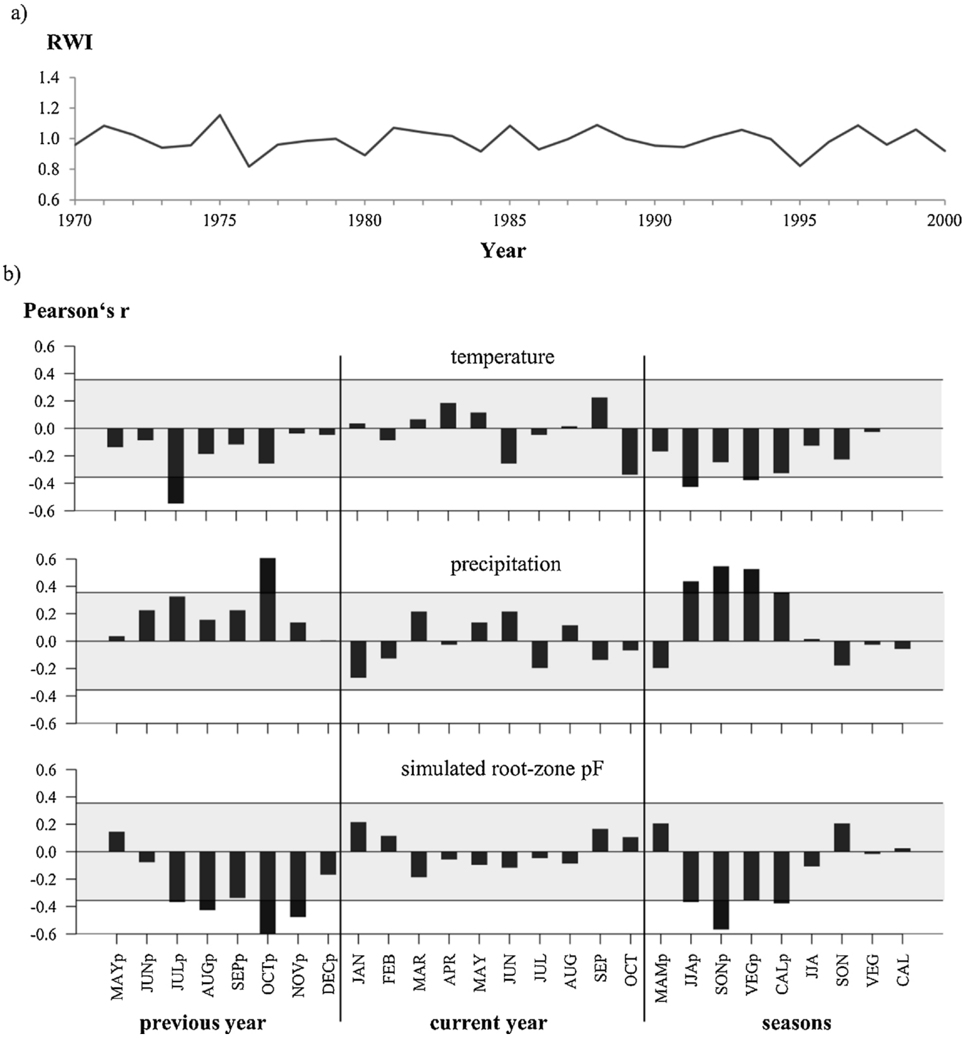

Fig. 1. WÜ chronology (a) and correlation between respective RWI values and monthly/seasonal temperatures, precipitation sums, and simulated root-zone pF values (b). Horizontal black lines in Fig. 1b represent the 95% significance level.

growth response and (2) the investigation of the range of climate signals among trees (Carrer, 2011; Nehrbass-Ahles et al., 2014; Sullivan and Csank, 2016). However, to draw ecological conclusions from heterogeneities in the individual climate-growth response of trees, a comprehensive sampling design including quantitative data on tree and site characteristics is indispensable (Babst et al., 2013; Nehrbass-Ahles et al., 2014).

In this study, we analyze tree ring chronologies of 144 Norway spruce trees (*Picea abies* Karst) on different levels of data aggregation with the aim to identify the relevance of small-scale heterogeneities in site conditions for the detected climate-growth signal. Since Norway spruce is known to be particularly vulnerable to drought (Boden et al., 2014; Bouriaud et al., 2005; Neuwirth, 2010; Zang et al., 2014, 2012), we focus on small-scale variabilities in simulated soil water supply and on site characteristics, which indirectly modify the water availability for trees. Further potentially growth relevant factors we consider in our analysis are soil nutrient states and pH level. The study area is an even-aged Norway spruce plantation in the Eifel National Park (western Germany). Hence, age-related modifications of the climate-growth signal do not play a role in our study.

2. Material and methods

2.1. Study area and data base

This study was conducted in the 27 ha Wüstebach experimental test site, which belongs to the TERENO Eifel/Lower Rhine Valley Observatory and is located in the Eifel National Park close to the German Belgian border (Bogena et al., 2018). The area is forested with Norway spruce that were planted in the late 1940ies (Etmann, 2009). In 2013, one quarter of the trees (8.6 ha) was removed to investigate the effects of deforestation on hydrological and biogeochemical cycling (Bogena et al., 2014). Altitudes range from 595 m a.s.l. in the north to 628 m a.s.l. in the south. While the hillslopes are dominated by shallow Cambisols and Planosols, Gleysols and Histosols have developed in the Riparian zone (a map of the study area is given in the results section). The soil texture is mainly silty clay loam with a medium to high coarse material fraction (Gottselig et al., 2017). The mean annual temperature and precipitation sum for the period 1970–2000 are 7.9 °C (DWD weather station Kall-Sistig in 13.1 km distance to the test-site) and 1280 mm (DWD weather station Kalterherberg in 9.6 km distance to the test-site), respectively.

We analyzed tree ring data of 48 microsites with slightly varying soil water supply to explore small-scale variations in the climate-growth relations. Soil moisture was monitored with the TERENO sensor network SoilNet (Bogena et al., 2010). SoilNet provides catchment-wide

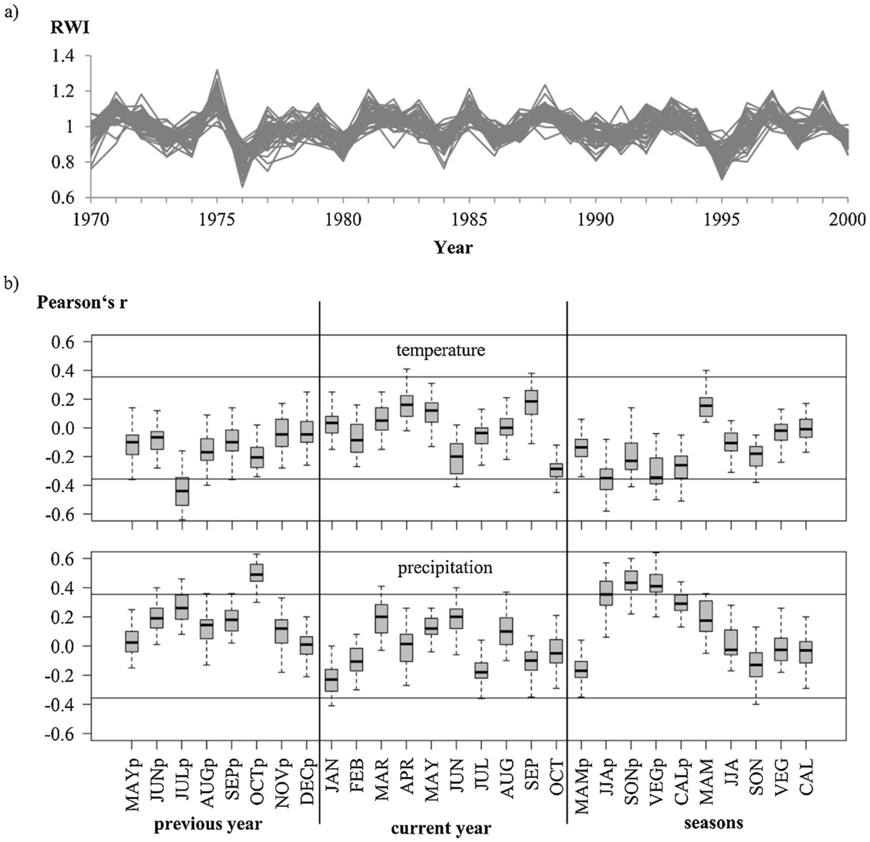

Fig. 2. SN chronologies (a) and correlation between respective RWI values and monthly/seasonal temperatures and precipitation sums. Black horizontal lines represent the 95% significance level.

information on soil water dynamics in 5, 20 and 50 cm depths with 15 min resolution since 2009 using ECH2O EC-5 and ECH2O 5TE sensors (Decagon Devices, Pullman, WA, USA). We used the soil hydrological model HYDRUS-1D (Šimůnek et al., 2013). to generate long-term information on soil water supply from the SoilNet data, First, we inversely estimated the soil hydraulic properties for each of our microsites as described in Rabbel et al. (2018) using SoilNet data from 2010 to 2012 for the model calibration and data from 2013 to 2015 for the model validation. Based on the validated model setup we conducted long-term simulations of soil water supply in terms of root-zone pressure heads for the period 1951 to 2000. Daily climate and precipitation data for the long-term simulations were taken from the DWD weather stations Kall-Sistig and Kalterherberg, respectively. We considered the effect of forest growth on the water balance by using a dynamic leaf area index (LAI) as obtained from long-term simulations with the process-based forest hydrological model LWF-Brook90 (Hammel and Kennel, 2001). For more detailed information on the climate data processing and simulated LAI, we refer to Cornelissen (2016). Through logarithmic transformation and aggregation of the daily modelled pressure heads we obtained mean monthly root-zone pF values for each of our microsites. As additional growth relevant factors, we considered planting density and soil properties as microsite characteristics in our study. In this context, we made use of the comprehensive spatially distributed biogeochemistry dataset of the Wüstebach (Gottselig et al., 2017). For this study we selected information on soil horizon depths and horizon-wise bulk density, pH and C-, N- and P-contents.

2.2. Tree ring data and chronology building

We selected our microsites with regard to the existing SoilNet measuring locations to draw the closest possible link between tree ring data and local site conditions. However, since our sampling campaign took place after the deforestation event in 2013, Gleysol sites could not be considered in this study. Each microsite consists of three trees in direct proximity (< 10 m) to one of the SoilNet stations. We used a HAGLÖF increment corer with 5 mm diameter to extract two opposite cores at breast height per tree. The sample preparation followed standard procedures (Stokes and Smiley, 1968). Ring widths were measured at the dendrochronological lab DeLaWi Tree Ring Analyses (Windeck, Germany) using the moveable object table Lintab 5 (Rinntech, Heidelberg, Germany) and a stereo microscope (Carl Zeiss, Jena, Germany) in a measuring accuracy of 10 µm. Synchronization and cross-dating were carried out with the software tools TSAP-WIN (Rinn, 2003) and COFECHA (Holmes, 1983). Tree mean curves (TMC) were calculated with TSAP-WIN. We detrended each TMC using a high-pass filter based on binomially weighted 5-year running means (Schweingruber, 1988) to remove age-related trends and emphasize inter-annual growth variations. Indices (RWI) were calculated as ratio between actual tree ring widths and the filtered value. In total, we considered 144 trees to create 48 SoilNet related microsite chronologies (SN) and one regional chronology across all microsites in the Wüstebach catchment (WÜ). To avoid data inconsistencies, we excluded the juvenile phase from our investigations and thus only used the period 1970 to 2000 for further analyses. More recent years were not considered, because of a multi-year data gap in the Kall-Sistig weather station data. Applying the hierarchical cluster analysis after Ward, which has already been proven to provide a clear distinction of growth clusters in previous studies (e.g. Friedrichs et al., 2009), we used the squared Euclidian distance as a measure of similarity to detect SN chronologies (RWI series) with similar growth dynamics. These were aggregated to respective cluster chronologies (CL) using arithmetic means.

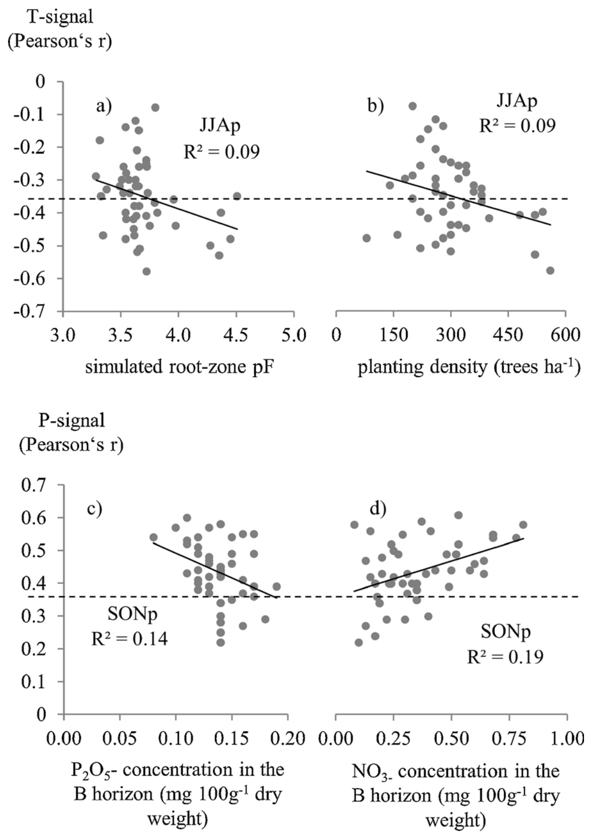

Fig. 3. Correlation between SN climate signal strength (Pearson's r) and simulated root-zone pF (a), planting density (b), P_2O_5 concentration (c), and NO_{3-} concentration (d). The dashed black lines indicate the 95% significance level for the observed climate-growth relations. T-signal: temperature signal as resulting from the correlation of the SN chronologies and mean monthly/seasonal temperatures; P-signal: precipitation signal as resulting from the correlation of the SN chronologies and monthly/seasonal precipitation sums; reference periods for the illustrated climate signals: JJAp: Juli to August of the previous year; SONp: September to November of the previous year.

2.3. *Statistical analysis*

We analyzed the climate-growth relationships in the Wüstebach catchment at different levels of data aggregation using Pearson's product-moment correlations. WÜ, CL and SN chronologies were correlated with monthly temperature and precipitation data and mean monthly root-zone pF over a 18-month window from May of the previous year (denoted with the index p) until October of the current year of ring formation. Additionally, we considered temperature means, precipitation sums and mean simulated root-zone pF for the periods March-May (MAM), June-August (JJA), September-November (SON), April-October (VEG), and annual values (CAL) for the previous and current year of ring formation.

We correlated the climate signal strength (Pearson's r) observed on the SN level with the respective microsite characteristics (exposition, inclination, planting density, mean root-zone pF, and soil biogeochemistry) to identify the relevance of site characteristics for the detected climate signal. We conducted this analysis (1) for all 48 SN microsites across the Wüstebach catchment and (2) for each growth cluster separately.

Since the cluster characteristics considered in this study typically exhibit non-normal distributions, we used U-tests instead of T-tests to identify statistically significant differences in the mean cluster characteristics and therewith to explain the cluster formation itself. In this context, we applied the software package R (R Core Team, 2018). Significance for both Pearson's correlations and U-tests was tested on the 95% significance level ($p < 0.05$).

3. Results and discussion

3.1. *Regional climate-growth relations*

For the WÜ chronology (Fig. 1a), we found significant negative correlations between mean monthly and seasonal temperatures and RWI for JULp, JJAp and VEGp (Fig. 1b), whereas the strong correlation of RWI and JULp (r = -0.55) seems to dominate the observed seasonal temperature-growth relations. Significant positive correlations with RWI were observed for OCTp, JJAp, SONp, and VEGp precipitation sums (Fig. 1b). In this case, the strong correlation of RWI and OCTp (r = 0.61) dominates the observed significant correlation of RWI and SONp. The sensitivity to high summer temperatures and low precipitation of the previous year is typical for Norway spruce in lower altitudes (Fischer and Neuwirth, 2012; Hartl-Meier et al., 2014; Mäkinen et al., 2002; van der Maaten-Theunissen et al., 2013). The interplay between positive correlations of RWI with precipitation and negative correlations with temperature for the same periods (JJAp and VEGp) suggests that radial growth rates in the Wüstebach catchment are mainly controlled by water availability. This finding is supported by the significant negative correlations of RWI with the mean monthly (JULp, AUGp, OCTp, NOVp), seasonal (JJAp, SONp, VEGp), and annual (CALp) root-zone pF (Fig. 1b) and in line with other studies reporting the particularly high vulnerability of Norway spruce to drought (Boden et al., 2014; Bouriaud et al., 2005; Neuwirth, 2010; Zang et al., 2012, 2014).

3.2. *Climate growth relations across microsites*

The SN chronologies show a considerable scatter in RWI values (Fig. 2a). Nevertheless, the general growth dynamic is similar among SN chronologies. For most of the SN series, we observed negative RWI peaks in the years 1976 and 1995, which have already been identified as negative pointer years for the Wüstebach area in a previous study (Thomas et al., 2018). Particularly high ranges of RWI values among SN chronologies were found for the years 1970 (0.31), 1977 (0.36), and 1996 (0.33) and hence for years that follow negative pointer years (Thomas et al., 2018). This indicates that the recovery of growth rates after drought years depends on small-scale environmental conditions.

The monthly/seasonal climate signals among SN chronologies are strongly scattered (Fig. 2b), which we attribute to small-scale variabilities in the microsite conditions (e.g. soil properties).

We found significant negative correlations between the SN chronologies' temperature signals and the simulated summer root-zone pF of the previous year (JJAp; Fig. 3a). Hence, drier microsites react stronger to high summer temperatures than wetter microsites, which was also found by other studies on the regional scale (Ashiq and Anand, 2016; Helama et al., 2016; Jiang et al., 2016; Lévesque et al., 2014; Zhang et al., 2016). Significant negative correlations with seasonal temperature signals (JJAp, VEGp) were also found for the local planting density (Fig. 3b).This effect indicates an increasing competition for soil water with increasing number of trees per ground area, which was already observed by Linares et al., (2010) and Primicia et al. (2015).

Interestingly, we did not find any correlations between the precipitation signal of the SN chronologies and water related microsite characteristics. Instead, seasonal precipitation signals (SONp, VEGp) were significantly related to the microsite's soil N and P states. We observed decreasing precipitation signals with increasing plant available P (P_2O_5) indicating that insufficient P supply increases the drought vulnerability of Norway spruce (Fig. 3c).

Nitrate N (NO_{3-}), in contrast, shows a significantly positive correlation with the precipitation signal strength (Fig. 3d). One possible explanation is that the enhanced N levels in the Wüstebach catchment as indicated by C/N ratios well below 25 (Gundersen et al., 1998)

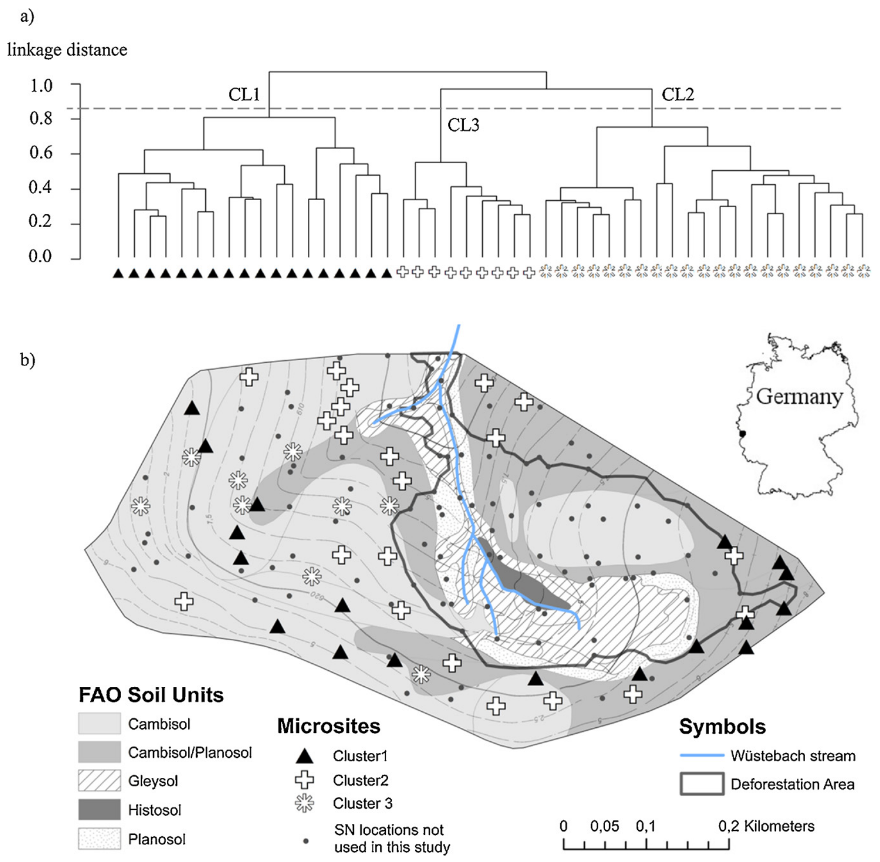

Fig. 4. Dendrogram as resulting from the hierarchical cluster analysis after Ward (a) and spatial distribution of the clusters within the Wüstebach catchment (b).

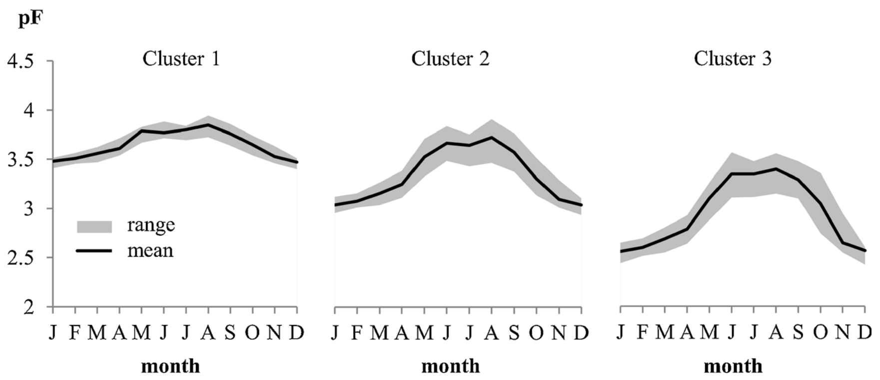

Fig. 5. Simulated mean monthly soil water supply (black line) and inter-annual variation of the simulated mean monthly soil water supply (grey) for the period 1970–2000 by growth cluster. Field capacity and permanent wilting point are generally assumed for pF 2–2.5 and 4.2, respectively.

reduce fine-root growth and limit the uptake of other nutrients. The resulting negative effects of excess N on tree growth and vitality have been described before and may result in a decreased tolerance against soil-related stress-factors (Braun et al., 2010; Kazda, 1990; Mohren et al., 1986; Puhe, 2003; Seith et al., 1996; Thelin et al., 1998). Hence, it seems reliable that microsites of excess N supply are more vulnerable to water stress than microsites with a more balanced nutrient supply.

3.3. Cluster formation and characteristics

Our cluster analysis resulted in three primary growth clusters with 18 (CL1), 21 (CL2), and 9 SN members (CL3) (Fig. 4a). The spatial proximity of the SN sites was not important for cluster formation (Fig. 4b). Instead, the site characteristics of the clusters mainly differed in the mean simulated soil water supply (Fig. 5). However, while the mean simulated root-zone pF of cluster 1 was significantly higher than that of cluster 2 and 3, no significant difference was found between the moisture regimes of cluster 2 and 3.

Nevertheless, the cluster's climate signal strength was clearly connected to the observed gradient in the mean cluster's soil water supply: The cluster chronology of the driest cluster (CL1, Fig. 6a) showed the strongest correlation with monthly/seasonal mean temperatures (JULp, JJAp, CALp, VEGp), while the wettest cluster (CL3) did not show significant temperature-growth relations at all (Fig. 6b). Also, the temperature signal of CL1 was even 0.06 (JULp) to 0.08 (VEGp) points stronger than that of the mean WÜ chronology. This indicates that our small-scale clustering approach can help to improve the extraction of a regional climate signal.

The precipitation signal of the cluster chronologies was also modified by mean soil water supply. However, the effect was not as strong as for the temperature signal. Even though the precipitation signal strength decreased with increasing root-zone pF, all cluster

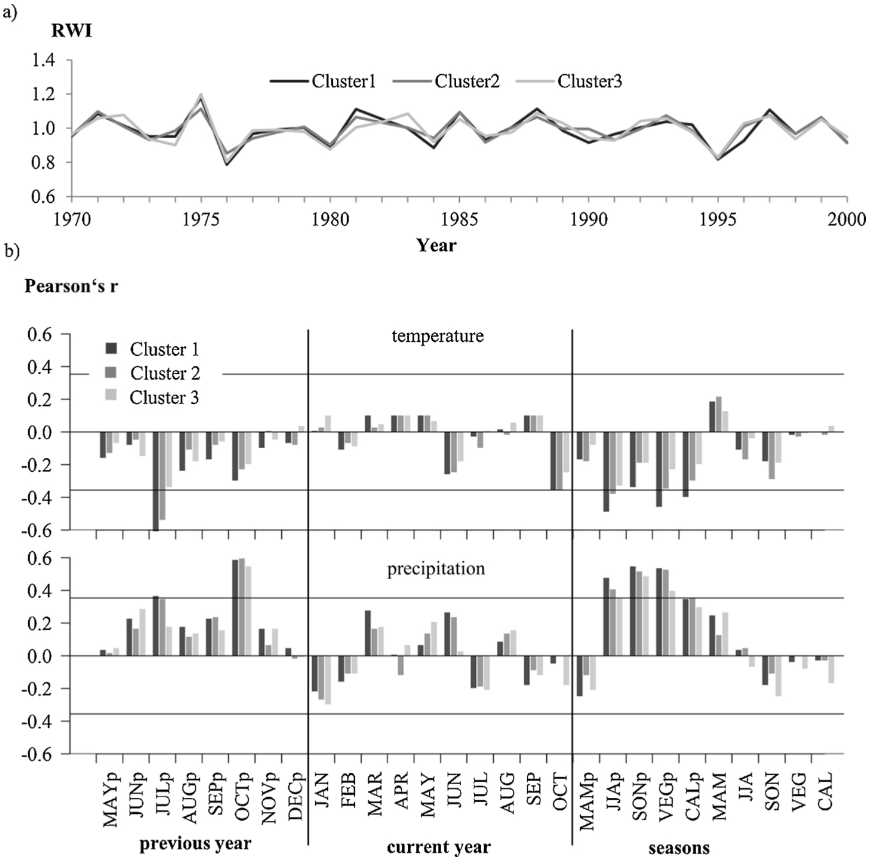

Fig. 6. Cluster chronologies (a) and respective correlation between RWI values and monthly/seasonal temperatures and precipitation sums. Black horizontal lines represent the 95% significance level.

chronologies still showed significant correlations with mean seasonal precipitation sums (JJAp, SONp, VEGp). The OCTp precipitation signal was highly significant ($p < 0.001$) for all cluster chronologies and the only signal appearing to be independent from the soil moisture regime.

Internal relations between SN climate signal and microsite characteristics varied among clusters. The analyzed microsite characteristics within the clusters were found to be independent from each other and also from absolute soil water states. In contrast to our findings on the regional scale, cluster internal SN temperature signals were not correlated with the simulated soil water supply. Instead, temperature signals significantly correlated with the planting density (Fig. 6a), which reflects the above described increased competition for water resources under drought, and with the bulk density of the B horizon (Fig. 6b). The increasing climate sensitivity with increasing bulk density can be explained, because Norway spruce is known to preferably root humus-rich soil horizons. High skeleton contents and clay-rich B horizons as present in the Wüstebach catchment hamper the development of the deeper rooting system, which is particularly important to compensate water shortage under drought (Puhe, 2003).

The cluster internal SN precipitation signals were significantly correlated to soil NO_{3-} (positive correlation, Fig. 6c) and P_2O_5 (negative correlation, Fig. 6d). Furthermore, increasing sensitivities to monthly/seasonal precipitation sums can be observed with increasing bulk densities (Fig. 6e), decreasing soil depth (Fig. 6f) and ongoing soil acidification (Fig. 6g). We found a noteworthy negative correlation between soil depth and drought sensitivity, which is reasonable as total soil water storage increases with increasing soil depth. This finding is also in correspondence to other studies (e.g. Tromp-van Meerveld and McDonnell, 2006), who explained patterns in forest basal area with spatial variations in soil depth. The negative effect of soil acidification on root growth and thus on the potential water uptake of Norway spruce has been reviewed by Puhe (2003) and explains the negative correlation between soil pF and SN precipitation signal.

Apart from the mean soil water supply, we did not find significant differences in the microsite characteristics among clusters. Therefore, we attribute the observed cluster-internal dependencies of climate-growth relations from microsite characteristics to the underlying cluster moisture regimes.

4. Conclusion: soil water supply as a dominating growth factor across scales

In this study, we explored the growth response of Norway spruce along a small-scale gradient of soil water supply. We used different levels of data aggregation to identify the relevance of the soil water regime and other microsite characteristics on the climate-growth relations in the Wüstebach catchment. We found significant impacts of soil water supply across all levels of data aggregation.

On the regional scale (WÜ chronology), the mean seasonal simulated root-zone pF showed similar (SONp, CALp) or slightly weaker (JJAp, VEGp) correlations with tree growth than the mean seasonal precipitation sums. However, on the monthly scale, growth variability was better explained by soil water supply than by monthly precipitation sums (Fig. 1b). This emphasizes the function of the soil as a buffer of precipitation and is in line with other studies comparing the growth response of trees to soil related wetness indices and to precipitation sums alone (Scharnweber et al., 2011; van der Maaten-Theunissen et al., 2013).

Across all 48 microsites (SN chronologies), the temperature-growth response was directly (simulated root-zone pF) and indirectly (planting density) related to local soil water supply. Cluster-internally, correlations between simulated root-zone pF and climate growth response

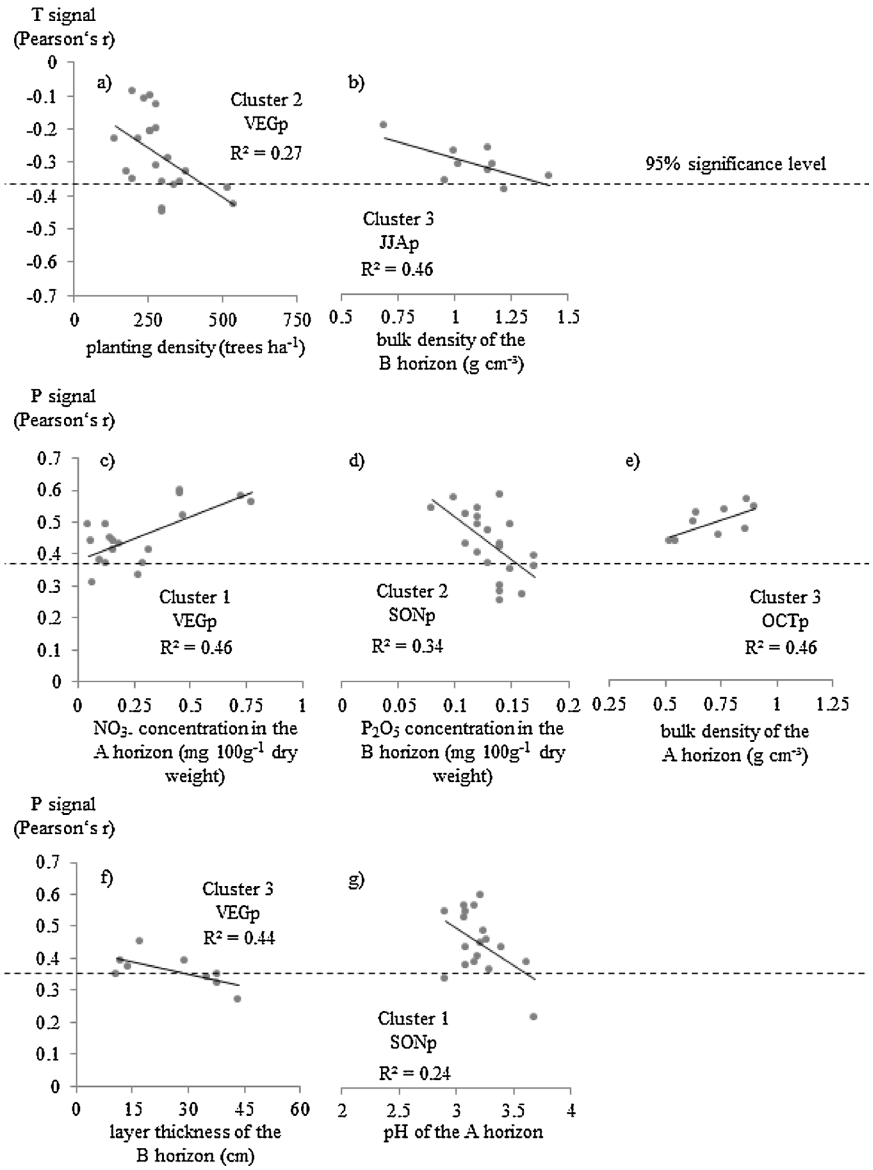

Fig. 7. Correlation between cluster internal SN climate signal strength (Pearson's r) and microsite characteristics for cluster and season as given in the plots. The dashed black lines indicate the 95% significance level for the observed climate-growth relations. T-signal: temperature signal as resulting from the correlation of the SN chronologies and mean monthly/seasonal temperatures; P-signal: precipitation signal as resulting from the correlation of the SN chronologies and monthly/seasonal precipitation sums; reference periods for the illustrated climate signals: OCTp: October of the previous year; JJAp: Juli to August of the previous year; SONp: September to November of the previous year; VEGp: April to October of the previous year.

were not observed. However, we identified the local soil water supply to be the most dominating factor in the formation of the growth clusters. Hence, cluster-internal feedbacks between SN climate signal strength and microsite characteristics already represent a second level of signal modification. Significant correlations of cluster-internal SN climate-signals were found for planting density, soil depth, and bulk density and hence for site characteristics that indirectly modify the availability of soil water for trees (Fig. 7).

In conclusion, we identified soil water supply as a dominating growth factor across scales. Even though the growth response across our microsites showed a high scatter, which indicates that a clear climate signal extraction is nearly impossible on that scale (also cf. Carrer, 2011) our clustering approach helped to close the gap between the individualistic growth-response of forest trees and the regional climate signal. Therefore, we are confident that integrating small-scale information on site characteristics, particularly on soil water supply, can help to gain a deeper understanding of species specific growth limitations.

Acknowledgements

The authors thank the DWD (Deutscher Wetterdienst, German Meteorological Service) and TERENO (Terrestrial Environmental Observatories, funded by the Helmholtz-Gemeinschaft) for providing soil and weather data for this study; we thank DFG (Deutsche Forschungsgemeinschaft) for financial support of sub-project C1 of the Transregional Collaborative Research Center 32 "Patterns in Soil-Vegetation-Atmosphere Systems". Many thanks to Alexander Graf, Inge Wiekenkamp, and Thomas Cornelissen for providing scripts and data for the calculation of grass reference evapotranspiration and to Sara Maria Stücker and Johann Neugebauer for their help in data preparation for the soil moisture simulations. Thanks to Michael Röös and Hans-Joachim Spors (Eifel National Park) for their cooperation and the necessary research permits.

References

Adams, H.D., Kolb, T.E., 2004. Drought responses of conifers in ecotone forests of northern Arizona: tree ring growth and leaf δ13C. Oecologia 140, 217–225. https://doi.org/10.1007/s00442-004-1585-4.

Ashiq, M.W., Anand, M., 2016. Spatial and temporal variability in dendroclimatic growth response of red pine (*Pinus resinosa* Ait.) to climate in northern Ontario, Canada. For. Ecol. Manage. 372, 109–119.

Babst, F., Poulter, B., Trouet, V., Tan, K., Neuwirth, B., Wilson, R., Carrer, M., Grabner, M., Tegel, W., Levanic, T., Panayotov, M., Urbinati, C., Bouriaud, O., Ciais, P., Frank, D., 2013. Site- and species-specific responses of forest growth to climate across the European continent. Glob. Ecol. Biogeogr. 22, 706–717. https://doi.org/10.1111/

geb.12023.

Boden, S., Kahle, H.-P., Wilpert, Kvon, Spiecker, H., 2014. Resilience of Norway spruce (*Picea abies* (L.) Karst) growth to changing climatic conditions in Southwest Germany. For. Ecol. Manage 315, 12–21. https://doi.org/10.1016/j.foreco.2013.12.015.

Bogena, H.R., Herbst, M., Huisman, J.A., Rosenbaum, U., Weuthen, A., Vereecken, H., 2010. Potential of wireless sensor networks for measuring soil water content variability. Vadose Zo. J. 9, 1002. https://doi.org/10.2136/vzj2009.0173.

Bogena, H.R., Bol, R., Borchard, N., Brüggemann, N., Diekkrüger, B., Drüe, C., Groh, J., Gottselig, N., Huisman, Ja., Lücke, A., Missong, A., Neuwirth, B., Pütz, T., Schmidt, M., Stockinger, M., Tappe, W., Weihermüller, L., Wiekenkamp, I., Vereecken, H., 2014. A terrestrial observatory approach to the integrated investigation of the effects of deforestation on water, energy, and matter fluxes. Sci. China Earth Sci. 57, 61–75. https://doi.org/10.1007/s11430-014-4911-7.

Bogena, H.R., Montzka, C., Huisman, J.A., Graf, A., Schmidt, M., Stockinger, M., von Hebel, C., Hendricks-Franssen, H.J., van der Kruk, J., Tappe, W., Lücke, A., Baatz, R., Bol, R., Groh, J., Pütz, T., Jakobi, J., Kunkel, R., Sorg, J., Vereecken, H., 2018. The TERENO-Rur hydrological observatory: a multiscale multi-compartment research platform for the advancement of hydrological science. Vadose Zo. J. 17, 0. https://doi.org/10.2136/vzj2018.03.0055.

Bouriaud, O., Leban, J.-M., Bert, D., Deleuze, C., 2005. Intra-annual variations in climate influence growth and wood density of Norway spruce. Tree Physiol. 25, 651–660. https://doi.org/10.1093/treephys/25.6.651.

Braun, S., Thomas, V.F.D., Quiring, R., Flückiger, W., 2010. Does nitrogen deposition increase forest production? The role of phosphorus. Environ. Pollut. 158, 2043–2052. https://doi.org/10.1016/j.envpol.2009.11.030.

Carrer, M., 2011. Individualistic and time-varying tree-ring growth to climate sensitivity. PLoS One 6. https://doi.org/10.1371/journal.pone.0022813.

Carrer, M., Urbinati, C., 2004. Age-dependent tree-ring growth responses to climate in *Larix decidua* and *Pinus cembra*. Ecology 85, 730–740. https://doi.org/10.1890/02-0478.

Cornelissen, T., 2016. 3D-Modeling of Unsaturated Flow Dynamics and Patterns. Potentials and Limitations at Different Spatial and Temporal Scales. Dissertation. Rheinische Friedrich-Wilhelms Universität Bonn, Bonn, Germany. http://hss.ulb.uni-bonn.de/2016/4396/4396.htm.

Esper, J., Frank, D.C., Luterbacher, J., 2007. On selected issues and challenges in dendroclimatology. In: Kienast, F., Wildi, F., Ghosh, S. (Eds.), A Changing World: Challenges for Landscape Research. Springer, Dordrecht, pp. 113–132.

Etmann, M., 2009. Dendrologische Aufnahmen im Wassereinzugsgebiet Oberer Wüstebach anhand verschiedener Mess- und Schätzverfahren (in German). Diploma Thesis, Westfälische Wilhelms-Universität Münster. Münster, Germany. .

Fischer, S., Neuwirth, B., 2012. Climate sensitivity of Douglas-fir in Eifel and Kellerwald. Allg. Forst- und Jagdzeitung 183, 23–33.

Friedrichs, D.A., Neuwirth, B., Winiger, M., Löffler, J., 2009. Methodologically induced differences in oak site classifications in a homogeneous tree-ring network. Dendrochronologia 27, 21–30. https://doi.org/10.1016/j.dendro.2008.02.001.

Galván, J.D., Camarero, J.J., Gutiérrez, E., 2014. Seeing the trees for the forest: drivers of individual growth responses to climate in *Pinus uncinata* mountain forests. J. Ecol. 102, 1244–1257. https://doi.org/10.1111/1365-2745.12268.

Gleason, K.E., Bradford, J.B., Bottero, A., D'Amato, A.W., Fraver, S., Palik, B.J., Battaglia, M.A., Iverson, L., Kenefic, L., Kern, C.C., 2017. Competition amplifies drought stress in forests across broad climatic and compositional gradients. Ecosphere 8. https://doi.org/10.1002/ecs2.1849.

Gottselig, N., Wiekenkamp, I., Weihermüller, L., Brüggemann, N., Berns, A.E., Bogena, H.R., Borchard, N., Klumpp, E., Lücke, A., Missong, A., Pütz, T., Vereecken, H., Huisman, J.A., Bol, R., 2017. A three-dimensional view on soil biogeochemistry: a dataset for a forested headwater catchment. J. Environ. Qual. 46, 210. https://doi.org/10.2134/jeq2016.07.0276.

Gundersen, P., Callesen, I., De Vries, W., 1998. Nitrate leaching in forest ecosystems is related to forest floor C/N ratios. Environ. Pollut. 102, 403–407. https://doi.org/10.1016/S0269-7491(98)80060-2.

Hammel, K., Kennel, M., 2001. Charakterisisierung und Analyse der Wasserverfügbarkeit und des Wasserhaushalts von Waldstandorten in Bayern mit dem Simulationsmodell BROOK90 (in German, with English summary). Forstl. Forschungsberichte München 185.

Hartl-Meier, C., Zang, C., Dittmar, C., Esper, J., Göttlein, A., Rothe, A., 2014. Vulnerability of Norway spruce to climate change in mountain forests of the European Alps. Clim. Res. 60, 119–132. https://doi.org/10.3354/cr01226.

Helama, S., Läänelaid, A., Bijak, S., Jaagus, J., 2016. Contrasting tree-ring growth response of *Picea abies* to climate variability in western and eastern Estonia. Geogr. Ann. Ser. A Phys. Geogr. 98, 155–167. https://doi.org/10.1111/geoa.12128.

Holmes, R.L., 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bull. 43, 69–78.

Ibáñez, I., Zak, D.R., Burton, A.J., Pregitzer, K.S., 2018. Anthropogenic nitrogen deposition ameliorates the decline in tree growth caused by a drier climate. Ecology 99, 411–420. https://doi.org/10.1002/ecy.2095.

Jiang, X., Huang, J.-G., Stadt, K.J., Comeau, P.G., Chen, H.Y.H., 2016. Spatial climate-dependent growth response of boreal mixedwood forest in western Canada. Glob. Planet. Change 139, 141–150.

Kazda, M., 1990. Indications of unbalanced nitrogen nutrition of Norway spruce stands. Plant Soil 128, 97–101. https://doi.org/10.1007/BF00009401.

Lévesque, M., Rigling, A., Bugmann, H., Weber, P., Brang, P., 2014. Growth response of five co-occurring conifers to drought across a wide climatic gradient in Central Europe. Agric. For. Meteorol. 197, 1–12.

Linares, J.C., Camarero, J.J., Carreira, J.A., 2010. Competition modulates the adaptation capacity of forests to climatic stress: insights from recent growth decline and death in relict stands of the Mediterranean fir Abies pinsapo. J. Ecol. 98, 592–603. https://doi.org/10.1111/j.1365-2745.2010.01645.x.

Mäkinen, H., Nöjd, P., Kahle, H.-P., Neumann, U., Tveite, B., Mielikäinen, K., Röhle, H., Spiecker, H., 2002. Radial growth variation of Norway spruce (*Picea abies* (L.) Karst.) across latitudinal and altitudinal gradients in central and northern Europe. For. Ecol. Manage 171, 243–259. https://doi.org/10.1016/S0378-1127(01)00786-1.

Martín-Benito, D., Cherubini, P., Del Río, M., Cañellas, I., 2008. Growth response to climate and drought in *Pinus nigra* Arn. trees of different crown classes. Trees - Struct. Funct. 22, 363–373. https://doi.org/10.1007/s00468-007-0191-6.

Mohren, G.M.J., van den Burg, J., Burger, F.W., Oterdoom, J.H., 1986. Phosphorus deficiency induced by nitrogen input in Douglas fir stands. Ned. Bosbouwtijdschrift 58, 238–245.

Nehrbass-Ahles, C., Babst, F., Klesse, S., Nötzli, M., Bouriaud, O., Neukom, R., Dobbertin, M., Frank, D., 2014. The influence of sampling design on tree-ring-based quantification of forest growth. Glob. Chang. Biol. 20, 2867–2885. https://doi.org/10.1111/gcb.12599.

Neuwirth, B., 2010. Interannuelle Klima-Wachstums-Beziehungen zentraleuropäischer Bäume von AD 1901 bis 1971 (in German), Bonner Geographische Abhandlungen 125. E. Ferger Verlag, Bergisch Gladbach, Germany.

Piutti, E., Cescatti, A., 1997. A quantitative analysis of the interactions between climatic response and intraspecific competition in European beech. Can. J. For. Res. 27, 277–284. https://doi.org/10.1139/x96-176.

Pretzsch, H., Dieler, J., 2011. The dependency of the size-growth relationship of Norway spruce (*Picea abies* [L.] Karst.) and European beech (*Fagus sylvatica* [L.]) in forest stands on long-term site conditions, drought events, and ozone stress. Trees - Struct. Funct. 25, 355–369. https://doi.org/10.1007/s00468-010-0510-1.

Primicia, I., Camarero, J.J., Janda, P., Čada, V., Morrissey, R.C., Trotsiuk, V., Bače, R., Teodosiu, M., Svoboda, M., 2015. Age, competition, disturbance and elevation effects on tree and stand growth response of primary *Picea abies* forest to climate. For. Ecol. Manage. 354, 77–86. https://doi.org/10.1016/j.foreco.2015.06.034.

Puhe, J., 2003. Growth and development of the root system of Norway spruce (*Picea abies*) in forest stands: a review. For. Ecol. Manage. 175, 253–273. https://doi.org/10.1016/S0378-1127(02)00134-2.

R Core Team, 2018. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org.

Rabbel, I., Bogena, H., Neuwirth, B., Diekkrüger, B., 2018. Using sap flow data to parameterize the feddes water stress model for Norway spruce. Water 10 (3), 279. https://doi.org/10.3390/w10030279.

Rinn, F., 2003. TSAP-Win. Time Series Analysis and Presentation for Dendrochronology and Related Applications. Version 4.64 for Microsoft Windows. User Reference. Rinntech, Heidelberg.

Scharnweber, T., Manthey, M., Criegee, C., Bauwe, A., Schröder, C., Wilmking, M., 2011. Drought matters - declining precipitation influences growth of *Fagus sylvatica* L. and *Quercus robur* L. in north-eastern Germany. For. Ecol. Manage 262, 947–961. https://doi.org/10.1016/j.foreco.2011.05.026.

Schweingruber, F.H., 1988. Tree Rings: Basics and Applications of Dendrochronology. Kluwer Academic Publishers, The Netherlands.

Seith, B., George, E., Marschner, H., Wallenda, T., Schaeffer, C., Einig, W., Wingler, A., Hampp, R., 1996. Effects of varied soil nitrogen supply on Norway spruce (*Picea abies* [L.] Karst.): I. Shoot and root growth and nutrient uptake. Plant Soil 184, 291–298. https://doi.org/10.1007/BF00010458.

Šimůnek, J., Šejna, M., A, Saito, H, Sakai, Genuchten, M., Van, M.T., 2013. The HYDRUS-1D software package for simulating the movement of Water, heat, and multiple solutes in variably saturated media, version 4.17. HYDRUS Software Series 3, 343.

Stokes, M.A., Smiley, T.L., 1968. Reprinted 1996. An Introduction to Tree-Ring Dating. University of Chicago. University of Arizona Press, Tucson, USA (1968).

Sullivan, P.F., Csank, A.Z., 2016. Contrasting sampling designs among archived datasets: implications for synthesis efforts. Tree Physiol. 36, 1057–1059. https://doi.org/10.1093/treephys/tpw067.

Thelin, G., Rosengren-Brinck, U., Nihlgård, B., Barkman, A., 1998. Trends in needle and soil chemistry of Norway spruce and Scots pine stands in South Sweden 1985–1994. Environ. Pollut. 99, 149–158. https://doi.org/10.1016/S0269-7491(97)00192-9.

Thomas, F., Rzepecki, A., Lücke, A., Wiekenkamp, I., Rabbel, I., Pütz, T., Neuwirth, B., 2018. Growth and wood isotopic signature of Norway spruce (*Picea abies*) along a small-scale gradient of soil moisture. Tree Physiol. 00, 1–16. https://doi.org/10.1093/treephys/tpy100.

Tromp-van Meerveld, H.J., McDonnell, J.J., 2006. On the interrelations between topography, soil depth, soil moisture, transpiration rates and species distribution at the hillslope scale. Adv. Water Resour. 29, 293–310. https://doi.org/10.1016/j.advwatres.2005.02.016.

van der Maaten-Theunissen, M., Kahle, H.P., van der Maaten, E., 2013. Drought sensitivity of Norway spruce is higher than that of silver fir along an altitudinal gradient in southwestern Germany. Ann. For. Sci. 70, 185–193. https://doi.org/10.1007/s13595-012-0241-0.

Zang, C., Pretzsch, H., Rothe, A., 2012. Size-dependent responses to summer drought in Scots pine, Norway spruce and common oak. Trees - Struct. Funct. 26, 557–569. https://doi.org/10.1007/s00468-011-0617-z.

Zang, C., Hartl-Meier, C., Dittmar, C., Rothe, A., Menzel, A., 2014. Patterns of drought tolerance in major European temperate forest trees: climatic drivers and levels of variability. Glob. Chang. Biol. 20, 3767–3779. https://doi.org/10.1111/gcb.12637.

Zhang, J., Gou, X., Zhang, Y., Lu, M., Xu, X., Zhang, F., Liu, W., Gao, L., 2016. Forward modeling analyses of Qilian Juniper (*Sabina przewalskii*) growth in response to climate factors in different regions of the Qilian Mountains, northwestern China. Trees - Struct. Funct. 30, 175–188. https://doi.org/10.1007/s00468-015-1286-0.

Zhang, L., Jiang, Y., Zhao, S., Jiao, L., Wen, Y., 2018. Relationships between tree age and climate sensitivity of radial growth in different drought conditions of Qilian Mountains, northwestern China. Forests 9. https://doi.org/10.3390/f9030135.