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Different responses of multispecies tree ring growth to various drought indices across Europe

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ABSTRACT

Increasing frequency and intensity of drought extremes associated with global change are a key challenge for forest ecosystems. Consequently, the quantification of drought effects on tree growth as a measure of vitality is of highest concern from the perspectives of both science and management. To date, a multitude of drought indices have been used to accompany or replace primary climatic variables in the analysis of drought-related growth responses. However, it remains unclear how individual drought metrics compare to each other in terms of their ability to capture drought signals in tree growth.

In our study, we employ a European multispecies tree ring network at the continental scale and a set of four commonly used drought indices (De Martonne Aridity Index, self-calibrating Palmer Drought Severity Index, Standardized Precipitation Index and Standardized Precipitation Evapotranspiration Index, the latter two on varying temporal scales) to derive species-specific growth responses to drought conditions. For nine common European tree species, we demonstrate spatio-temporal matches and mismatches of tree growth with drought indices subject to species, elevation and bioclimatic zone. Forests located in the temperate and Mediterranean climate were drought sensitive and tended to respond to short- and intermediate-term drought (<1 year). In continental climates, forests were comparably more drought resistant and responded to long-term drought. For the same species, stands were less drought sensitive at higher elevations compared to lower elevations. We provide detailed information on the month-wise performance of the four drought indices in different climate zones allowing users the selection of the most appropriate index according to their objective criteria. Our results show that species-specific differences in responses to multiple stressors result in complex, yet coherent patterns of tree growth.

1. Introduction

Droughts are complex multi-dimensional climatic phenomena with detrimental effects on social and natural systems (Wilhite and Glantz, 1985; Obasi, 1994; Mishra and Singh, 2010). The impacts of drought have been aggravated in the recent years by the increasing rise in water demand due to global climate change, the latter being signified by the increase in mean global air temperature by 0.85 °C during the period 1880–2012 (IPCC, 2013).

The frequency and their duration is likely to increase by factors of two and six, respectively, due to anthropogenic climate change (Kogan et al., 2013). Important natural systems challenged by this intensification of (especially summer) drought events are forest ecosystems (Bolte et al., 2009). Forests are characterized by large carbon stocks and flows, both sensitive to climatic extremes, most importantly drought, resulting in large (and potentially lagged, Anderegg et al., 2015) effects on the carbon cycle (Frank et al., 2015). The impairment of tree vitality by drought is therefore one of the key processes controlling drought impact on forests. Tree species differ across biomes, rendering the comprehensive characterization of drought response of individual species a pivotal component of understanding drought impact on forest ecosystems (Bolte et al., 2009; Luyssaert et al., 2010; Zang et al., 2014).

Tree ring width or annual radial growth increment is a widely used proxy for tree vitality (Fritts et al., 1971; Dobbertin, 2005) and its connection to climate and extreme climatic events, such as drought. The high abundance of tree ring data allows tree growth and drought variability to be studied on local to continental scales.

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Yet, the study of forest vulnerability to climatic extremes, particularly drought events, is complicated by macroclimatic, structural, and compositional differences of forest sites at continental scales (Vicente-Serrano et al., 2014; Gazol et al., 2016). These differences explain the difficulty to find generalized descriptors of drought that match the temporal resolution of processes at the scale of individual forests. A typical example for a commonly used drought index that does not allow for varying temporal resolutions is the Palmer Drought Severity Index, PDSI (Dai et al., 2004). Since site-specific macroclimatic and species-specific physiological response characteristics mediate the differential drought response at the level of sites (Babst et al., 2013) and individual trees (Dittmar et al., 2012; Zang et al., 2014), the PDSI and other drought metrics with fixed time scales are not able to capture the ecologically meaningful temporal offset between onset of drought conditions and growth response of forests (Vicente-Serrano et al., 2012).

Acknowledging this shortcoming of traditional drought metrics, Vicente-Serrano et al. (2010) proposed the Standardized Potential Evapotranspiration Index SPEI as a novel drought index. It is available for varying time scales like the older Standardized Precipitation Index, SPI (Mckee et al., 1993), but in contrast to the SPI it incorporates the effect of temperature. Vicente-Serrano et al. (2012) provided a global assessment of the performance of different drought indices including the ones discussed in the paper for monitoring drought impacts on streamflows, soil moisture, forest growth, and crop yields. The study detected small differences in the comparative performance of the SPI and the SPEI indices, but SPEI best captured the responses of hydrological, agricultural and ecological variables. It has been recommended for use when the responses of the variables of interest to drought are not known. On the other hand PDSI has been widely used for decades particularly in the United States, and also in climate change analyses (Seneviratne et al., 2012). In a hemispherical assessment of drought response of forests using tree ring data, Vicente-Serrano et al. (2014) identified characteristic differences in response time, with a clear gradient in drought response in the northern hemisphere: response to long-term drought conditions in xeric environments, and a response to increasingly shorter time scales of drought with increasingly humid conditions. This pattern confirmed earlier findings based on multiple data streams for vegetation activity on large scales (Maherali and Pockman, 2004; Vicente-Serrano et al., 2012) and tree ring parameters for small scale intensive case studies (Lévesque et al., 2013). However, many recent tree ring studies employ drought indices other than SPEI (Babst et al., 2013; Hogg et al., 2013; Zang et al., 2014). Moreover, the hemispherical approach of Vicente-Serrano et al. (2014) is focused on SPEI solely. Consequently, a direct comparison of potentially macroclimatic and species-specific differences in response to different commonly used drought indices and their varying temporal aggregation is currently not available.

In this study, we use a large data set of tree ring widths (Babst et al., 2013) to assess the connection between drought and tree growth and to provide a continental assessment of the performance of commonly used drought indices for quantifying drought impacts on forest growth. This is achieved through the study of drought impact on the radial growth of nine tree species as a function of elevation and bioclimatic zone. For this purpose, we compare tree growth with four of the most widely used drought indices – SPI (Mckee et al., 1993), self-calibrating Palmer Drought Severity Index, scPDSI (Palmer, 1965; Wells et al., 2004), SPEI (Vicente-Serrano et al., 2010) and De Martonne Aridity Index, DMI (de Martonne, 1926). For the SPI and SPEI time scales from 1 to 36 months have been applied. Considering the different vulnerabilities of different tree species to drought and a lack of appropriate descriptors of drought, the study aims to assess the connection between existing drought indices and the response of different tree species to a drought event. With our study we try to answer which indices best represent drought impacts for the species studied.

2. Material and methods

2.1. Tree ring data

The tree ring network used in this study is a compilation of published tree ring chronologies by Babst et al. (2013) which consists of 992 sites covering most of Europe and North Africa (30–70° N/10° W–40° E) (including information on elevation). A 32 year spline with 50% frequency cutoff response was used to remove the biological trend present in the original raw tree ring width time series while preserving the inter-annual to decadal variability at the same time. The resulting detrended series were power-transformed to remove temporal heteroscedasticity and then robustly averaged to site-wise dimensionless chronologies of ring width indices (RWI). Optimizing the trade-off between series length and replication, we selected RWI series with 56 years of data for the common period 1920–1975. When considering the nine most common species of the network and allowing a maximum period of overlap between climate data and RWI, a total of 850 sites were retained for the final analysis of the study. The following nine species were investigated for their drought vulnerability, namely *Abies alba* Mill. (ABAL, silver fir), *Fagus sylvatica* L. (FASY, European beech), *Larix decidua* Mill. (LADE, European larch), *Picea abies* (L.) Karst. (PCAB, Norway spruce), *Pinus cembra* L. (PICE, stone pine), *Pinus nigra* Arn. (PINI, black pine), *Pinus sylvestris* L. (PISY, Scots pine), *Quercus petraea* (Matt.) Liebl, (QUPE, sessile oak) and *Quercus robur* L. (QURO, common oak). All species' abbreviations are used subsequently in the figures and tables.

2.2. Climate data

We used mean temperature (TMP), precipitation sum (PRE), and potential evapotranspiration (PET) monthly datasets from the observational CRU TS 3.21 worldwide dataset available on a 0.5° grid (Harris et al., 2014; http://badc.nerc.ac.uk/). Data on climate classification was obtained from the world Köppen-Geiger climate classification map (Kottek et al., 2006). The climate classification data is based on recent data sets from the CRU and the Global Precipitation Climatology Centre (GPCC) at the German Meteorological Service. In the study, climate zone Cf, Cs and D denote temperate climate without dry season, temperate climate with dry summer (Mediterranean) and continental climate respectively. Taking into account the uncertainties involved with spatially coarse and interpolated gridded data, we have validated the results of the study using station data from E-OBS (Haylock et al., 2008). The details of the analysis can be found in Appendix B in Supplementary material.

2.3. Drought indices

The drought indices SPI and SPEI were calculated using the R package SPEI (Vicente-Serrano et al., 2010) for time scales of 1, 6, 12, 24 and 36 months based on input data from CRU. The DMI was also calculated using PRE and TMP data from CRU. The scPDSI, which is based on climatic data from the CRU, was downloaded from the KNMI Climate Explorer web page (available at http://climexp.knmi.nl/). The DMI is a measure of aridity obtained by calculating mean precipitation (in mm)/(temperature (in °C) + 10). It is subject to criticism because of its empirical nature but nevertheless provides information on the drought level at a given site. SPI is based on long-term precipitation records that are computed on different time scales. To calculate the SPI, precipitation data is converted to probabilities which are then transformed to standardized series