

3. How is Drought Affecting Forest Growth and How Can Stable Isotopes Contribute to Answer this Question?

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Abstract

We use a network of three differently exposed forest stands to evaluate the effect of micro-site conditions on tree-ring stable isotope composition in the Northern Limestone Alps, Austria. At each site, spruce, larch, and beech were sampled, and the climate signal in tree-ring width (TRW), stable carbon ($\delta^{13}\text{C}$), and oxygen ($\delta^{18}\text{O}$) isotope time series (1970–2010) was evaluated. Results indicate distinct drought signals in the carbon and oxygen isotope chronologies independent of site and species, while climate signals in TRW are weak and inconsistent. During severe drought events, tree-ring stable isotopes reflect species-specific physiological strategies with varying soil water availability explaining differing growth responses. Beech for example benefits from access to moist soils, allowing it to keep the stomata open, which is accompanied by an increased water loss through transpiration but simultaneously enables enhanced photosynthesis.

A more detailed description of findings is provided in Hartl–Meier et al. (2015).

3.1. Introduction

Forests offer a range of socio-economic and ecological services including sources for timber and fuelwood, refuges of biodiversity, and protection functions, for example (Björnsen et al., 2005; Bugmann et al., 2005; Schumacher & Bugmann, 2006; Lindner et al., 2010; McMorran & Price, 2011). It is expected that climate change and more frequent drought events may disturb these services (Hofer, 2005; Lindner et al., 2010). However, to assess the future suitability of the native forest species, knowledge about their capability of coping with drought and the physiological processes underlying climate-induced growth changes is required.

Dendroecological studies offer the possibility to analyze effects of climate change on forests as tree-ring width (TRW) data contain information of environmental stress conditions on growth (e.g., Hartl–Meier et al., 2014a; Hartl–Meier et al., 2014b; Zang et al., 2014). Information on physiological responses can be inferred from stable isotopes in tree rings (Gessler et al., 2014). Stable carbon ($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$) isotopes reflect more directly the plant physiological response to climate and other environmental variables, rather than net tree growth (Treydte et al., 2007; Gessler et al., 2013; Gessler et al., 2014; Treydte et al., 2014). $\delta^{13}\text{C}$ in tree rings is influenced by fractionation processes during photosynthesis and CO_2 uptake—i.e., it enables estimating stomatal closure and the rate of carboxylation during photosynthesis (Farquhar et al., 1989). $\delta^{18}\text{O}$ is controlled by the isotopic signature of rain and soil water (Roden et al., 2000) but is additionally constrained by the stomatal response to vapor pressure deficit via leaf water enrichment, which is coupled to transpiration (Yakir & DeNiro, 1990; Barbour et al., 2004). These factors controlling isotopic fractionation are closely related to meteorological variables. Therefore, tree-ring stable isotopes provide insight into the tree physiological responses caused by environmental stress conditions.

3.2. Materials and methods

This study was compiled in the National Park 'Northern Limestone Alps' in Austria. Climatic conditions are humid with high annual precipitation sums (~1370 mm/a) and moderate annual mean temperatures (~7 °C). Sampling was performed at three sites differing in their soil moisture conditions and soil depths (see Table 3.1). At each site, Norway spruce (*Picea abies* [L.] Karst.), common beech (*Fagus sylvatica* L.) and European larch (*Larix decidua* Mill.; absent at the southern site) were cored using increment borers. TRW measurement $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotopes were determined at annual resolution over the period 1970–2010. The relationship between tree ring parameters and June/July/August climatic elements (data from HISTALP, Auer et al.

2007) was calculated using bootstrapped correlations. Superposed epoch analysis (SEA) (Panofsky & Brier, 1958) was applied to assess the tree's drought response, considering the four years before and after the 1983, 1992, 1994 and 2003 drought events (Hartl–Meier et al., 2015).

Table 3.1. Site characteristics and mean $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ of the spruce (S) larch (L) and beech (B) chronologies over the 1970–2010 period.

Site/ Exposure	Moisture conditions	Slope [%]	Soil depth [cm]	Mean $\delta^{13}\text{C}$ [‰]			Mean $\delta^{18}\text{O}$ [‰]		
				S	L	B	S	L	B
South	Dry	100	28	-20.90	–	-23.76	30.18	–	29.78
North	Medium	25	52	-21.80	-22.90	-24.44	29.96	29.51	29.55
Plateau	Moist	4	60	-22.33	-23.42	-24.70	30.10	29.53	29.11

3.3. Results

Spruce consistently shows the highest and beech the lowest $\delta^{13}\text{C}$ mean values at all sites (Table 3.1). Within a species, the maximum $\delta^{13}\text{C}$ values are reached at the southern site and the minimum values at the Plateau site. For $\delta^{18}\text{O}$, again spruce shows higher and beech slightly lower values, but the isotopic signature does not differ significantly among sites and species (Table 3.1).

The summer climate signals inherent to the stable isotope chronologies are distinct and homogenous (Fig. 3.1a). Positive correlations to summer season sunshine duration and temperature, and negative correlations with Thornthwaite's moisture index (Thornthwaite 1948), precipitation and cloud cover are coherent among sites and species for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$. The overall strongest relationships in both C and O isotopes are observed with cloud cover reaching $r = -0.71$ for larch and $r = -0.72$ for beech $\delta^{18}\text{O}$ data. The correlations between TRW and climate data are weaker and characterized by distinct species dependencies.

Independent of site and species, the SEA shows distinct responses during severe drought events in all $\delta^{13}\text{C}$ chronologies (Fig. 3.1b). Drought signals in $\delta^{18}\text{O}$ are less pronounced and variable among sites. At the Plateau site, beech, spruce and larch show stronger positive deviations. For TRW, the drought responses are again strongly species and site dependent. Spruce growth declines sharply at every site, while beech declines only at the southern site, and larch shows no growth reaction.

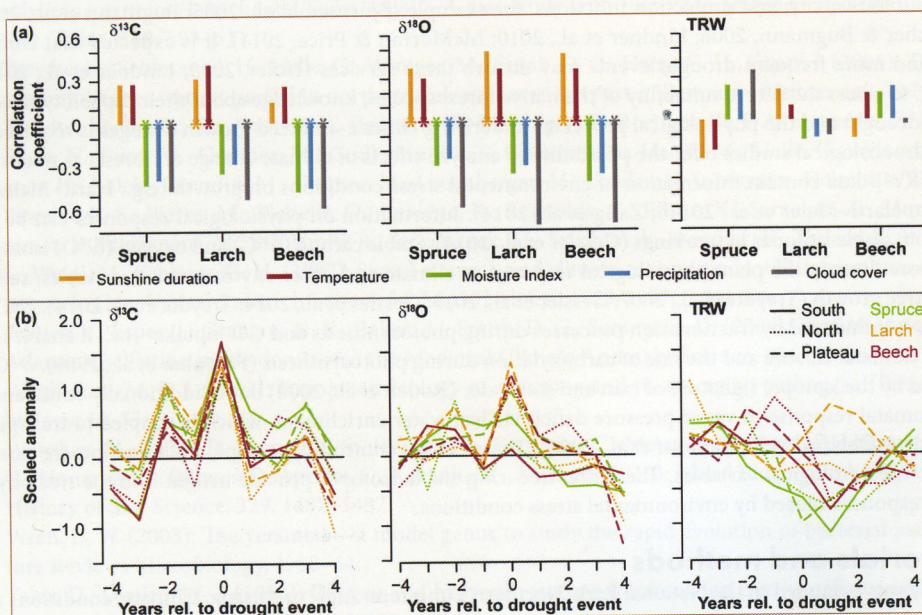


Figure 3.1. (a) Relationship of spruce, larch and beech $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and TRW mean chronologies to climate variables of the June/July/August season (* $p \leq 0.05$ significant correlations). (b) Superposed epoch analysis for spruce, larch and beech $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and TRW site chronologies. Curves represent scaled time series centered on the drought events in 1983, 1992, 1994 and 2003 (= year 0).

3.4. Discussion

A distinct dependency of the isotopic signature on soil moisture conditions is already revealed in the tree-ring raw values. The highest $\delta^{13}\text{C}$ mean values are reached at the driest, south-exposed site, indicating that trees respond with increased stomatal closure there, compared to the moister sites (Saurer et al., 1995; Treydte et al., 2001; Gessler et al., 2014; Saurer et al., 2014). In contrast, the mean $\delta^{18}\text{O}$ signature rather seems to more closely represent the source water signals and differing rooting depths of the tree species: sub-surface soil water is typically enriched in ^{18}O due to evaporation, while the $\delta^{18}\text{O}$ of the deeper soil water pools is lower (Roden et al., 2000; Sarris et al., 2013; Treydte et al., 2014). This pattern can be tracked with beech, a species characterized by a deep rooting system and access to deeper, ^{18}O -depleted soil water pools (Pretzsch et al., 2013). In contrast, spruce is a shallow rooting species and the water uptake concentrates in the upper soil horizons only (Przybylski, 2007; Pretzsch et al., 2013), explaining the similar $\delta^{18}\text{O}$ values among the sites.

The uniform climate response for the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ chronologies among species is striking and underlines the strong dependency of stable isotopes on atmospheric conditions even at sites where no climate parameter can be detected as a limiting factor for tree growth (Saurer et al., 2008; Haupt et al., 2014; Saurer et al., 2012; Rinne et al., 2013). The isotope chronologies contain substantial drought signals, especially compared to TRW. The correlations reported here exceeding $r = -0.70$ demonstrate the potential of using tree-ring stable isotopes from temperate environments for reconstructing past climate conditions (Esper et al., 2012).

The results of the SEA help our understanding of the physiological strategies of tree species coping with drought and their adaption to differing soil moisture availability. The increased $\delta^{18}\text{O}$ values at the moister sites point to increased transpiration during drought events as water can be delivered from deeper soil water pools. This is connected to an increased stomatal conductance and thus the high $\delta^{13}\text{C}$ values at the moist sites can be interpreted as a signal for enhanced photosynthetic activity (Gessler et al., 2014). In contrast, trees at the dry site close stomata for preventing water loss (represented by the high $\delta^{13}\text{C}$ values)—i.e., they reduce stomatal conductance during drought events. This site-specific strategy is also reflected in the growth response of beech, for example. At the dry site, beech growth declined during drought events, but kept growing faster at the moist site. Consequently, higher soil water availability allows a higher stomatal conductance and simultaneously an enhanced photosynthetic activity, supporting sustained biomass production. Our findings suggest that tree-ring stable isotopes provide great insights into the physiological mechanisms of tree species coping with drought under differing soil moisture conditions.

Acknowledgement

Supported by the Bavarian State Ministry for Food, Agriculture and Forestry, and the EU program INTERREG within the project SICALP (J00183). We thank Kerstin Treydte for performing stable isotope measurements and her comprehensive support interpreting the results.

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