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Bridging tree rings and forest inventories: How climate effects on spruce and beech growth aggregate over time

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ABSTRACT

Tree growth is strongly influenced, among other factors, by climate. Much knowledge regarding climate–growth relationships has been gained by studying tree rings. However, sufficient tree-ring data is rarely available if climate effects are required to be representative for large spatial scales, for example, in order to be used in scenario models to estimate forest development under climate change. Alternative data sources include large-scale forest inventories, although these usually provide lower temporal resolutions than tree rings. When working with temporally sparsely-resolved growth data, the question of how climate–growth relationships aggregate over time becomes relevant. To overcome this trade-off between spatial representativeness and temporal resolution, this study aims at optimally using the information contained in the annual resolution of tree rings to derive recommendations regarding the choice of climate variables for modeling tree growth based on forest inventories. We evaluated for *Picea abies* and *Fagus sylvatica*, which part of the year (spring, summer, vegetation period, whole year) and whether mean or extreme climatic conditions within inventory intervals should be taken into consideration. A three-step approach was used: (1) we used response functions to quantify the effect of monthly precipitation and temperature on annual basal area increments, (2) we temporally aggregated the annual basal area increments to hypothetical intervals of five and ten years, and correlated them with climate means and extremes – from different parts of the year – within the aggregated intervals, and (3) we fitted linear mixed-effects models to simultaneously quantify the effects of the climate variables, site characteristics and the years of the hypothetical inventories. The results did not generally differ between both species. Variables based on conditions during the whole year and partly during spring performed better than variables based on conditions during summer or the vegetation period. Defining the year as the period between October of the previous year and September of the current year allows possible lag effects of previous autumn and winter conditions to be taken into consideration. Mean climatic conditions reached or exceeded the correlations of the extremes and mostly performed similar to or better than the extremes in the models. Our results indicate that these relationships are insensitive to the often arbitrarily determined years, in which inventories take place. These findings can serve as basic recommendations for the choice of climate variables when modeling climate effects on multi-year growth of *P. abies* and *F. sylvatica* in the European lowlands.

1. Introduction

Tree growth is strongly influenced, among other factors, by climate. For several decades, many research efforts have aimed at a better understanding of the relationship between climatic conditions and tree growth (Fritts, 1976; Spiecker, 1999; Lindner et al., 2014). In the context of climate change, the quantification of this relationship has gained in importance. In particular, climate-dependent tree growth has been studied to increase the understanding of physiological processes behind tree growth (Orwig and Abrams, 1997), for climate reconstructions (Neukomm et al., 2014), to quantify expected tree growth under various climate scenarios (Fontes et al., 2010) and – based on such scenarios – to elaborate adaptation strategies for sustainable forest management under climate change (Lindner et al., 2014).

Much fundamental knowledge about climate–growth relationships has been gained from studying tree rings. Statistical methods to analyze the influence of climate variability on tree-ring widths

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were established already in the 1930s (Diller, 1935). Subsequently, dendroclimatology has evolved into a main branch of forest sciences. Mostly, monthly climate variables have been related to some measure of annual growth derived from tree-rings, often by considering past-year and current-year climatic conditions and taking into account the multicollinearity among them (Fritts, 1976; Blasing et al., 1984). Based on such 'response functions', climate-dependent tree growth has been compared among different species and varying site conditions (e.g., Lebourgeois et al., 2004; Weber et al., 2007; Scharnweber et al., 2011; Michelot et al., 2012).

For many research questions, however, representative tree-ring data (or other annually resolved growth data) is not available. In particular, to study tree growth at larger spatial scales, data from national forest inventories provides a useful alternative that allows for representative inferences. Empirical models that include stand, site, and management effects have, for example, been developed based on the Swiss (MASSIMO; Thürig et al., 2005) and Austrian (PrognAus; Monserud et al., 1997) national forest inventories, as well as on Europe-wide inventory data (EFISCEN; Nabuurs et al., 1997). However, in most cases, such models were originally designed to be climate-independent, and attempts to include climate effects on tree growth took place subsequently (Matala et al., 2005; Kindermann, 2010). When modeling climate effects based on inventory data, one challenge is that the temporal resolution of such inventories does usually not allow for annual growth analyses. Nevertheless, the inclusion of climate-dependent tree growth is an essential precondition if the inventory-based models are intended to estimate forest development under climate change.

Since there is a trade-off between temporal resolution and spatial representativeness, questions concerning potential explanatory climate variables fundamentally differ between tree-ring studies and inventory-based studies. Besides the basic decision about the considered climatic factors (e.g. temperature and precipitation), the question about how climate–growth relationships aggregate over time becomes additionally relevant when working with temporally sparsely-resolved growth data. Consequently, longer inventory periods imply the question of whether climate means or extremes (cf. Babst et al., 2012; Carrer et al., 2012) in the period should be considered. In addition, such means or extremes can be calculated based on different parts of the year, e.g., based on the whole year or on the vegetation period only. Many previous studies focused on the growth effects of mean annual climate variables (Matala et al., 2005; Condés and García-Robredo, 2012), or mean climate conditions during the growing season (Nothdurft et al., 2012). However, decisions regarding the type of climate variables to be taken into consideration in previous inventory-based studies, have been, to date, rather arbitrary or purely pragmatic, and mostly without any particular justification (but see Nothdurft et al., 2012).

The main goal of this study is to optimally use information contained in the annual resolution of tree rings to recommend well-founded choices of climate variables in studies based on forest inventories. Recent attempts to combine information from different temporal resolutions to investigate climate–growth relationships have focused on hourly to yearly intervals (King et al., 2013). The combination of information from tree-rings and forest inventories has been rather proposed in light of other applications, for example, to identify long-term growth trends (Biondi, 1999; Yue et al., 2011). Girard et al. (2014) also evaluated potential explanatory climatic variables on different temporal resolutions and concluded that variables on a monthly scale performed better than long-term averages for modeling tree growth in northern Canadian hardwoods.

In this study, we focus on *Picea abies* and *Fagus sylvatica*, because they are among the most abundant and economically important tree species in central European forests (cf. Pretzsch et al., 2014). In Switzerland, where the study sites are located, *P. abies* constitutes the highest proportion of the growing stock with 44%, followed by *F. sylvatica* with 18% (Brändli, 2010). In the Swiss lowlands, an average volume of 7.6 m^3/ha of *P. abies* is harvested every year (55% of the harvested volume in the lowlands), and 2.1 m^3/ha of *F. sylvatica* (15%, Brändli, 2010).

The following research questions are addressed:

- Are climate conditions during spring, summer, the vegetation period, or the whole year related most strongly to basal area increments (BAI)?
- Are climate means or extremes within inventory intervals related more strongly to BAI?
- For given interval lengths, how relevant is the timing of the inventories (i.e., in which years the inventories take place)?
- Do the findings differ with the length of the inventory intervals?
- Do the findings differ between *P. abies* and *F. sylvatica*?

To answer these questions, we took a three-step approach. First, we calculated standard dendroecological response functions to quantify the effect of monthly precipitation and temperature on annual BAI. Second, we temporally aggregated the annual BAI to hypothetical five- and ten-year intervals and correlated them with climate means and extremes (from different parts of the year) within the aggregated intervals. Third, we fitted linear mixed-effects models to simultaneously quantify the effects of the climate variables, site characteristics, and the arbitrarily chosen years of the hypothetical inventories on BAI.

2. Methods

2.1. Study sites

Nineteen study sites were selected in the Swiss lowlands (for details see Weber et al., 2015 Fig. 1). *F. sylvatica* was investigated at 13 and *P. abies* at 8 of these sites (at two sites, both species were investigated; see Fig. 1 and Table 1). The sites represent several aspects and comprise elevations from 440 to 870 m a.s.l. and slopes from 0% to 100% (Table 1). The available water capacity (AWC) was determined based on soil profile data at each site according to AG Bodenkunde (1982). AWC at one meter soil depth varies between 30 and 229 mm among the sites. Thus, the investigated study sites cover a broad range of environmental growth conditions.

2.2. Data collection and processing

2.2.1. Tree-ring data

In Weber et al. (2015), details regarding data collection and specifications of the selected trees are presented. For each site and species, ten dominant or co-dominant trees were selected for tree-ring sampling between 2007 and 2012. From every selected tree, two cores were extracted at one meter above ground. Tree-ring widths were measured using a LINTAB measuring system and the TSAP-Win software (both RINNTECH, Germany). For cores that missed the pith, the missing distance between the first complete ring on the core and the pith was estimated according to Bräker (1981). The tree-ring widths were converted to annual BAI. One BAI chronology per species and site (Fig. 2) was built by averaging the series of the individual trees. Analyses were performed based on BAI rather than raw tree-ring widths to reduce the geometrical age or size trend, which follows from the fact that constant resource investment in diameter growth results in decreasing tree-ring widths if the stem diameter increases. Moreover, many empirical forest scenario models that intend to account