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Summer climate variability over the last 250 years differently affected tree species radial growth in a mesic *Fagus–Abies–Picea* old-growth forest

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ABSTRACT

Sustainable forest management has to consider the long-term effects of climate change on species growth to develop adaptation measures. In this perspective, dendrochronology provides valuable information on climate-growth relationships over long time periods. Tree-ring analyses in mixed stands can elucidate how different species respond to climate change within the same environmental conditions. However, few studies have investigated such stands, especially in South-Eastern Europe. In the forest reserve of Lom, in Bosnia and Herzegovina, we had the opportunity to study three co-occurring species (silver fir, Norway spruce, European beech) in an old-growth forest characterized by reduced human and natural disturbances, and a climate favourable to the tree species. We evaluated tree growth response to climate on inter-annual and decadal time scales over about 250 years. Response to inter-annual climate variability changed over the study period. Climate signal in beech was generally low, with a negative correlation to April temperature in the last decades. In fir and spruce, the positive effect of current year's spring temperature decreased, while the negative effect of the previous summer temperature considerably increased over the last century. At the decadal scale, different responses have been detected among species: spruce was mostly negatively affected by summer temperature whereas summer precipitation benefited fir growth, probably balancing high evapotranspiration. Beech showed a peculiar delayed response, and protracted drought periods led to severe growth reductions. Despite a temperature increase over the last three decades, fir did not experience any growth reduction, while a strong decline was evident in spruce and beech productivity. Mesic sites are commonly underrepresented in tree-ring research. In our analysis, covering about 250 years, we observed that climate also affects species-specific growth patterns in these areas. Within a global change perspective, specific divergent responses are likely to occur even where current environmental conditions appear to be not limiting for tree species. Future management strategies should consider these outcomes.

1. Introduction

During the last decades, both positive and negative trends in productivity have been reported in many temperate forests, depending on species and site (Boisvenue and Running, 2006; Bellassen et al., 2011). Different factors, directly or indirectly related to human activities, have been identified as major drivers of the observed patterns.

Climate change, including global warming, lengthening of the growing season, variation in precipitation regime and climate extremes, has been widely indicated as a primary factor affecting forest growth patterns (Menzel and Fabian, 1999), with increased drought episodes reducing carbon assimilation over wide regions (Allen et al., 2010; Linares and Camarero, 2012a). More generally, global changes, including modifications in land management practices and disturbance regimes, have an impact on forest productivity, either favouring or repressing tree species growth (Bradford et al., 2012; Peters et al., 2013). Furthermore, alteration of biogeochemical fluxes has certainly affected forest ecosystems. An increase in atmospheric CO_2 concentration was expected to increase photosynthetic rates (Ciais et al., 2005), although recent observations indicated that tree growth can remain constant in spite of the increase in CO_2 (Bader et al., 2013), or only increase

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for a short period (Norby et al., 2010), as other co-occurring factors can limit carbon uptake (Linares and Camarero, 2012a). Increased nitrogen deposition over the last decades can have a fertilizing effect on temperate forests (Magnani et al., 2007). On the other hand, massive nitrogen and sulphur emissions both negatively impacted forest ecosystems, as widely observed in Eastern Europe during the 1970s and 1980s (Diaci et al., 2011; Bošela et al., 2014).

Whatever the cause, it is essential to place recent growth variations within the context of long-term variability, to understand whether observed patterns are unprecedented or reversible temporal fluctuations. Tree-ring analysis represents a valuable tool for this, as it allows variations in tree growth patterns to be studied over long time periods, and to investigate relationships between trees and environmental factors, such as climate. Most dendrochronological research has been conducted on trees growing near their environmental limits, as they have a more evident response to climate. However, processes observed in such conditions can only be barely indicative of climate change influence on most forested areas (Carrer et al., 2012), which do not lie at the altitudinal or latitudinal limits of species distributions (Drew et al., 2013).

A central aspect of research on forest adaptation to climate change is evaluating the different responses of species. However, both site and stand characteristics can confound species-specific responses (Castagneri et al., 2012; Eilmann and Rigling, 2012). To exclude site effect, a few studies have been conducted on response to inter-annual climate variability in co-occurring species (e.g., Battipaglia et al., 2009; Schuster and Oberhuber, 2013). Furthermore, analysing mixed stands allows the effect of species mixture on tree sensitivity to environmental stress to be evaluated (Lebourgeois et al., 2013). However, to date, very few studies have investigated climate effects on decadal growth fluctuations in mixed stands (Wilson and Elling, 2004; Bouriaud and Popa, 2009). Such trends are often not considered, as they are affected by size-age relationships, stand dynamics and disturbances (Cook et al., 1990), and climate signal is considered hardly detectable. However, the effect of decadal climate variations on tree growth can be observed in old living trees even in a forest stand, when other factors influencing growth, such as disturbances, are limited and/or randomly distributed (Bouriaud and Popa, 2009; Aakala and Kuuluvainen, 2011).

Future carbon sink estimates and forest management strategies should be driven by detailed information on different tree species response to climate change. As recent variations in growth trends, and in tree response to climate, have not followed a uniform pattern in Europe (Spiecker, 1999; Mäkinen et al., 2002; Babst et al., 2013), there is a need to investigate growth patterns in different areas, especially those not previously much explored, such as mesic forests in Eastern Europe (Bošela et al., 2013; Poljanšek et al., 2013). In the current study, we aimed to evaluate growth patterns and response to climate over the last few centuries of three widely distributed tree species, i.e. European beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* (L.) Karst.) and silver fir (*Abies alba* Mill.), in an old-growth forest in Bosnia and Herzegovina. As the three species co-occur in the same stand, it was possible to study their response to climate within the same environmental conditions. Moreover, in the study area the three species grow vigorously, allowing species sensitivity to climate change to be studied in not-limiting conditions. Lastly, the forest has scarcely been affected by humans, and there were no signs of intermediate or large scale disturbances over the last centuries affecting tree growth patterns (Bottero et al., 2011; Motta et al., 2011). To better understand the climate influence on the species growth, we aimed to answer the following research questions: in the three species. (1) Is the inter-annual growth response to climate similar, and stable over time? (2) Is there an effect of decadal climate variations on growth trends?

On the basis of observed climate-growth relationships, we then discussed recent growth trends in comparison to those we observed in previous periods, and those reported for the same species in other regions of Europe.

2. Materials and methods

2.1. Study area

The study was conducted in the Lom forest reserve (298 ha, 44°27′N, 16°28′E, 1250–1500 m a.s.l.) in the Dinaric Alps, Bosnia and Herzegovina. Annual precipitation averaged 1600 mm, with maximum in December (173 mm) and minimum in July (108 mm), and mean annual temperature in the lower part of the reserve was 5.0 °C, with maximum in August (13.3 °C) and minimum in February (−3.9 °C) (Maunaga, 2001). The morphology had typical karst characteristics, such as limestone outcrops and deep cavities, with reduced soil water holding capacity. Shallow soils (dark soil and shallow brown) were predominant, and water deficit could occur during summer (Maunaga, 2001).

The reserve was established in 1956 in an old-growth mixed montane forest. The most widespread vegetation type was *Piceo–Abieti–Fagetum illyricum*. In the reserve core area, total basal area averaged 47.1 m^2 ha^{-1} (47% silver fir, 31% European beech, 22% Norway spruce, less than 1% other species), while the average density of live canopy trees was 489 ha^{-1} (60% European beech, 25% silver fir, 14% Norway spruce, less than 1% other species). Spruce and fir trees exceeded 120 cm in diameter and 40 m in height, and the largest beech trees grew to over 70 cm and 35 m (Motta et al., 2011). Previous studies pointed out that forest dynamics are characterized by small-scale processes, while no intermediate, large, or stand replacing disturbances were recorded (Bottero et al., 2011; Garbarino et al., 2012). Evidences of past human activities (selective logging) were observed only near the reserve borders.

2.2. Field sampling and tree-ring analysis

During 2008 and 2009, covering an area of approximately one square kilometre in the lower part of the reserve, we sampled 34 Norway spruce, 35 silver fir and 47 European beech trees among dominant and co-dominant individuals. Diameter at breast height (dbh) was recorded, and two cores were taken from each tree at 1.30 m above ground level.

Ring width was measured to the nearest 0.01 mm in the laboratory and cross-dating accuracy was checked using COFECHA (Holmes, 1983). Cores not reliably cross-dated were excluded from the analyses. We finally kept 64 cores (34 trees) for spruce, 63 (35) for fir, and 85 (47) for beech. Raw ring width series were used to build basal area increment (BAI) chronologies.

To remove age-size related trends, raw ring width series were detrended using cubic smoothing splines with 50% frequency–response cutoff equal to 200 years using the ARSTAN program (Cook, 1985). This method partially removed multi-century trends, possibly related to multi-century climatic fluctuations, but was able to keep most of the year to year and decadal variability. Mean chronologies (MC) for each species were calculated as the biweight robust mean of detrended individual series (Cook, 1985), and truncated when one of the following criteria was not met: (i) sample size <5 series; (ii) mean correlation among series <0.50 over 50 year windows; (iii) Expressed Population Signal <0.85 over 50 year windows (Wigley et al., 1984).

For individual raw series, and for the mean chronologies, we calculated mean sensitivity to assess the high-frequency variations (Fritts, 1976), and the first-order autocorrelation to measure the influence of the previous year's growth on the current ring. To