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Reconstruction of a 253-year long mast record of European beech reveals its association with large scale temperature variability and no long-term trend in mast frequencies

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ABSTRACT

Synchronous production of large seed crops, or mast years (MYs), is a common feature of many *Fagus* species, which is closely linked to the dynamics of forest ecosystems, including regeneration of canopy trees and changes in animal population densities. To better understand its climatic controls and check for the presence of long-term temporal trends in MY frequencies, we reconstructed MY record of the European beech (*Fagus sylvatica* L.) for the southern Swedish province of Halland over 1753–2006. We used superimposed epoch analysis (SEA) to relate MY (a) to summer temperature fields over the European subcontinent and (b) to the patterns of 500 mb geopotential heights over the 35–75°N. For the MY reconstruction, we used newly developed regional beech ring-width chronology (1753–2006), an available summer temperature reconstruction, and a discontinuous historical MY record. A Monte Carlo experiment allowed identification of the thresholds in both growth and summer temperature anomalies, indicative of historical MYs, which were verified by dividing data into temporally independent calibration and verification sub-periods.

MYs were strongly associated with both the 500 mb height anomalies and average summer temperatures during two years preceding a MY: a mast year (*t*) followed a cold summer two years (*t*-2) prior to the mast year and a warm summer one year prior (*t*-1) to the mast year. During *t*-2 years, the geographical pattern of 500 mb height anomalies exhibited a strong height depression in the region centered in the Northern Sea and extending toward eastern North America and statistically significant ($p < 0.05$) temperature anomalies covering predominantly southern Scandinavia (area below 60 N) and British Isles. A year immediately preceding a mast year (*t*-1) was characterized by a strong regional high pressure anomaly centered in southern Scandinavia with significant temperature anomalies extended mostly over southern Scandinavia and Germany.

The long-term mean MY return interval was 6.3 years, with 50 and 90% probabilities of MY occurrence corresponding to 6 and 15 years, respectively. Periods with intervals significantly shorter than the long-term mean were observed around 1820–1860 and 1990–2006 (means – 3.9 and 3.2 years, respectively). However, the difference in return intervals between two sub-periods themselves was not significant.

Geographically large and temporally rapid changes in atmospheric circulation among years, responsible for summer temperature conditions in the Northern Europe, are likely primary environmental drivers of masting phenomenon. However, decadal and centurial variability in MY intervals is difficult to relate directly to temperature variability, suggesting the presence of conditions "canceling" would-be MYs. Long-term MY reconstruction demonstrates high variability of reproductive behavior in European beech and indicates that a period with shorter MY intervals at the end of 20th may be not unique in a multi-century perspective.

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1. Introduction

Strong variability in annual seed production and occurrence of years with exceptionally large crops often synchronized over large geographical regions, so-called mast years, is a common feature of trees in the *Fagaceae* family (Hiroki and Matsubara, 1995; Hilton and Packham, 2003). At tree level, such events imply large shifts in resource allocation toward reproductive organs, suggesting trade-offs between seed production and biomass accumulation (Monks and Kelly, 2006; Drobyshev et al., 2010). At the stand and regional levels, mast years are important for species regeneration and subsequent canopy dynamics (Emborg, 1998; Frey et al., 2007; Barna, 2011), as well as for dynamics of animal species utilizing beech seeds as a food resource (Schnurr et al., 2002; Clotfelter et al., 2007; Jensen et al., 2012). Mast seeding, specifically of *Fagus* spp., has been widely acknowledged in forestry as a way to promote natural tree regeneration on clearcut areas (Henriksen, 1988; Övergaard et al., 2007; Bileik et al., 2009).

Mast years in European beech (*Fagus sylvatica* L.) have been shown to be strongly affected by annual climatic variability. Temperature dynamics apparently plays the major role in controlling mast events (Piovesan and Adams, 2001). Warm and dry conditions were typically observed during the summers preceding the mast year, and cold summers with sufficient amount of precipitation were often observed two years prior to a mast year. A study in southern Sweden has revealed a strong effect of temperature on beech masting behavior (Drobyshev et al., 2010). In line with these findings, physiological studies have repeatedly pointed to European beech as a temperature sensitive species, e.g. relative to the onset of the cambial cell production and growth period (Murray et al., 1989; Prislan et al., 2013), leaf unfolding (Prislan et al., 2013), and leaf growing period (Tikvic et al., 2006).

A strong climatic control of beech masting implies that both short- and long-term variations in the frequency of mast years are driven by the frequency of specific climatic conditions. These conditions trigger the formation of flower buds and subsequent shifts in the allocation of bioassimilates toward the production of nuts. Although no published studies looked at the changes in the actual frequency of such triggering conditions, many have reported an increase in the masting frequency across different parts of the European subcontinent over the second half of the 20th century, linking this trend to the changing climate (Schmidt, 2006; Övergaard et al., 2007; Paar et al., 2011). An example of such a trend in Northern Europe was an unusual occurrence of two consecutive mast years reported in Sweden for 1992 and 1993 (Övergaard et al., 2007).

Although a number of previous studies analyzed climatic controls of beech masting in Scandinavia (Övergaard et al., 2007; Drobyshev et al., 2010), understanding long-term masting patterns and their linkages to the regional climate is still limited. In particular, two aspects warranting further studies are (a) the geographic extent of climate anomalies linked to the masting behavior of beech at its northern distribution limit and (b) the century-long pattern of mast return intervals, which could provide an insight into historic variability of mast year occurrence and its relation to long-term climate variability. Both aspects of beech masting behavior are of direct practical interest since this species is an important timber resource in southern Scandinavia and its practical management (e.g. use of natural regeneration methods on clearcuts) calls for a better understanding of beech reproduction ecology (Agestam et al., 2003).

In this study, we provide a 253-year long reconstruction of mast frequencies in the southern Swedish province of Halland, compiling historical records, a newly-developed dendrochronological reconstruction, and modern observation of mast events. Our main goal was to quantify the pattern and geographical scale of the climatic controls exerted on mast years and identify long-term temporal trends in MY frequencies. Such trends could reflect decadal and century-long changes in summer temperature regime over southern Scandinavia.

2. Study area

The data analyzed in the paper was collected in the south-western Swedish county of Halland (Fig. 1). The mean annual temperature in this part of southern Sweden is between 6 °C and 7.5 °C. The long-term mean temperature in January varies between −4 and 0 °C and in July – between 14 and 18 °C. Each year, between 190 and 220 days occur with temperatures above 5 °C. The county has one of the largest amounts of annual precipitation in Sweden (1000–1300 mm), mainly due to the dominance of westerly and south-westerly winds carrying humid air from the Atlantic (Raab and Vedin, 1995). Geologically, the region is dominated by gneiss rocks and soils formed on sandy and stony moraines (Fredén, 2002). The region lies in the nemoral and boreo-nemoral vegetation zones (Ahti et al., 1968, Fig. 1). Oaks (*Quercus robur* L. and *Q. petraea* (Matt.) Liebl.), European beech (*F. sylvatica* L.), and small-leaved species (downy birch, *Betula pubescens* Ehrh. and quaking aspen, *Populus tremula* L.) represent the deciduous component in the forest cover (Nilsson, 1996). Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) are the main coniferous species. The tree-ring dataset used for reconstruction was collected in mature and old-growth beech-dominated stands. The main data set originated from of the Biskopstorp nature reserve (Fig. 1). The area encompasses around 900 ha, almost completely covered by forest. The broadleaved forests (beech and oak-dominated) make up approximately 30% of the total forest cover (Fritz, 2006).

3. Material and methods

3.1. Field sampling, sample preparation and development of regional beech chronology

To obtain tree ring data, we cored trees along two radii at a height of 1.36 m with a standard increment corer. We also used a chainsaw to obtain wedges from both living and dead trees. Core samples were mounted on wood planks and all samples were progressively polished with up to 600-grit sandpaper to allow clear recognition of annual rings under the microscope (using up to 40× magnification). We employed a visual cross-dating method (Stokes and Smiley, 1968) to precisely date each sample, using a regional list of pointer years. In all of the single-tree chronologies (total number of trees in the analyses, $n = 69$), we removed data corresponding to the period when a tree was younger than 40 years to exclude the part of the tree lifespan when mast behavior is not yet well pronounced (Simak, 1993).

We removed low frequency trends in tree-ring data (e.g. age- and size-related) by detrending single tree chronologies with a cubic spline with a 50% frequency response at 32 year frequency band. Autoregressive modeling on the detrended ring-width series removed temporal autocorrelation and enhanced the common signal in the tree-ring chronologies. Autoregressive modeling used the *ar* function of the R statistical software (R Development Core Team, 2009) and relied on the values of Akaike's Information Criterion (AIC) to select the optimal order of the autoregressive model. The individual residual series were then averaged together using a biweight robust mean to develop a mean standardized chronology for a site, which retained high-frequency variation and contained no low-frequency trend.