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Original article

Increased tree-growth synchronization of beech (*Fagus sylvatica* L.) in response to climate change in northwestern Europe

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ABSTRACT

To better understand how the radial growth of beech (*Fagus sylvatica* L.) high forests has responded to climate change, we selected 12 sites (137 trees) with optimal growing conditions along a W–E altitudinal gradient (67–590 m) in Belgium. We evaluated temporal changes in growth response to climate by using pointer year analysis, moving mean sensitivities (1860–2011), and moving bootstrapped correlation coefficients (1952–2011). The strongest driving climatic variables were identified by using the partial least squares method.

The common patterns of growth trends, pointer years, and mean sensitivities among sites provided evidences for the impact of environmental changes operating at a regional scale. The results of growth–climate analysis indicated that these changes were strongly influenced by the climatic conditions of the previous year. The climate sensitivity of beech increased progressively in response to more frequent and intense heat waves and warming-related droughts, especially during recent decades, leading to remarkable inter-site synchronization. The changes were much more pronounced for sites located in lowlands (<300 m). The differences in growth responses along the altitudinal gradient and the consequences of warming for beech growth and physiology are discussed.

Introduction

Common beech (*Fagus sylvatica* L.) is one of the most widespread and important tree species in Europe. This species is distributed from Sicily in southern Italy to Bergen in southern Norway, and it occurs in various habitats from mountainous regions to lowlands (Fang and Lechowicz, 2006; Seynave et al., 2008). Recently, numerous tree-ring studies have revealed long-term changes in the tree-growth–climate relationships of several broadleaved and coniferous tree-species; this phenomenon is termed the "divergence problem" (D'Arrigo et al., 2008; Lebourgeois and Mérian, 2011). For beech, changes have been observed throughout Europe (Dittmar et al., 2003; Jump et al., 2006; Di Filippo et al., 2007, 2012; Friedrichs et al., 2009; Bolte et al., 2010; Scharnweber et al., 2011; Lebourgeois et al., 2012; van der Maaten, 2012; Weber et al., 2013; Castagneri et al., 2014). At high-elevation and/or high-latitude sites, temperature is the key driving factor of tree growth and observed changes in the tree-growth–climate relationships correspond to a loss of response to temperature. At mid- and low-latitude sites, tree growth is dependent on the interaction between temperature and water availability (Lebourgeois and Mérian, 2011). Thus, to disentangle the specific warming effect of water availability on beech, it seems more appropriate to sample trees from stands with optimal growing conditions. Changes in temperature thresholds in these stands might play a major role in influencing carbon stock (Latte et al., 2013), carbon uptake projections (De Vries et al., 2006; Campioli et al., 2012) and management policies; moreover, they may induce severe economic losses (Hanewinkel et al., 2013).

Since the 1990s, anomalies in beech health (e.g., worsening crown conditions) have been observed throughout Europe (UNECE, 2005) and in Belgium (Laurent and Lecomte, 2007). During the same period, beech height growth and productivity changes have been reported in Belgium (Kint et al., 2012; Aertsen et al., 2014) and northeastern France (Bontemps et al., 2010; Charru et al., 2010). Beech is sensitive to drought during the period between budburst and the month of July and also to summer heat waves (Mund et al., 2010; Scharnweber et al., 2011). These factors are considered to be the major limiting abiotic disturbances for beech in Belgium in the

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context of climate change (Campioli et al., 2012). Since the end of the 19th century, precipitation has remained relatively stable over time; however, temperatures have increased by approximately 2 °C (Demarée et al., 2002) and will likely continue to increase in the future (Baguis et al., 2010; Collins et al., 2013). The higher frequency and intensity of heat waves and warming-related droughts have altered tree functioning and will probably continue to do so (Bréda et al., 2006; McDowell, 2011); this will be particularly true at sites with lower water availability, where beech is more sensitive to climate (Lebourgeois et al., 2005). Thus, niche-based models forecast a reduction in the beech distribution area during the 21st century, especially for lowlands in northwestern Europe (Piedallu et al., 2009; Kramer et al., 2010).

In the present study, we evaluated the influence of global warning on the tree-growth–climate relationships of northwestern European beech forests. We selected 12 beech stands along the entire altitudinal and climatic gradient of southern Belgium. To specifically investigate the effect of warming along the gradient, we defined the selection criteria so as to minimize differences between stands and growing conditions, as well as to reduce the effects of interactions between warming and water availability. Our hypotheses were that (1) global warming and related heat waves have progressively affected beech, thereby reducing its growth and increasing its sensitivity, and (2) resulting changes in growth responses to climate should vary with altitude and are probably more intense in lowlands.

Materials and methods

Study area and site and tree selection

Twelve beech stands were selected along a W–E gradient in Belgium (Fig. 1), spanning the entire elevation gradient from the lowlands (67 m) to the Ardennes Plateau (590 m). Along this gradient, the mean annual temperature decreases (from 10.3 °C to 7.2 °C) and the annual precipitation increases (from 743 mm to 1047 mm; Table 1). We restricted our stand selection to sites that were optimal for beech growth and had no noticeable topographic or soil constraints (slope ≤3%). Thus, the selected stands were among the most productive in Europe (dominant height of 19–30 m at the age of 80 years; Table 1). Soil boreholes were used to roughly estimate the maximal soil water content (≥90 mm; Table 1) based on the soil texture, stoniness, and depth (Ridremont et al., 2011). In addition, we limited our sampling to a fixed silvicultural context of mature and dominant trees within pure beech forests (>75% of basal area) that had been managed according to an even-aged (or regular) structure by forest administration for more than half a century. The selection criteria were thus defined to minimize differences between stands and site growing conditions, in order to focus on the influence of temperature along the altitudinal gradient. We restricted our stand selection to stands ranging in age from 84 years old to 206 years old (Table 1), in order to focus on mature trees and eliminate juvenile and senescence effects.

In each beech site, 8–15 dominant or co-dominant healthy beech trees of comparable dimensions were selected (137 trees, Table 1) and cut down in the winter of 2011–2012. One disk per tree was collected at breast height (1.3 m) at eight sites, and because of technical constraints, from higher up the stem at four sites (Table 1). The variation in sampling height did not markedly influence the results or their interpretation (Supplementary material: Figs. A and B). To facilitate handling, two bars (each 12 cm wide) were extracted from opposite side of the disk. Bars represent a good compromise between disks and cores. Bar dimensions are more practical than disks for sample preparation; moreover,

Table 1
Characteristics of the 12 beech sites. Site index = dominant height at the age of 80 years.

Site	Local site parameters		Climate parameters		Stand characteristics			Sampled tree characteristics			
	Altitude (m)	Maximum soil water content (mm)	Mean annual temperature (°C)	Annual precipitation (mm)	Mean DBH[a] (cm)	Site index (m)	Number of trees	Mean DBH[a] (cm)	DBH standard deviation (cm)	Mean cambial age (years) (min–max)	Mean sampling height (m) (min–max)[b]
STA	67	139	9.3	743	49	28.6	13	50	5	84 (70–89)	1.3
ENG	99	253	9.8	771	53	28.1	9	68	11	99 (81–123)	9 (6–12)
FLO	99	260	9.2	749	53	30.0	11	67	7	95 (89–107)	1.3
TER	112	260	10.3	774	57	26.2	13	80	8	163 (153–169)	6 (1.3–10)
LES	171	142	9.4	820	58	28.5	15	65	7	127 (118–140)	1.3
TIH	225	163	9.8	827	41	24.5	13	71	7	105 (90–127)	1.3
HES	413	90	8.5	1024	41	19.3	10	62	8	131 (119–135)	1.3
POR	425	101	9.0	894	53	19.1	8	71	4	190 (153–209)	8 (4–12)
REC	458	124	8.2	994	39	20.5	12	64	6	178 (152–191)	1.3
MAR	478	105	8.0	999	38	19.3	11	70	5	206 (178–215)	6 (3–9)
SAI	521	111	8.4	971	38	20.9	10	49	8	123 (101–157)	1.3
ROC	590	98	7.2	1047	43	20.5	12	62	5	136 (111–156)	1.3

[a] DBH, diameter at breast height.
[b] Variations in sampling height were caused by technical constraints (see text).