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Influence of climate drivers and the North Atlantic Oscillation on beech growth at marginal sites across the Mediterranean

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ABSTRACT: European beech *Fagus sylvatica* L. represents one of the most commercially and ecologically important forest tree species in Europe. The study of climate–growth relationships may provide relevant information to assist projections of future species' distribution as well as forest management strategies. In this study, 9 European beech stands were selected at the rear edges of the species' distribution across an east–west gradient in the Mediterranean Basin (MB). Most of the tree-ring chronologies reached back more than a century; however we investigated the common period 1950–2012 in order to avoid past intensive management activities at some sites. The influences of temperature and precipitation on tree growth as well as their geographical patterns were investigated. Furthermore, the influence of the dominant atmospheric circulation pattern, the North Atlantic Oscillation (NAO), was also assessed. The results reveal that tree growth in stands located in the western MB are limited by the combined influences of summer temperature and precipitation while stands located in central and eastern MB are mainly limited by summer temperature and show consistent lag effects on growth. The dry conditions prevailing during positive phases of the winter NAO have exerted a significant negative influence at sites located in western and central MB for the last 6 decades. However, the significance of NAO influence has generally decreased from western to eastern MB during recent decades. The results also provide evidence for the existence of carry-over effects that may be essential for the persistence and survival of some of these marginal populations.

KEY WORDS: Mediterranean Basin · European beech · *Fagus sylvatica* · North Atlantic Oscillation · Tree rings · Summer drought

1. INTRODUCTION

The Mediterranean climate is a particular variety of the temperate climate characterized by a summer period of water deficit that covers the entire Mediterranean Basin (MB) (Kottek et al. 2006). During the past 2000 years, the Mediterranean region has experienced various humid/dry and warm/cold periods that largely influenced the prevailing environmental conditions such as the Medieval Climate Anomaly and the Little Ice Age (Colombaroli et al. 2007, Carrión et al. 2010). The Mediterranean climate is generally characterized by mild, wet winters and hot, dry summers. However, due to the complex effects of large-scale atmospheric circulation patterns, the influence of the Mediterranean Sea and orographic

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factors, sub-regional climate may vary substantially (Bolle 2003). In recent decades, changes in some climate phenomena such as El Niño–Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) may have contributed to the significant increase in the frequency of heat waves and drought episodes within the MB (Lionello et al. 2006). Climate model simulations point out the MB as one of the regions at risk of persistent droughts during the 21st century (Giorgi & Lionello 2008, Hartmann et al. 2013).

Among large-scale atmospheric circulation patterns, the NAO is the dominant mode of winter climate variability over the middle to high latitudes of the Northern Hemisphere (Hurrell et al. 2003). During the positive NAO phases, the subtropical high pressure is enforced leading to sunny and dry weather in the MB but mild and wet conditions in Northern Europe. In contrast, during negative NAO phases, cyclones move southward and precipitation increases in MB, while cold and dry conditions affect Northern Europe (Trigo et al. 2002, Visbeck et al. 2001). The NAO is considered one of the main forcings responsible for extreme climatic events in the MB such as droughts, floods and heat waves (Gallego et al. 2006, Della-Marta et al. 2007). Previous work showed a distinct effect of the NAO across the MB: the western Mediterranean regions are likely under a stronger effect of the winter NAO than the eastern regions (Serre-Bachet et al. 1992, Maheras et al. 1999). Furthermore, instrumental records of the NAO have shown a remarkable decadal variability. Luterbacher (2001) described persistent positive NAO phases during the first and last decades of the 20th century, while negative NAO phases prevailed during the mid-20th century. This decadal NAO variability coincides with periods of severe droughts and heat waves in the MB. Induced by the positive NAO phases, Western Europe has experienced an unprecedented rate of summer warming since 1976 (Della-Marta et al. 2007).

Tree-ring formation is directly influenced by temperature and precipitation as well as by the underlying forcing of atmospheric circulation patterns such as the NAO and the ENSO (Fritts 1976). The characteristic of tree-rings to encode the climate factors affecting tree growth turned them into one of the most widely used terrestrial archives in climate research. Numerous studies have shown how winter NAO variations exert significant influences on tree growth (e.g. D'Arrigo et al. 1993, Neuwirth & Winiger 2004, Linderholm et al. 2008, Schultz et al. 2008, Camarero 2011). On the other hand, the Summer North Atlantic Oscillation (SNAO; Linderholm et al. 2008) may also have considerable effects on tree growth. For instance, tree-ring chronologies from European beech in Italy responded mainly to summer precipitation; however, no significant influence of year-to-year winter NAO was found (Piovesan & Schirone 2000). Similarly Folland et al. (2009) also described significant correlations between tree growth of various species and the SNAO in northern Great Britain, and central and northern Norway.

Analysis of the influence of NAO variations on tree growth along an east–west gradient across the MB has not yet been discussed, although it would be important for understanding the NAO influence on tree growth as well as potential further impacts on the persistence and survival of forests.

In this study, 9 European beech stands growing under dry to xeric conditions at the rear edge of the species' natural distribution were selected in Spain, Italy and Bulgaria across an east–west gradient in the MB. The objectives of the study are (1) to identify and analyze the climate drivers that influence tree growth along the spatial gradient; and (2) to evaluate the spatio-temporal patterns of the climate–growth relationship and the NAO influence on tree growth across the MB and southeastern Europe.

2. MATERIALS AND METHODS

2.1. Study area

A sample of 9 European beech *Fagus sylvatica* L. marginal stands were taken in 3 countries across the MB (Table 1). The stands were selected at the dry and warm (rear) edges of the natural species distribution in order to cover an east–west gradient across the MB and southeastern Europe. Some of the selected sites have been intensively managed for commercial purposes in the past. However, most of these forests are now in protected areas, and logging has been abolished or tightly restricted for the last decades. No sign of intensive logging activities was observed at the study sites during the field campaign. The stands are located from 3.49° W to 27.26° E longitude covering a range from coastal Mediterranean to continental-like climates. The latitudinal variation is small, with all sites located between 40.76 and 43.89° N. Stands from Hayedo de Montejo (Sp1) and Hayedo de Tejera Negra Nature Reserve (Sp2) are located in the center of the Iberian Peninsula (Spain). The National Park Els Ports (Sp3) and Montseny (Sp4) are located in the northeast of

Table 1. Geographical characteristics of each sampling stand, number of trees and cores per chronology, time span, mean inter-tree correlation (rbar), first order autocorrelation (AC), and soil type information among individual tree-ring series. AC was significant at $p < 0.05$

Stand name	ID	Latitude	Longitude	N (tree/cores)	Time span	rbar	AC	Soil type
Montejo	Sp1	41.11° N	3.49° W	16/30	1750–2012	0.69	0.725	Humic cambisol
Tejera Negra	Sp2	41.24° N	3.38° W	20/34	1874–2012	0.58	0.738	Humic cambisol
Els Ports	Sp3	40.76° N	0.29° E	17/30	1844–2012	0.71	0.744	N/A
Montseny	Sp4	41.76° N	2.46° E	19/29	1919–2012	0.65	0.649	Cambic leptosol
Pietraporciana	It1	43.01° N	11.81° E	20/39	1865–2012	0.64	0.678	Cambisol
Rosello	It2	41.86° N	14.38° E	20/40	1860–2012	0.66	0.658	Rendzic leptosol
Gargano	It3	41.82° N	16.01° E	19/38	1852–2012	0.63	0.653	Humic cambisol
Vidin	Bu1	43.89° N	22.73° E	19/38	1870–2012	0.71	0.710	Rendzic leptosol
Nikola Kozlevo	Bu2	43.56° N	27.26° E	19/38	1890–2012	0.74	0.558	Leptosol

the Iberian Peninsula facing the Mediterranean Sea. In Italy 3 sites were sampled: Pietraporciana Natural Reserve (It1) at the southeast border of Tuscany; Regional Reserve Abetina di Rosello (It2), near the northern limit of the Molise region and National Park Gargano (It3) in Apulia facing the Adriatic Sea. In Bulgaria there were 2 stands: Vidin (Bu1) in the northwest adjacent to the border with Romania and Serbia; and Nikola Kozlevo (Bu2) in the northeast, which is close to steppe ecosystems and not far from the Black Sea (80 km).

WorldClim data, i.e. mean monthly climate values, corrected for altitude, in high spatial resolution (1 km), were used for the period 1950–2000 for local site descriptions (nearest grid cell) (Hijmans et al. 2005). The annual mean precipitation is lowest in the eastern MB (607 and 589 mm yr^{-1} at Bu1 and Bu2, respectively) in agreement with Aleksandrov (2011) (Fig. 1). In the central and western MB precipitation ranges from 633 mm yr^{-1} in It3 to 978 mm yr^{-1} in Sp4, in agreement with Gil et al. (2010) and Piovesan et al. (2005a). Overall, Bu2 is the driest site and Sp4 the rainiest.

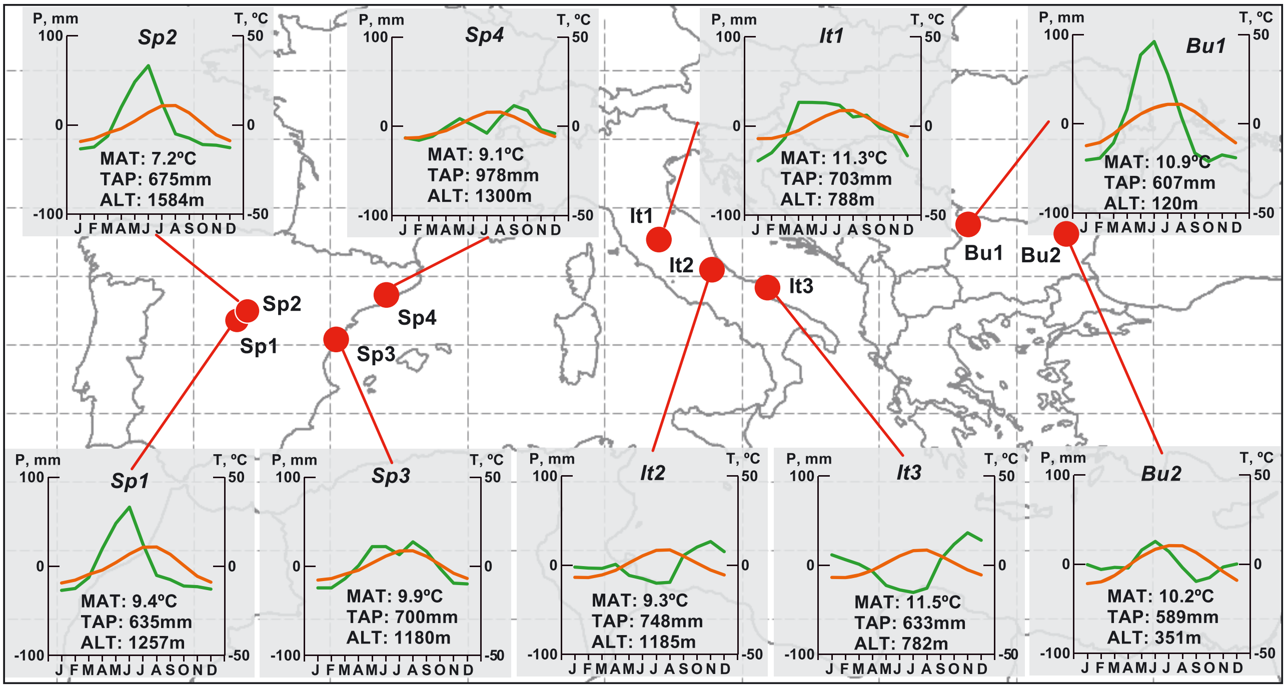

Fig. 1. Sampling sites and the corresponding climatograms of temperature (orange lines) and precipitation (green lines) anomalies based on NCEP/NCAR monthly data from the corresponding 2.5° grid-cell for each study site. The corresponding WorldClim based mean annual temperature (MAT), total annual precipitation (TAP), and elevation of the sampling site (ALT) are provided

Annual mean temperature is generally higher at stands located in Italy (e.g. 11.3 and 11.5°C at It1 and It3, respectively) than in the eastern and western MB. Sp2 on the Iberian Peninsula shows the lowest annual mean temperature (7.2°C), while the adjacent site Sp1 and the 2 coastal stands (Sp3 and Sp4) display higher values despite similar altitude (between 9.1 and 9.9°C). Annual mean temperatures of 10.9 and 10.2°C are reported for stands in the eastern MB (Bu1 and Bu2, respectively). Thus, Sp2 is the coldest stand and It3 is the warmest among all the sampling sites.

According to the anomalies shown in the climatograms (Fig. 1), during the summer months (June, July and August) Sp4, It2, and It3 display recurring droughts; Sp1, Sp2, and Bu2 are prone to sporadic droughts; and It1, Sp3 and Bu1 do not show signs of summer drought.

2.2. Sampling and measurements

Sampling was carried out during spring and summer of 2013. At each site, 2 cores per tree were taken at breast height from 20 adult trees using increment borers. Cores were air-dried and polished using sandpaper of increasing grit size up to 1000. Subsequently, samples were visually crossdated under a stereomicroscope following procedures described in Stokes & Smiley (1996). Tree-ring widths (TRW) were measured with 0.01 mm precision using tree-ring measuring system (LINTAB 6) and software (TSAP-Win, Rinntech). The visually crossdated measurements were checked for possible errors with the computer program COFECHA (Holmes 1983) to ensure that the original dating and measurements were correct.

Each single TRW series underwent a statistical treatment to build the final site chronologies using ARSTAN software (Cook & Krusic 2005). We applied the negative exponential curve to remove the biological age trend from individual series and to preserve as much low frequency climatic information as possible. The Keith-Briffa rbar-weighted method (Briffa et al. 2002) was then applied to homogenize the variance along the series, and the bi-weight robust mean estimation was used to calculate the final mean TRW chronologies. From the ARSTAN output, the standard chronology was taken for further analysis. The Expressed Population Signal (EPS) was used to assess the reliability of the final chronology (Wigley et al. 1987). A minimum value for EPS of 0.85 was considered an acceptable level of reliability.

2.3. Climate and NAO data

The reanalysis dataset developed by the National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR; Kalnay et al. 1996) was used as input data. The NCEP/NCAR dataset comprises layers of climatic data with a grid cell resolution ranging from 0.5° to 1° and starts in 1948. The meteorological variables precipitation and temperature were extracted from the 2 m layer of a 2.5° × 2.5° grid cell around each of the sampled sites for the common period 1950–2012.

Reanalysis products are not only instrumental data but include forecast models and data assimilation (Kalnay et al. 1996). The advantage of using this kind of dataset is the consistent spatial and temporal resolution in all variables derived from the same reanalysis product.

Monthly and seasonal NAO indices were extracted from the NOAA/National Weather Service for the period 1950–2012.

2.4. Statistical analyses

In order to avoid the period of intensive management activities in some sites in the first half of the 20th century, the common period 1950–2012 was used for further analysis. Statistical analyses were performed using R-3.1.2 (R Development Core Team 2013).

With the application of R package ‘vegan’ (Oksanen et al. 2013), principal component analysis (PCA) was applied to assess the common variance among individual chronologies. The results were used to analyze the potential links to synoptic drivers underlying the common climatic patterns at the different sites. For that purpose, the scores of the first and second principal component (PC1 and PC2, respectively) were correlated with the 850 mb fields of geopotential height (GH; a gravity-adjusted height referenced to Earth’s mean sea level) and temperature derived from the NCEP/NCAR for the period 1950–2012.

By using R package ‘stats’ (R Development Core Team 2013), Pearson correlation analysis was performed at monthly and seasonal scales in order to establish the influence of temperature and precipitation from June of the previous year to December of the current year of tree growth. The significance of the correlations was assessed according to the effective degrees of freedom of each series. Only significant correlations at the $p < 0.05$ significance level are presented.

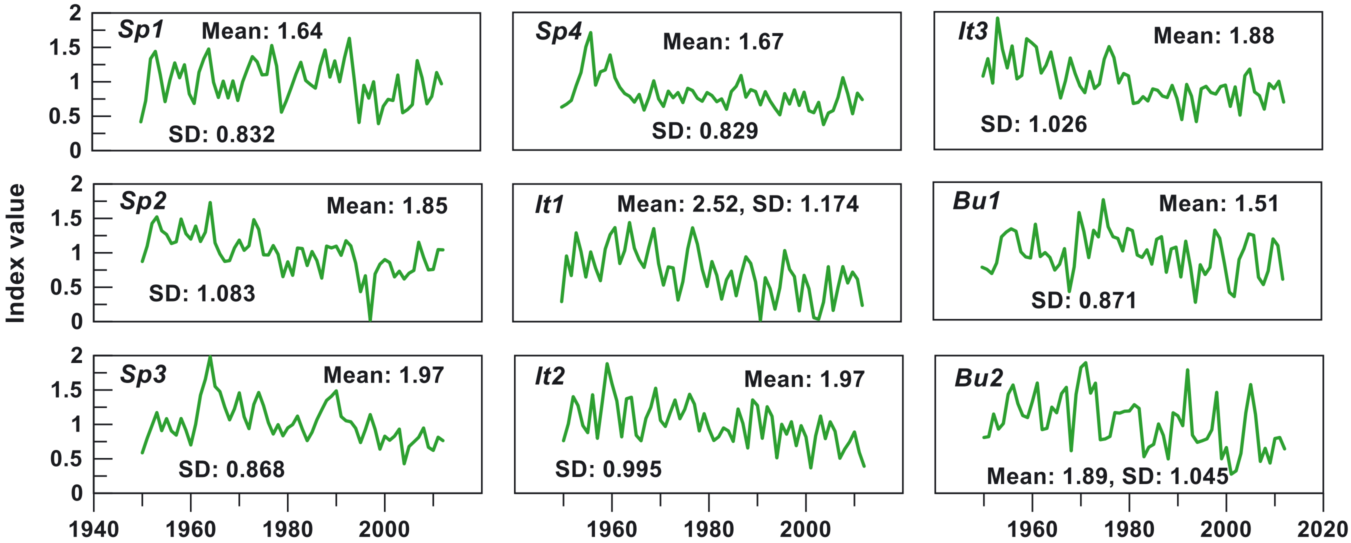

Fig. 2. European beech tree-ring width (TRW) chronologies for the common period 1950–2012. Mean and SD of each chronology are shown. Iberian Peninsula (Sp), Italy (It) and Bulgaria (Bu)

Similarly, the tree-ring chronology of each site was correlated with the monthly and seasonal NAO indices to test the degree of linear relation between variations in tree growth and positive/negative NAO phases. Since the focus lies on extreme climate/NAO events, each standard chronology as well as the NAO indices underwent a 10 yr high-pass filtering using a centered moving average in order to remove the low frequency variations

Significant correlations ($p < 0.05$) were further tested for 2 periods: 1950–1980 and 1981–2012 in order to assess the stability of the NAO signal. In case of sites displaying only non-significant correlations, a defined NAO season from November of the previous year to February of the current year ($NAO_{11\text{-}02}$ hereafter) was chosen.

3. RESULTS

3.1. Tree-ring width chronologies and PCA

All chronologies displayed EPS > 0.85 for the common period used for further analysis (1950–2012). According to Table 1, trees in Sp1 are the oldest and provide the longest TRW chronologies spanning back to 1750, and Sp4 is the youngest stand. The mean correlation among samples (rbar) is similar at all sites ranging from 0.58 (Sp2) to 0.74 (Bu2). All chronologies display a significant first level autocorrelation, and missing rings were scarce within a single stand and across the different sites.

Growth of European beech differs across sites (Fig. 2). It1 displays the highest mean ± SD growth index (2.52 ± 1.17), and Bu1 the lowest (1.51 ± 0.87). Sp4 displays a marked reduction in growth variability since the mid-60s. Sp2, It1, It2 and It3 show declining trends for several decades, while sites such as Sp3 and Bu1 decline only during the most recent decades. Correlations among the TRW chronologies reveal increasing similarity with geographical proximity (Table 2). However, the table also reveals significant correlations between far-distant sites such as Sp4 with It1, and It2 and Bu1 with It2 and It3.

The PCA reveals that PC1 and PC2 account for 25.2 and 22.0%, respectively, and altogether explain almost half (47.2%) of the variance shared by all

Table 2. Correlation among the tree-ring chronologies from stands in the Iberian Peninsula (Sp), Italy (It) and Bulgaria (Bu). Significant correlations at $p < 0.05$ **in bold**

	Sp1	Sp2	Sp3	Sp4	It1	It2	It3	Bu1
Sp2	**0.571**							
Sp3	**0.456**	**0.369**						
Sp4	0.041	0.037	0.080					
It1	0.160	−0.010	0.053	**0.297**				
It2	0.070	0.0170	−0.056	0.169	**0.263**			
It3	−0.032	−0.012	−0.135	**0.245**	**0.561**	**0.538**		
Bu1	−0.130	−0.037	0.092	0.127	0.046	**0.222**	**0.248**	
Bu2	−0.136	−0.010	−0.038	0.093	0.117	0.153	0.039	**0.609**

chronologies. The chronologies from Sp1, Sp2 and Sp3 do not significantly correlate with PC1, while Sp4, It1, It2, It3, Bu1 and Bu2 display a significant positive correlation. In contrast, Sp1, Sp2 and Sp3 present high positive correlation values with PC2, while Sp4, It1, It2, It3, Bu1 and Bu2 exhibit either non-significant or negative correlation values (Fig. 3). Thus, with the only exception of Sp4, PC1 marks a distinction between chronologies from western MB, and those from central and eastern MB; furthermore, PC2 differentiates western, central and eastern Mediterranean sites.

3.2. Climate–growth relationships

With respect to temperature impact in current year, summer temperature exerts a general negative impact on beech growth (Fig. 4). High negative correlations mostly occur with late spring and summer monthly temperatures at all sites. Additionally, some stands also show negative effects of autumn temperatures on tree growth. Sp1, Sp2, Sp4 and It2 display significant negative correlations with October temperature (r = −0.339 to −0.268), while Bu2 shows the same negative effect of September temperatures on tree growth (−0.278).

Seasonal summer temperatures usually exert a higher impact on tree growth than any other of the individual months. Sp1, Sp2, Sp3, Sp4 and Bu2 chronologies are negatively correlated (−0.526 to −0.281) with June–July temperature. Similarly, It1, It2 and It3 display high negative correlations with the June–August season (−0.598 to −0.508), while Bu1 shows the most negative correlation with May–July temperatures (−0.458). Other seasonal mean temperatures, such as those of winter and spring, display mainly non-significant correlations with TRW.

Regarding the influence of current year precipitation on tree growth, rainfall usually exerts a positive effect, except for It2 and It3 that do not show any significant correlation with current year precipitation. Significant positive correlations were found for Sp4 and It1 with late winter precipitation (r = 0.288 and 0.312, respectively), Sp3 with summer precipitation (0.317), and Sp1, Sp2, Bu1 and Bu2 with spring to summer precipitation (0.300 to 0.500).

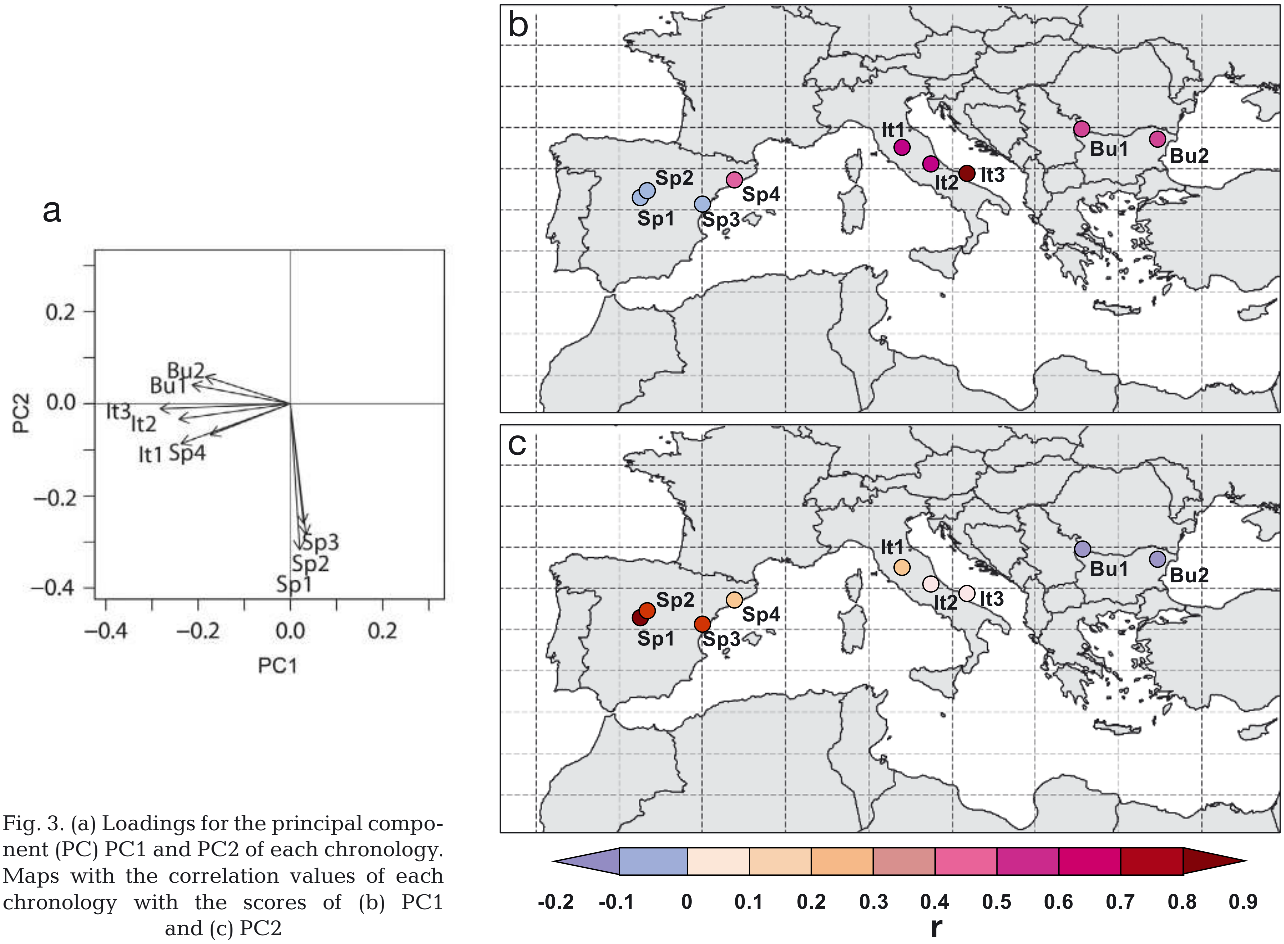

Fig. 3. (a) Loadings for the principal component (PC) PC1 and PC2 of each chronology. Maps with the correlation values of each chronology with the scores of (b) PC1 and (c) PC2

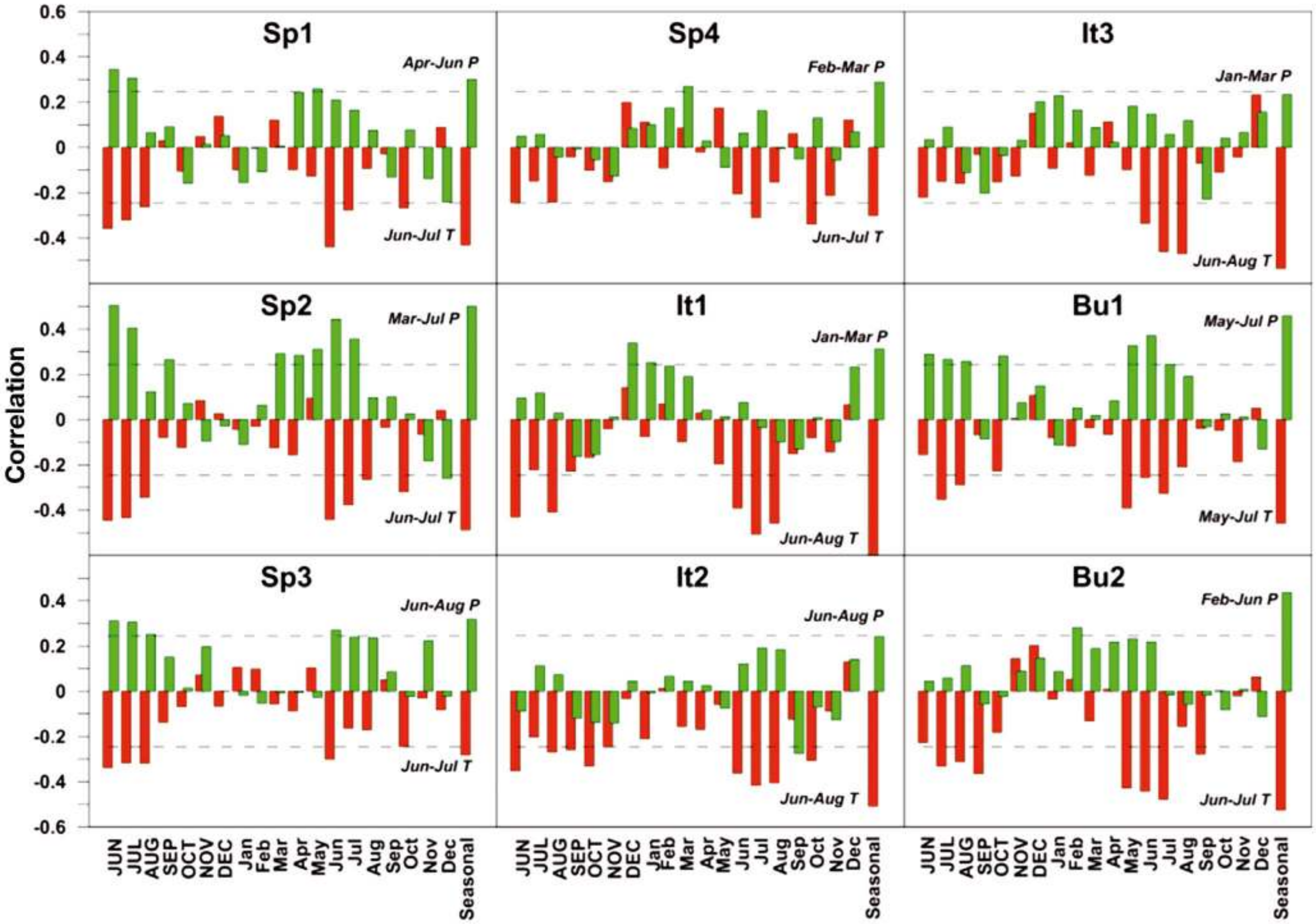

Fig. 4. Monthly correlation coefficients of each chronology (with the corresponding temperature and precipitation data from June of the previous year (uppercase) to December of the current year (lowercase). Bars = correlations with mean monthly temperature (red) and total monthly precipitation (green). Dashed lines = $p < 0.05$ significance level. Significant seasonal correlations are shown at the right of the corresponding bar graph indicating month and variable: precipitation (P), temperature (T). Iberian Peninsula (Sp), Italy (It) and Bulgaria (Bu)

With respect to the influence of previous year climate on current year growth, the correlation coefficients between tree growth and climate show similar signals with previous summer temperature (negative) and precipitation (positive). Out of the 9 sites considered in the present study, It3 is the only site not influenced by previous year summer temperatures. In addition to the negative correlation with previous year summer temperature, Sp1, Sp2, Sp3 and Bu1 also display significant correlations with previous summer precipitation ($r = 0.288$ to 0.50). It1 and Bu1 also show significant positive correlation with precipitation in previous December and October (0.338 and 0.281), respectively.

The correlation of PC1 and PC2 with the fields of GH evidences the synoptic patterns underlying differences in climate sensitivity among the different sites (Fig. 5). The correlations of the PC1 with the 850 mb GH and temperature fields reveal that higher (lower) GH over the MB exert a negative (positive) impact on tree growth from central and eastern MB. The spatial pattern of correlations of PC2 with GH and temperature describes the negative influence of previous year summer conditions on current year growth. High pressure over the Iberian Peninsula during June to September of the year prior to tree growth negatively affects next year's tree growth at the western and central MB.

3.3. Influence of NAO

Sp1 and Sp2 display significant positive correlations with NAO in late winter (February) and late spring (May) of previous year (Table 3). Sp2 also shows a significant negative correlation with NAO in June to July ($NAO_{06\text{-}07(p)}$) from the previous year which is higher than that for the seasonal February to

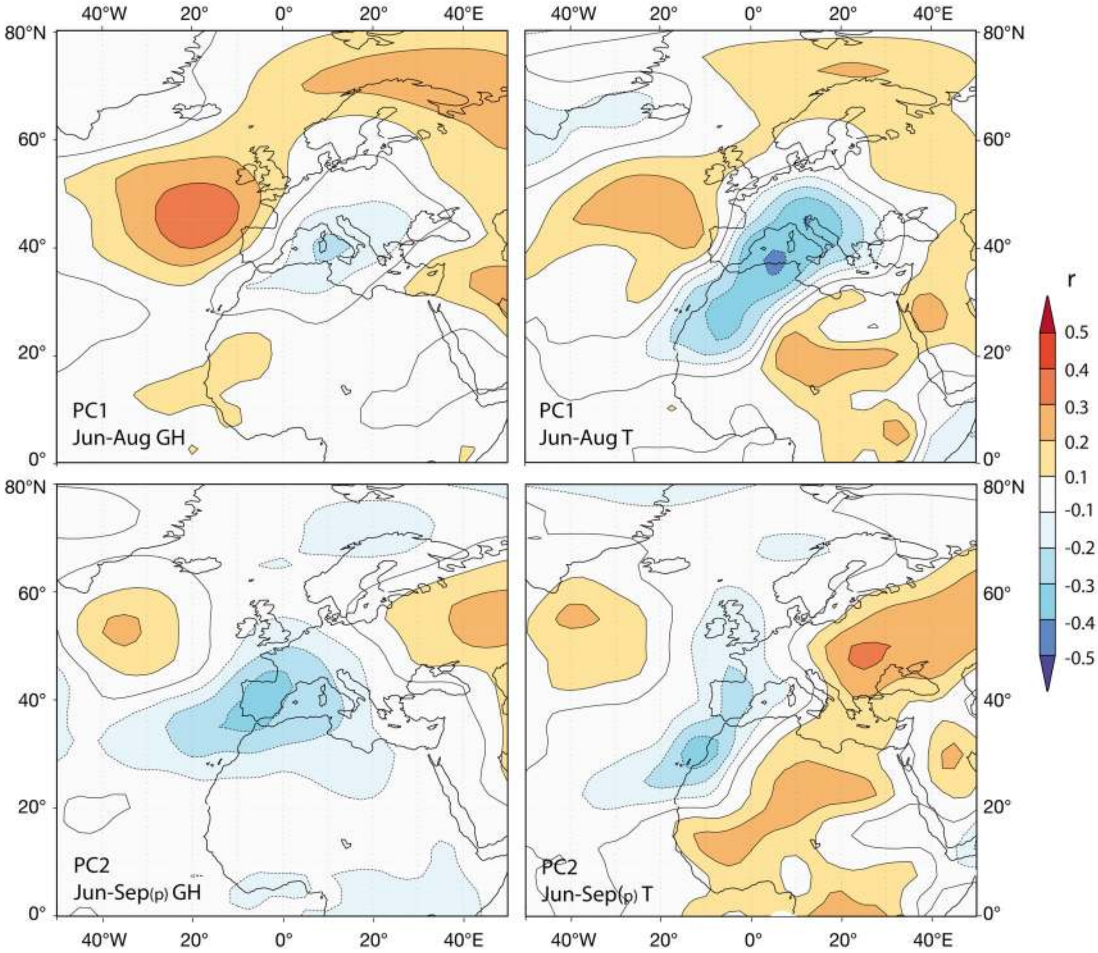

Fig. 5. Field correlations of the principal component (PC) PC1 (upper panel) and PC2 (lower panel) and the seasonal 850 mb NCEP-NCAR fields of geopotential height (GH; left panels) and temperature (T; right panels). The season is displayed at the bottom-left of each panel. (p) = previous year

Table 3. Significant ($p < 0.05$, **bold**: $p < 0.01$) Pearson's correlations between monthly and seasonal NAO and average chronology of each site (for 1950–2012). Seasonal NAO: subscript numbers indicate the months included; (p) = previous year, (c) = current year. Significant values at $p < 0.01$ are **in bold**. Non-significant values are not shown

Stand	Feb (p)	May (p)	Jun (p)	Nov (p)	Dec (p)	Jan (c)	May (c)	Sep (c)	Seasonal NAO	
Sp1	**0.361**	**0.328**							NAO_{02-05}(p)	**0.347**
Sp2	**0.336**	**0.332**	−0.297						NAO_{06-07}(p)	**−0.319**
Sp3				**−0.330**					NAO_{11-12}(p)	**−0.350**
Sp4						−0.280	**0.332**		NAO_{01-02}(c)	**−0.353**
It1					−0.311				NAO_{11-02}(p+c)	**−0.359**
It2								**0.319**		
It3										
Bu1					−0.285					
Bu2									NAO_{10-11}(p)	−0.294

May NAO ($NAO_{02-05(p)}$). Sp3, Sp4 and It1 display common significant negative correlations with the winter NAO preceding the growing season. Concretely, the significant negative correlation is November–December of the previous year for Sp3 ($NAO_{11-12(p)}$), January–February of the current year for Sp4 ($NAO_{01-02(c)}$) and from previous November to current February ($NAO_{11-02(p+c)}$) for It1.

Sp4 also displays a significant positive correlation with NAO in current May, while It2 shows a significant positive correlation with NAO during September of the current year. Bu1 shows a significant negative effect of late autumn NAO of previous year ($NAO_{10\text{-}11(p)}$). It3 and Bu2 only show non-significant correlation coefficients that will not be considered in the present study.

The negative influence of $NAO_{06\text{-}07(p)}$ on tree growth at Sp2 increased during the period 1981–2012 (Fig. 6). In contrast, the influence of winter NAO on Sp3 and It1 and the previous year autumn NAO on Bu1 decreased. Only the influence of winter NAO on tree growth at Sp4 remained constant and significant.

Regarding the changes on the influence of winter NAO at the other sites, no significant influence of $NAO_{11\text{-}02}$ was found for the period 1950–1980 for Sp1, Sp2, It2, It3, Bu1 and Bu2, and the influence remained non-significant during the last 3 decades (1981–2012).

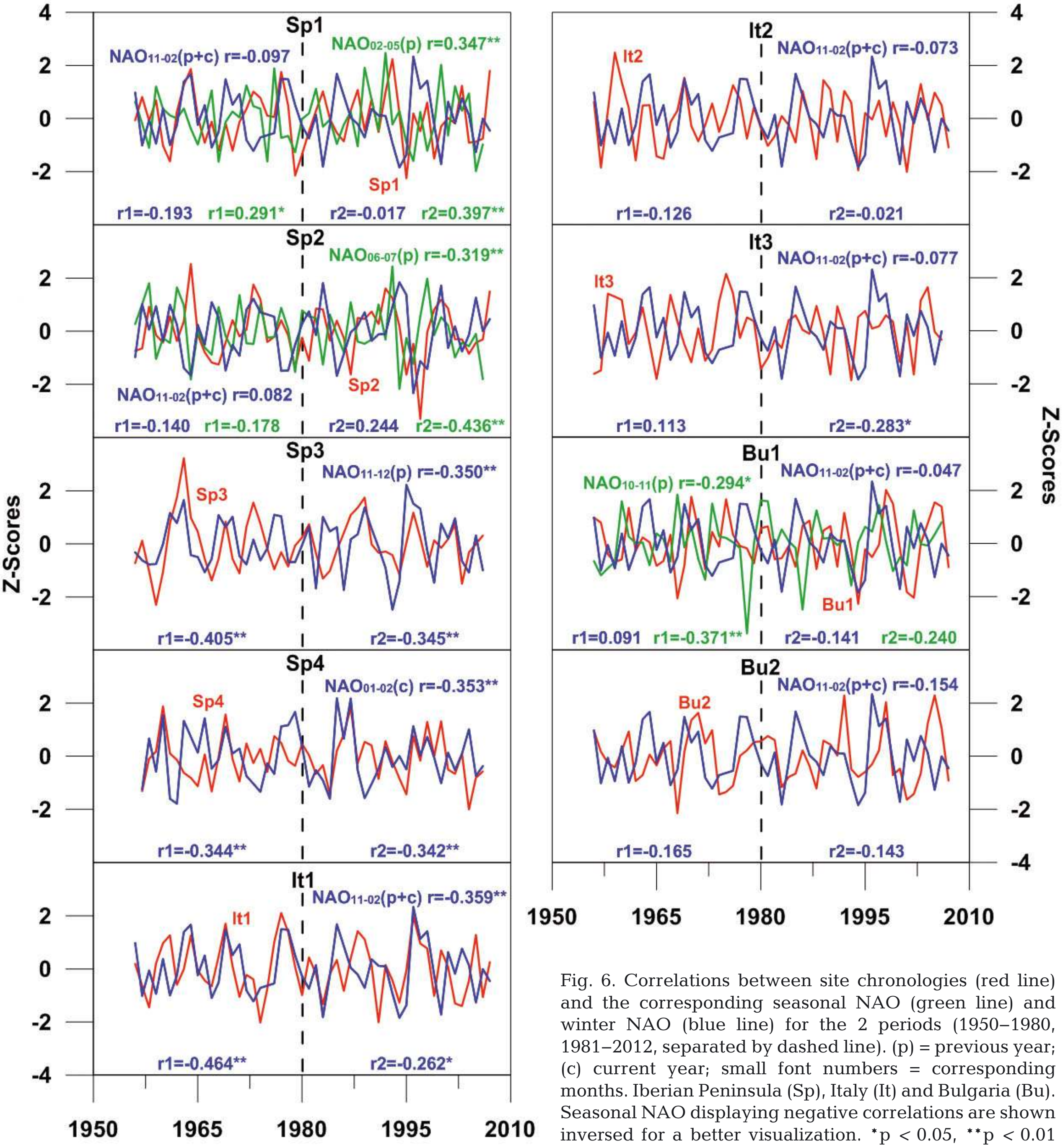

Fig. 6. Correlations between site chronologies (red line) and the corresponding seasonal NAO (green line) and winter NAO (blue line) for the 2 periods (1950–1980, 1981–2012, separated by dashed line). (p) = previous year; (c) current year; small font numbers = corresponding months. Iberian Peninsula (Sp), Italy (It) and Bulgaria (Bu). Seasonal NAO displaying negative correlations are shown inversed for a better visualization. $^*p < 0.05$, $^{**}p < 0.01$

4. DISCUSSION

4.1. Climatic influences on beech growth

As shown in Fig. 4, all study sites display significant negative correlations with high summer temperature of the current year indicating that high summer temperatures may negatively affect tree-ring formation during the growing season. Similar negative impacts of summer temperature during the growing season were also described for other marginal beech stands in Spain (Gutierrez 1988), in the Mediterranean Alps in France (Lebourgeois et al. 2005), and for beech forests located in the Italian pre-Alps (Piutti & Cescatti 1997). Furthermore, high summer temperature and drought have been shown to significantly negatively influence growth of European beech trees in the north of the Iberian Peninsula (Rozas et al. 2015) and the central Apennines (Biondi 1993, Piovesan & Schirone 2000, Piovesan et al. 2005b, 2008). However, these studies together with our results are in contrast with the positive influence of summer temperature on beech growth at non-marginal stands on the Balkan Peninsula recently reported by Tegel et al. (2014). Such a contrast may be explained by the different temperature signals that can be found between low (negative) and high elevation (positive) beech sites (Piovesan et al. 2005a, Di Filippo et al. 2007) that directly relate to the level of marginality. In the present study, the significant negative effect of summer temperature on tree growth is common to all chronologies irrespective of the elevation, pointing to a correct selection of marginal sites at the rear edges of the species distribution. High temperatures, especially during summer, could greatly increase the water vapor pressure deficit (VPD). European beech shows a high stomatal sensitivity to VPD even under moist soil conditions, which could cause stomatal closure in order to avoid water loss (Aranda et al. 2000, Lendzion & Leuschner 2008). Closing stomata during summer reduces carbon assimilation and growth, and enhances the lag effects on tree growth (Bréda et al. 2006), which can imply negative consequences for tree performance including tree decline and eventually death from carbon starvation (McDowell 2011).

The determinant role of temperature in increasing evapotranspiration and severity of summer drought (Rebetez et al. 2006) has been described for beech forests in the MB (Aranda et al. 2000, Jump et al. 2006, Piovesan et al. 2008) and is expected to play a more prominent role for forest growth and tree mortality in the future (Park Williams et al. 2013). Kostopoulou & Jones (2005) described significant warm conditions and increases in the Heatwave Duration Index (HWDI) over the Mediterranean region during the period 1958–2000. In addition, the MB also experienced a negative trend of precipitation during the last decades pointing to a drying period (Giorgi & Lionello 2008). Thus, increasing negative effects of summer temperature on beech growth at its warm and dry limits in the MB are expected. Although all study sites show a negative summer temperature signal, some differences in the response to climate can be disentangled within the study sites. Summer precipitation has significant positive effects on tree growth at the western Mediterranean sites Sp1, Sp2 and Sp3. Such a positive influence of precipitation is due to the fact that summer precipitation may reduce the water stress induced by higher temperatures on beech stands growing in Mediterranean climate (Biondi 1993, Dittmar et al. 2003, Augustaitis et al. 2012). Furthermore, the combined influences of temperature (negative) and precipitation (positive) of the previous year at Sp1, Sp2 and Sp3 are highly significant ($p < 0.01$). This evidences a prominent lag effect in which growth during the previous growing season determines the carbohydrate reserves available for leaf growth and development during the next growing season (Scartazza et al. 2013).

Despite differences in altitude and continentality among our sites, we could identify geographical patterns that seem to be linked to climate responses. The PCA (Fig. 3) reveals common influencing factors on tree growth at Sp1, Sp2 and Sp3, while Sp4, It1, It2, It3, Bu1 and Bu2 show a distinct pattern of influences. This is in accordance with the correlation pattern among chronologies. The fact that Sp4 and other sites in central Italy are located at a similar altitude to Sp1, Sp2 and Sp3 and show different correlations to PC1, excludes altitude as a factor driving the observed pattern. Based on the correlation with the GH and temperature fields, PC1 describes a distinct east–west dipole of climatic influences that seems to be related to the single effect of current year summer temperature on tree growth in central and eastern MB. In contrast, Sp1, Sp2 and Sp3 are affected by the combined effects of both current and previous year summer temperatures and precipitation which is further supported by the correlation of the PC2 with the previous summer GH and temperature fields. This distinct east–west dipole also seems to be related to the previous year June to September conditions that will determine next year growth, underlining once more the importance of the lag effect for survival and growth of the western MB forests.

The described spatial patterns of correlation with PCs, especially with PC1 are in line with the results of Seim et al. (2014), who provided supportive evidence of a distinct Mediterranean east–west dipole in climate sensitivity of mountain pine chronologies. According to their results, the climate responses of the western Mediterranean sites are generally weaker than the eastern Mediterranean sites on both spatial and temporal scales. The eastern Mediterranean sites showed significant negative (positive) correlation with summer temperatures (precipitation) of the previous as well as the current year, while the correlations of the western chronologies with precipitation and temperature were rarely significant. Our results also provide evidence of a distinct east–west pattern of European beech sensitivity to temperature and precipitation effects, though the pattern of influence is different to that described for pine in Seim et al. (2014), maybe due to the markedly different physiological characteristics and strategies of the species used in each study. The dipole described by Seim et al. (2014) and this study is consistent with the eastern–western differences in climate described by Xoplaki et al. (2003).

4.2. NAO-tree growth links

The significant positive influence of previous year $NAO_{02\text{-}05(p)}$ in Sp1 and Sp2 and $NAO_{10\text{-}11(p)}$ in Bu1 (Table 3) could evidence the positive effect of an extended growing season on the carbon reserves available for next year growth (Simard et al. 2013). Carbon reserves are determinant for tree growth at Sp1, Sp2, and Bu1, as shown by the strong lag effects. Furthermore, Sp4 and It2 display a positive correlation with $NAO_{05\text{-}09(c)}$, which may further indicate that positive NAO phases may extend the warm temperatures in spring and autumn and prolong the growing season.

Although NAO is expected to have a lower impact on central Spain during summer season, the increase of the influence of previous year SNAO on tree growth at Sp2 supports the hypothesis of the link between SNAO and the increase in droughts and heat waves described by several authors (Herrera et al. 2001, Gallego et al. 2006, Della-Marta et al. 2007). However, no significant influence was detected in Sp1.

Regarding the winter NAO, 3 sites (Sp3, Sp4 and It1) display significant negative correlations for the last 6 decades with the NAO preceding the growing season. Similarly, winter NAO phases in recent years were described as negatively associated with tree growth in Southern Europe (Piovesan & Schirone 2000). Campelo et al. (2009) found that winter NAO negatively affects tree growth of *Quercus ilex* L. in a coastal population in central Portugal. Roig et al. (2009) analysed *Castanea sativa* M. and *Q. pyrenaica* W. populations close to their upper-altitudinal limit in central-western Spain, and the growth of both tree species was negatively influenced by winter NAO variability. Thus, high NAO indices of previous winter are linked to the reduction of precipitation and water availability; this impact could negatively influence the recharge of soil moisture and result in a low radial growth during the following growing season (Osborn 2011).

Although winter NAO shows negative impacts in sites across the MB, the influences are not identical. In western MB, significant winter NAO negative impacts were observed at Sp3 and Sp4. However, in the central and eastern MB, only It1 showed significant correlations with winter NAO, but not at the other 2 sites located in the Italian peninsula (It2 and It3). Esper et al. (2014) described a clear distinction between Atlantic and Mediterranean synoptic drivers of juniper tree growth on the Iberian Peninsula. Similarly, Piraino & Roig-Juñent (2014) described significant influences of winter NAO in pine stands located in the central north of the Italian peninsula, such as It1, but not in central-southern coastal region of Italy, such as It2 and It3. Furthermore, Piovesan & Schirone (2000) described a weak correlation between winter NAO and beech growth in the central Apennines. Kahya (2011) reported that NAO has the influences on interannual to decadal variations of main climate and hydrological variables towards the eastern Mediterranean regions. However, the effects for these regions differed from one location to another. For instance, NAO signals were quite identifiable in various hydrologic variables in Turkey while fewer signals were detected in the areas of Iran, Kuwait, Oman and Israel (Türkeş 1996).

Overall, from western to eastern and northern to southern MB, the significance of the NAO effect generally decreases. The result is also in line with the studies of Serre-Bachet et al. (1992) and Maheras et al. (1999) reporting that the western MB region is likely to be more affected by winter NAO than the eastern part. However, the persistent positive NAO phases described since the 1980s and the associated increase in summer warming (Luterbacher 2001, Hurrell et al. 2003, Della-Marta et al. 2007, Hoerling et al. 2012) do not seem to have increased the influence of NAO in eastern MB. In contrast, the only site in central Italy (It1) that showed sensitivity to winter

NAO has experienced a significant reduction of such sensitivity during the last 3 decades. Thus, the influence of winter NAO on tree growth in central Europe seems to be decreasing despite the persistence of positive NAO phases described during the last decades.

5. CONCLUSIONS

High summer temperatures are the main limiting factors on European beech growth across the MB, likely by inducing high evapotranspirative demands. Several sites also display high correlations with summer precipitation indicating that rainfall may alleviate the water stress induced by higher temperatures.

The spatial pattern of correlations with summer precipitation and temperature clearly marks differences between central-eastern and western regions of the MB. Beech forests located at the western MB are limited by both summer precipitation and temperature from previous and current year. On the other hand, beech forests located at central and eastern MB are affected mostly by the single effect of summer temperature in both previous and current year of growth. In addition, most of the study sites showed significant influences of previous year climate on current year growth, which shows the existence of essential carry-over effects. These effects were especially relevant for the western populations, and could be determinant for tree survival in future climate scenarios.

The described increase in positive winter NAO phases do not seem to affect beech forests across the MB. Indeed, its influence has decreased during the last decades in the central MB.

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