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## North Atlantic Oscillation influences on radial growth of *Pinus pinea* on the Italian mid-Tyrrhenian coast

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### Abstract

The North Atlantic Oscillation (NAO) is the most important source of winter atmospheric variability in the northern hemisphere. NAO inversely reflects the precipitation regime, which plays a fundamental role in Mediterranean regions, e.g., by recharging the water table. As no attempt has been made thus far to analyze the relationship between NAO variability and tree radial growth in coastal Mediterranean conifers, this paper identifies the monthly, winter, annual, and decadal influence of NAO on tree-ring chronologies of six planted *Pinus pinea* L. populations distributed along the Tyrrhenian coasts of central Italy. Through multidimensional analyses, we identified tree-ring chronology associations in two main groups. The influence of NAO on the regional chronologies was identified with correlation functions for the comparison period between 1949 and 2003 at both annual and decadal timescales. Results indicate that winter NAO influence on radial tree growth at annual and decadal timescales may depend on geographical location, site characteristics, and the age structure of tree-ring chronologies. These results contribute to a better understanding of the *P. pinea* coastal forest ecology and provide evidence of large-scale climatic forcings that influence forest Mediterranean ecosystems.

**Keywords:** Dendroclimatology, high-frequency and low-frequency variability, Mediterranean coastal forest, tree-ring width, winter NAO

### Introduction

The North Atlantic Oscillation (NAO) represents the main cause of boreal winter atmospheric variability over the North Atlantic (van Loon & Rogers 1978; Hurrell 1995a; Hurrell & van Loon 1997). The NAO is associated with changes in surface westerlies across the Atlantic into Europe, and it refers to a meridional oscillation in atmospheric mass, with centers of action near the Icelandic low and the Azores high (van Loon & Rogers 1978; Hurrell & van Loon 1997). Although its effect is evident throughout the year, winter activity is dominant in total annual precipitation and variability at intra-seasonal to inter-decadal timescales (Hurrell 1995a; Hurrell & Van Loon 1997; Jones et al. 1997). Thus, during winters with a high NAO index, storm tracks shift much farther into northern Europe, with subsequent drier conditions across the Mediterra-

nean area (Hurrell 1995a; Mann et al. 2001). The link between Mediterranean Sea level variability and NAO, due to the effects of atmospheric pressure anomalies and changes in evaporation and precipitation, further supports the conclusion that the Mediterranean area is under the influence of NAO variability (Tsimplis & Josey 2001).

The Mediterranean region has been defined as a climate change hotspot, where climatic shifts have already taken place, such as increases in daily temperature and decreases in monthly precipitations (Brunetti et al. 2006; Giorgi 2006; Toreti & Desiato 2008). The future variability of the surface climate will be in part influenced by an increase in the frequency of anticyclone conditions associated with a decrease in both the frequency and the intensity of Mediterranean cyclones (Giorgi & Lionello 2008; Lionello et al. 2008; Pasho et al. 2011).

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The increasing attention paid to both global change and its ecological consequences suggests additional reasons for analyzing the effect of NAO influence on Mediterranean ecosystem functioning. The anomalous behavior of NAO during the twentieth century may depend on multi-decadal climate variability, probably linked to global warming and greenhouse gas forcing (Rogers 1984; Schlesinger & Ramankutty 1994; Hurrell & van Loon 1997; Cook et al. 1998; Paeth et al. 1999; Shindell et al. 1999; Ulbrich & Christoph 1999; Hurrell et al. 2001).

Although it has been suggested that forests located south of 53°N latitude do not show clear signals of the NAO effects (Cook et al. 1998), relationships between NAO and tree rings have been found in southern Europe, mainly on the Iberian Peninsula (Piovesan & Schirone 2000; Campelo et al. 2009; Roig et al. 2009; Rozas et al. 2009b; Camarero 2011; Pasho et al. 2011).

*Pinus pinea* is a common tree species in Mediterranean region. Along the Italian coastline, *P. pinea* forests have an important environmental and historical value, where the species has been systematically planted since ancient times, mostly for cone and wood production as well as for coastline protection from soil erosion (Ayrilmis et al. 2009; Ciancio et al. 2009; Arduini & Ercoli 2012).

Several studies point out that precipitation strongly influences the radial growth of *P. pinea*, mainly during spring and summer months but also during the previous winter period (Cherubini 1993; Campelo et al. 2006; De Luis et al. 2009). As large-scale atmospheric circulation patterns influence climate variability over large regions (Gordo et al. 2011; Pasho et al. 2011), we expect that NAO influences the radial growth of tree species in stands distributed along the mid-Tyrrhenian coast. In this study, we analyze the relationship between NAO fluctuations and six tree-ring width chronologies of *P. pinea* from the coast of central Italy at intra-seasonal to decadal timescales. These results make possible an improved understanding of the ecology and management of these Mediterranean coastal forests in the face of climate changes influencing the Mediterranean ecosystems.

## Materials and methods

### *Site description*

Six sites distributed along a latitudinal transect on the west coast of central Italy were selected for a dendroclimatological analysis: San Rossore, Cecina, Duna Feniglia in Tuscany and Castelporziano, Lago di Fogliano, and Parco del Circeo in Latium (Figure 1 and Table I). All six sites are forest plantations. The stands of San Rossore, Cecina, Parco del Circeo, and

Lago di Fogliano were planted in swamps that were drained in the first half of the twentieth century. The latter was placed close to a lake, connected to the sea by a tidal channel, and hence brackish water is present. The Duna Feniglia population was planted in 1911 and grows near to a brackish lake. At Castelporziano, the pine stands are plantations established in the eighteenth to nineteenth century (Spada, personal communication). The forests grow in a Mediterranean climate (Figure 2), and, at all sites, trees grow on sandy well-drained soils. The Lago di Fogliano and Parco del Circeo sites, despite their close proximity, were analyzed separately, due to differences in site characteristics and tree age structure.

### *The development of tree-ring chronologies*

At each site, a single wood core per tree was taken from 15 to 20 trees at breast height (Fritts 1976) with an increment borer. Sampling sites were selected in areas without any evidence of nearby human intervention (e.g., thinning and logging) to avoid possible biases in the analysis. To improve the sample depth at San Rossore and Lago di Fogliano sites, 14 individual tree-ring series developed by Biondi (1992) (6 for the former and 8 for the latter one) were also considered in this study.

For standard dendrochronological procedures, we follow Stokes and Smiley (1968). Wood samples were glued on wooden supports and surfaced with a scalpel. Tree-ring widths were dated and measured from pith to bark to the nearest 0.01 mm with a sliding stage micrometer CCTRMD, and measurements were recorded with the CATRAS program (Aniol 1983, 1987). Tree-ring series were cross-dated by both visual (via CATRAS) and statistical controls (COFECHA program; Holmes 1983). The mean correlation (MC) is defined as the average of the correlations for each individual dendrochronological series, which were calculated by comparing each series with the average of all other series. The MC was taken into account in the cross-dating quality control process (Grissino-Mayer 2001).

The age-related trend usually present in raw tree-ring width measurements was removed by standardization procedures in the program ARSTAN40c (Cook & Krusic 2006). We chose a negative exponential function to fit each raw tree-ring series. To examine the internal quality of each chronology, we calculated the expressed population signal (EPS) as an estimate of how well a finite-sample chronology represents the theoretical population chronology with an infinite number of trees and average correlation between all series (RBAR) as a measure of the common variance between the single series in a chronology (Wigley et al. 1984). Both statistics were calculated for the common period 1949–2003.

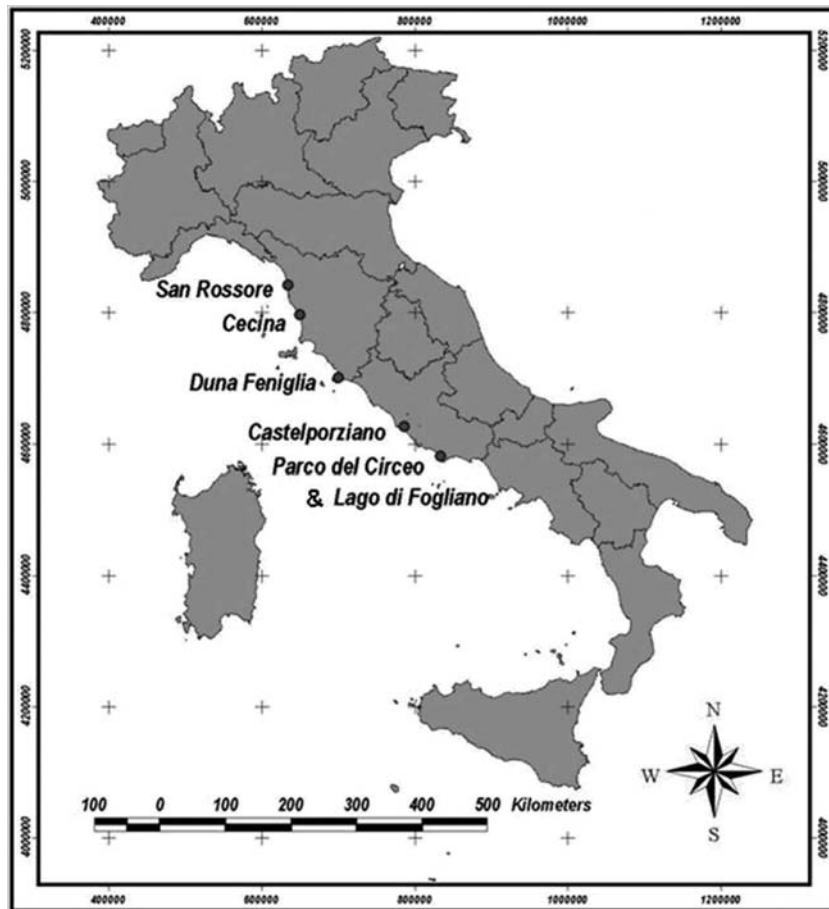


Figure 1. Geographical location of the sampled sites.

RBAR, particularly, differs from MC since it represents the average correlation between all series as an expression of the common percentage variance in common (Wigley et al. 1984).

Relationships between site tree-ring chronologies were explored through principal component analysis (PCA; Legendre & Legendre 1998). Once the groups were highlighted, regional chronologies were built based on PCA results, and standardization processes were carried out as previously explained. PCA was

run with the SPAD package (Lebart et al. 1999). The grouping is meant to search for a common dendrochronological signal shared between the sampled populations.

#### *NAO–tree growth relationships*

NAO influence on radial growth was investigated through correlation functions (Fritts 1976) for the common period 1949–2003 (55 years). Correlations

Table I. Characteristics of sampled sites.

Site	Lat (°N)	Long (°E)	Trees	DBH (cm)	Period	EPS <sup>a</sup>	RBAR <sup>a</sup>	MC
San Rossore <sup>b</sup>	43.72	10.31	19	56–82	1861–2003	0.915	0.405	0.490
Cecina	43.31	10.52	17	41–57	1851–2003	0.880	0.312	0.472
Duna Feniglia	42.44	11.22	19	35–76	1925–2003	0.947	0.548	0.578
Castelporziano	41.74	12.40	21	60–76	1897–2003	0.972	0.655	0.763
Lago di Fogliano <sup>b</sup>	41.31	13.03	16	71–84	1878–2004	0.929	0.493	0.595
Parco del Circeo	41.31	13.03	15	55–81	1945–2004	0.950	0.594	0.650

Notes: Lat = latitude, Long = longitude; Trees = number of sampled trees per site; DBH = range of diameters at breast height; Period = time range of the sampled cores; EPS = expressed population signal, RBAR = average correlation between all series; MC = mean correlation between series at each stand. <sup>a</sup> Calculated for the period 1949–2003. <sup>b</sup> At San Rossore and Lago di Fogliano stands, a total of 14 individual chronologies (6 for San Rossore and 8 for Lago di Fogliano) were taken into account. Individual chronologies are available at <http://www.ncdc.noaa.gov/paleo/treering.html>.

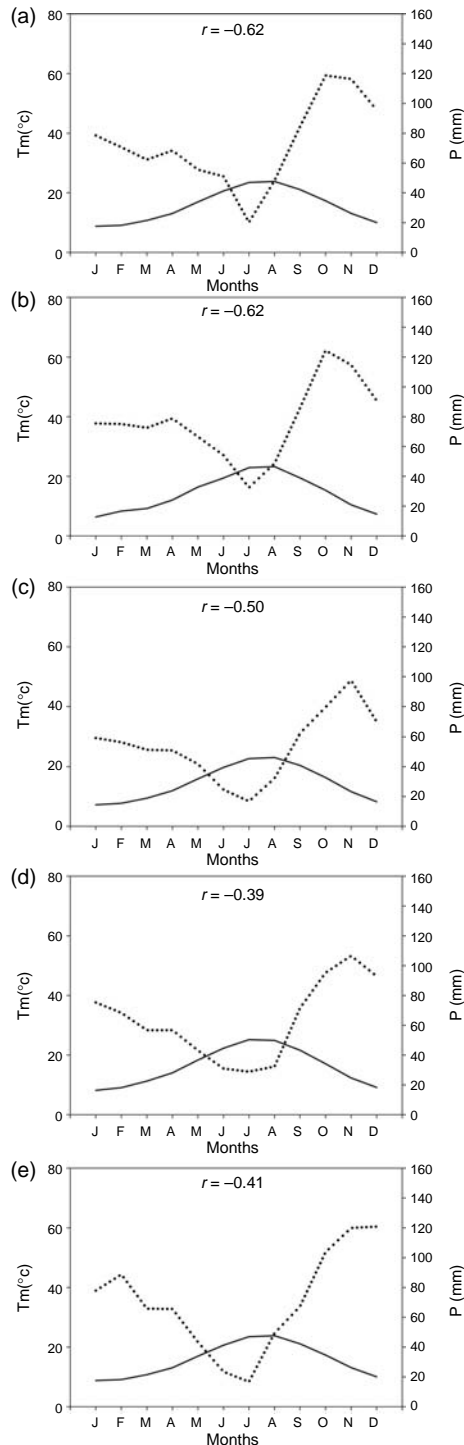


Figure 2. Ombrothermic diagram of San Rossore (a), Cecina (b), Duna Feniglia (c), Castelporziano (d), and Circeo (e) for the period 1949–2003 according to Bagnouls and Gaussen (1953). Data were available from the Military Air Force – National Centre of Meteorology and Climatology (at <http://clima.meteoam.it/downloads.php>).  $T_m$  = monthly air temperature;  $P$  = monthly total rainfall. Solid line refers to monthly air temperature, dotted line to monthly total rainfall. Correlation values are shown between winter (December to March) NAO values and winter amount of precipitation, calculated for the period 1949–2003 for each site. All values are significant at  $p < 0.05$ .

were computed with the software DENDROCLIM 2002, and tests for significance were determined with the bootstrap method (Guiot 1991; Biondi & Waikul 2004). A set of 11 months was selected for correlation, from November of the preceding year to September of the growth year. This period was chosen based on the physiology of *P. pinea*, considering that radial growth begins in March and ends in September (Liphshitz et al. 1984).

The group chronologies resulting from PCA were matched against monthly, winter, and annual NAO values. NAO data were obtained from <http://www.cgd.ucar.edu/cas/jhurrell/indices.data.html> (Hurrell 1995b). Winter was defined as the period from December of the preceding year to March of the current year. Since NAO shows a clear decadal variability, especially during the second half of the twentieth century (Hurrell & Van Loon 1997), we investigated this low-frequency influence on chronology fluctuations by smoothing winter and annual NAO series as well as the raw tree-ring width chronologies with a 50% frequency response in 11-year periods (Cook & Peters 1981). For the latter analysis, due to the strong autocorrelation in both NAO and dendrochronological series, the effective number of degrees of freedom was calculated to avoid any possible overestimation of the correlation function results (Oort & Yienger 1996).

## Results

### *Characteristics of the dendrochronological network*

Six chronologies were built from 107 wood samples from forest sites of different ages, ranging from 60 years at Parco del Circeo to 153 years at Cecina (Table I). The MC values between individual chronologies range from 0.472 (Cecina) to 0.763 (Castelporziano) at  $p < 0.05$ . Mean EPS ranges between 0.880 (Cecina) and 0.972 (Castelporziano), and the mean RBAR oscillates between 0.312 (Cecina) and 0.655 (Castelporziano) (Table I).

In the multidimensional analysis, the first two PCA eigenvalues explain 33.70% and 22.23% of the total variance, respectively, contributing up to 55.93% (Figure 3). The PCA suggests the existence of four possible groups of chronologies: Duna Feniglia and Lago di Fogliano are positively correlated with the first axis and negatively with the second; Castelporziano contributes to the first axis and to a lesser extent to the second; San Rossore and Cecina dominate the second axis, and Parco del Circeo is not correlated with the first two axes. Since these groups are recognizable, we separated the tree-ring chronologies in Tuscany (the two northern sites, San Rossore and Cecina), Latium (Duna Feniglia



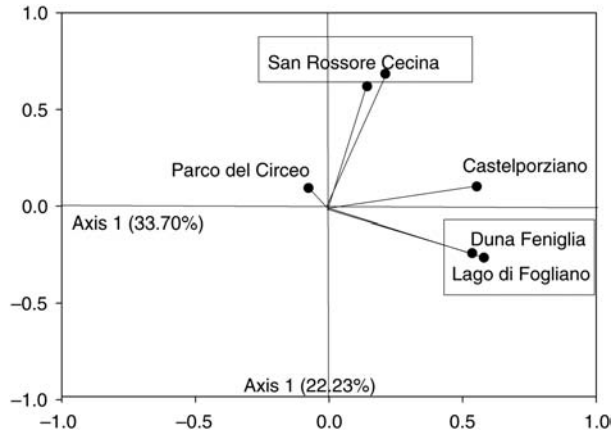


Figure 3. Pattern of the first principal components of PCA carried out on tree-ring width chronologies for the common period 1949–2003.

and Lago di Fogliano), while Castelporziano and Parco del Circeo remained as separate sites. We again cross-dated the tree-ring series for each group as previously explained and then decided to remove 12 individual tree-ring series from the Tuscany group and 13 from the Latium group to improve the average correlation between series. The statistical parameters of the Tuscany and Latium groups are shown in Table II. PCA was carried out again to analyze possible changes to the original multi-dimensional analysis in removing these individual tree-ring series. The new PCA showed the same four groups (data not shown).

#### Radial growth–NAO relationships

The monthly correlation function analysis is shown in Figure 4a. The Tuscany chronology is negatively and significantly correlated with NAO values in February, while that of Parco del Circeo is negatively and significantly correlated with NAO values in December, January, and March. On the other hand, Latium and Castelporziano chronologies are not significantly correlated with NAO on a monthly scale.

Table II. Characteristics of the group chronologies merged from PCA.

Site	Trees	Period	EPS <sup>a</sup>	RBAR <sup>a</sup>	MC
Tuscany	24	1861–2003	0.877	0.342	0.464
Latium	22	1878–2004	0.943	0.511	0.561

Note: Trees = number of sampled trees; Period = time range of the sampled cores; EPS = expressed population signal, RBAR = average correlation between all series; MC = mean correlation between series for each group. <sup>a</sup> Calculated for the period 1949–2003.

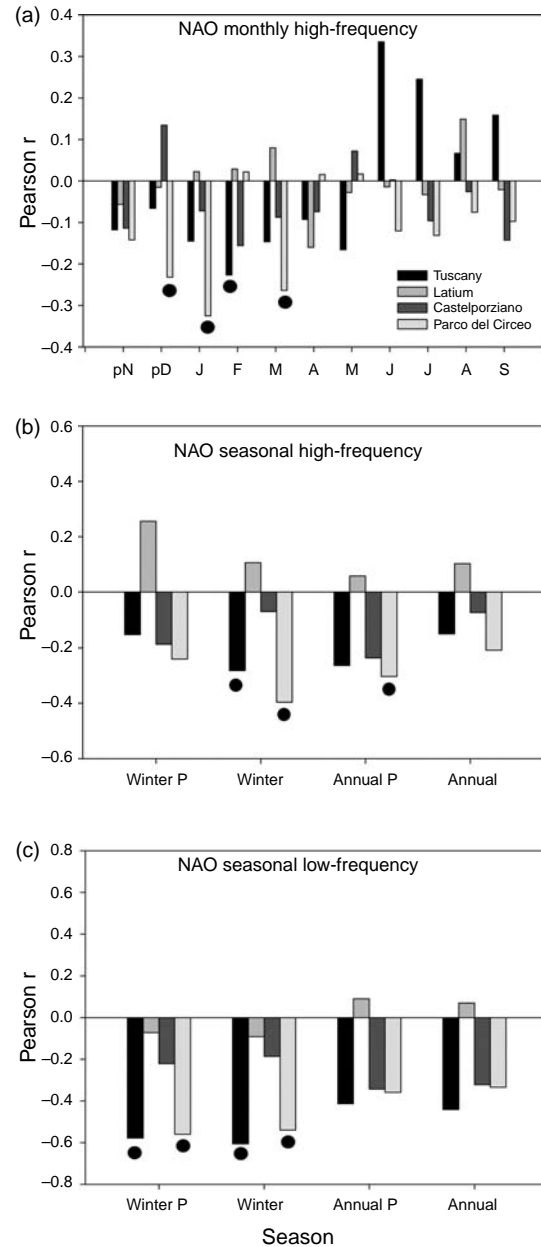


Figure 4. Correlation functions calculated for the common period 1949–2003. (a) Correlation between tree-ring chronologies and monthly NAO values. (b) Correlation between tree-ring chronologies and winter and annual NAO values of year preceding growth and current year. (c) Correlation between low-frequency (decadal) tree-ring chronologies and low-frequency (decadal) winter and annual NAO values of previous and current years of growth. Dots indicate significance at  $p < 0.05$ .

The winter season NAO values for the running year negatively and significantly affect both Tuscany and Parco del Circeo chronologies (Figure 4b). Castelporziano shows an almost zero negative correlation with winter NAO, while the signal is slightly positive for the Latium group. Annual NAO values from the previous year have a negative impact on the Tuscany, Castelporziano, and Parco del Circeo chronologies, but only in the latter case is the

correlation statistically significant at the  $p < 0.05$  level. On the other hand, the Latium chronology shows a weak positive relationship with NAO variability at an annual timescale.

Correlation functions modeled at low frequency (Figure 4c) indicate that *P. pinea* is sensitive to NAO events at a decadal timescale. Winter NAO variability in the preceding and current years strongly influences radial growth, but only the Tuscany and Parco del Circeo chronologies significantly respond to NAO values at decadal timescales. The Latium chronology does not seem to respond to NAO at low-frequency variability. In the Castelporziano chronology, correlation values with the annual NAO index are relatively high, but not significant at the  $p < 0.05$  level, due to the reduced degrees of freedom, which is the result of strong autocorrelation in both NAO and dendrochronological series (Oort & Yienger 1996).

### Discussion and conclusion

This is the first attempt to describe the radial growth variability of a coastal conifer in central Italy in terms of its relationship to NAO at high- and low-frequency timescales. *P. pinea* ecology, in terms of the relationship between radial growth and climatic variability, is well known in the two core areas of its natural distribution (e.g., Akkemik 2000; Campelo et al. 2006; De Luis et al. 2009; Rozas et al. 2009b). However, there is little information on the woodlands in the heart of the Mediterranean basin (but see Piraino et al. 2013). Thus, analyzing the relationship between radial growth and NAO variability can highlight the ecological requirements of the species and help improve the management of these important Mediterranean pine forests in a context of climate change.

Looking at the statistical parameters corresponding from six different sites, a high percentage of common variance suggests that there is a signal shared by all individuals at each site, probably as a consequence of a single dominant factor on radial growth. The EPS values for the regional chronologies are always higher than the 0.85 empirical threshold for the common period taken into account (Table I); so, we can assume that these tree-ring chronologies suitably approximate hypothetically infinite *P. pinea* populations at each of the sampled sites (Wigley et al. 1984).

In the PCA, the Tuscany and Latium groups were separated from the others. However, the statistical values of MC, RBAR, and EPS are not remarkably lower than the other individual site chronologies (Table II). Furthermore, the RBAR for both group chronologies and the Latium EPS fall in the range of the original values, while for the Tuscany, EPS is lower. However, its value (0.877) is still above the

empirical 0.85 threshold (Wigley et al. 1984). Hence, we consider it valid to merge these series into regional groups.

The PCA shows four possible groups. The Tuscany group's chronology is separated from the Latium and Castelporziano chronologies, possibly due to the geographical setting of the sampled populations. Otherwise, the Castelporziano chronology seems to be quite independent from those of Duna Feniglia and Lago di Fogliano, a result that can be understood considering site characteristics. The Duna Feniglia stand grows close to a brackish lake, while the pine population of Lago di Fogliano is near to a lake connected to the sea through a drainage channel, and hence, there is brackish water (Gabrielli 1993; Izzo et al. 2003; Prato et al. 2009). Thus, we may hypothesize that the grouping of these two stands may depend on the shared site's characteristics, namely brackish water. Finally, the Parco del Circeo chronology remains isolated in the PCA, probably due to the younger age structure of this forest.

At inter-annual to decadal timescales, winter NAO significantly influences the radial growth of the Tuscany and Parco del Circeo groups, while at Castelporziano, there are no statistically significant relationships with NAO variability, nor does the Latium group respond clearly to this large-scale atmospheric pattern. These results can be understood by considering the combined influence of three principal factors: (i) different relationships between winter NAO variability and winter precipitation regimes at each study site, (ii) differences in site characteristics, and (iii) possible age-dependent mechanisms.

First, we consider the different intensities of winter NAO influence on winter precipitation, which is the primary precipitation forcing in the Mediterranean (Gordo et al. 2011). In the study area, the northern pine populations are under a strong negative influence of winter NAO variability, while this same signal is slightly reduced for the southern sites, and especially for the Castelporziano and Circeo stands (correlation values between winter NAO index and winter precipitation regime are reported in Figure 2).

Second, the lack of coherent signals connected to NAO variability in the Latium chronology seems to be consistent with the result emerged from the multidimensional analysis. As previously reported, at both Lago di Fogliano and Duna Feniglia, the pine stands grow close to a permanent source of brackish water; so, the water table has been apparently affected by salty water (Bianchi et al. 2005; Prato et al. 2009). Although the studied species is considered to be salt tolerant, it has been shown that salty groundwater can negatively influence

sensitivity to abiotic factors in *P. pinea* (Teobaldelli et al. 2004). Thus, the particular location of Lago di Fogliano and Duna Feniglia might possibly bias the relationship between radial growth and NAO variability.

Finally, Parco del Circeo shows the strongest relationship with winter NAO variability at both high- and low-frequency timescales. The difference between Castelporziano and Parco del Circeo may depend on the relatively young age of the latter tree population. Indeed, the relationship between winter NAO variability and winter precipitation regime at both stands does not present any particular difference (Figure 2). Age-dependent responses to the environment have been found in the Mediterranean area, which have been attributed to the longer growing season experienced by younger trees and increased sensitivity to climate variability (Vieira et al. 2009; Rozas et al. 2009a).

From a biological viewpoint, the negative influence of winter and annual NAO fluctuation upon the tree-ring width is understandable, considering that NAO has an inverse relationship with the precipitation regime in the Mediterranean area. Previous analysis showed that the radial growth of *P. pinea* along the central coastline of Italy has a bimodal response to the climatic variability. In fact, tree-ring development is negatively influenced by drought conditions in the late-spring summer during the growth year (from March to September) and enhanced by a positive moisture balance in the previous winter season, as seen in the positive relation between radial growth and Palmer Drought Severity Index (PDSI) values (Palmer 1965; Piraino et al. 2013).

Several physiological mechanisms may be taken into account to understand the biological meaning of the results reported in this study. Abundant soil moisture in the winter season may enhance the radial growth of the species by forming a top layer of fresh water, which can be used by the tree during the following spring–summer period (Teobaldelli et al. 2004). Furthermore, photosynthesis can take place during winter in conifer trees distributed in regions characterized by rainy and mild winters, such as the Mediterranean area (Kozłowski et al. 1991). Hence, for these study areas, we may hypothesize that carbohydrates are produced before cambium activity begins, which are possibly used for tree-ring formation in the following growing season. Finally, the NAO influence seems to be not only limited to the amount of precipitation during winter, as the positive phase of winter NAO also leads to drought conditions in southern Europe during the summer and autumn periods (e.g., with a decrease in levels of reservoir storage; López-Moreno & Vicente-Serrano 2008; Vicente-Serrano et al. 2011).

Several studies have demonstrated the relationships existing between winter NAO fluctuations and radial tree growth in southern Europe. Piovesan and Schirone (2000) found a correlation at annual timescale, although weak, between the winter NAO and *Fagus sylvatica* L. growth in the central Italian Apennines. However, after applying an 11-year running mean to both winter NAO values and raw tree-ring width chronologies, low-frequency (decadal) winter NAO values appear to have a strong influence on the radial growth. Campelo et al. (2009) found that winter NAO strongly and negatively affects the tree-ring development of *Quercus ilex* in a coastal population in central Portugal. Roig et al. (2009) analyzed *Castanea sativa* Miller and *Quercus pyrenaica* Willd populations at their upper-altitudinal tree-growth limit in central-western Spain. After smoothing dendrochronological and winter NAO series with a 5-year running mean, the tree-ring growth of both species appeared to be negatively influenced by winter NAO variability. Rozas et al. (2009b) studied *P. pinea* L., *P. pinaster* Ait, *Quercus robur* L., and *Q. pyrenaica* populations in a littoral island on northwest Spain, showing that the radial growth of *P. pinea* and both *Quercus* species is inversely related to NAO during the previous autumn, whereas *P. pinaster* seems to respond with less intensity to NAO fluctuations. Responses to NAO indices in a tree-ring network across a climatic gradient in northeastern Spain with contrasting habitats and different growth responses to climate showed that high NAO values during the previous December negatively influenced the tree-ring development, while high February NAO values enhanced the radial growth (Camarero 2011). Moreover, forests growing under the xeric continental climate show a higher sensitivity to NAO fluctuations than forests growing under more mesic conditions. NAO influences the growth of *Pinus halepensis* Mill. forests along the eastern Spain, with winter NAO values negatively correlating with early wood formation (Pasho et al. 2011).

These results, along with those presented in this paper, seem to indicate the influence of winter NAO fluctuations on Mediterranean forest growth. Even though these studies have analyzed different species, and the intensity of NAO influence may vary according to the different relationships between winter NAO fluctuations and local amount of winter precipitation, NAO seems to play an important role on the radial growth variability throughout southern Europe at both high- and low-frequency timescales. General circulation models developed climate change scenarios, which forecast a more robust and stable link between NAO and surface climate variables (Raible et al. 2006; Vicente-Serrano & López-Moreno 2008; Camarero 2011). This



suggests that future climate variability and its impact on the Mediterranean region might be even stronger under a warmer world. For this reason, NAO influence on radial growth must be taken into account in a comprehensive understanding of coastal Mediterranean *P. pinea* forest dynamics.

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### Note

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