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Gianluigi Mazza, Andrea Cutini, Maria Chiara Manetti. Site-specific growth responses to climate drivers of *Pinus pinea* L. tree rings in Italian coastal stands. *Annals of Forest Science*, 2014, 71 (8), pp.927-936. 10.1007/s13595-014-0391-3 . hal-01102945

HAL Id: hal-01102945

<https://hal.science/hal-01102945>

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Site-specific growth responses to climate drivers of *Pinus pinea* L. tree rings in Italian coastal stands

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Received: 7 October 2013 / Accepted: 26 May 2014 / Published online: 2 July 2014
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Abstract

• **Context** Six *Pinus pinea* stands growing under the Mediterranean type climate in Italy along the Tyrrhenian and Sardinian coasts.
• **Aims** To identify the main climatic factors driving variability in growth responses to contrasting climate conditions at local and regional scales using tree-ring analysis.
• **Methods** Common growth patterns in tree rings were explored with clustering techniques. Local and regional growth responses to climate were examined using a dendroclimatic analysis. To remove the age-dependent trend we decomposed the tree ring width data into age-bands, thereafter standardised and recombined into a single mean site chronology.
• **Results** The main grouping of tree ring series reflected climate-driven growth patterns, with a clear separation between stands from wetter and drier sites. The most interesting results were found at a seasonal scale and showed i) a shift of the main precipitation inputs from previous autumn–winter to current early–spring period, and ii) a bimodal pattern of sensitivity to water availability, when increasing drought conditions.
• **Conclusion** Our findings suggest that water deficit limits *P. pinea* growth also during late summer months in drier sites. In view of the projected increases in the frequency and duration of summer droughts in the Mediterranean basin, detecting

differences in growth responses to site-specific climate patterns may allow selection of more appropriate mitigation and conservation strategies across most of its present range.

Keywords Italian stone pine · Mediterranean pinewoods · Growth–spatial patterns · Climate–growth relationships · Drought

1 Introduction

Stone pine (*Pinus pinea* L.) is commonly considered the symbol of Italian coastal forests and has recently acquired a high recreational and landscape value, thus making a positive contribution to tourism activities. It has been used for the consolidation of sand dunes and to protect soil and crops from erosion and salty winds in exposed coastal areas due to the extensive root system and the large crown. The multi-layered root system permits the mature trees to obtain water from different levels of the soil profile by exploring the ground more intensively and homogeneously (Frattegiani et al. 1994). It is a light-demanding, xerophile and thermophile species, typical of the Mediterranean climate, which is characterised by a hot–dry summer, a rainy–mild winter and a high variability of precipitation on monthly, interannual, and interdecadal time scales.

Several studies have demonstrated the *P. pinea*'s high sensitivity to climate, particularly to previous autumn and winter precipitations, which are crucial for supporting tree growth during spring, due to the soil water recharge (Campelo et al. 2006; Cherubini 1993; Raventós et al. 2001; Mazza and Manetti 2013). In contrast, the lack of significant dendroclimatic signals during the summer period may indicate an adaptation to water shortage in terms of a decrease in cambial activity (De Luis et al. 2009). Rainfall appears to be

Handling Editor: Jean-Michel Leban

Contribution of the co-authors Gianluigi Mazza conceived the ideas, collected and analysed the data, wrote the paper; Maria Chiara Manetti and Andrea Cutini collected the data and led the writing.

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the main factor driving growth, and has marked cumulative effects over consecutive years because of the increase in soil water content. Indeed, highly significant correlations between tree growth and precipitation sums of previous years have been found for the period from October to December (Mazza and Manetti 2013; Raddi et al. 2009).

The influence of temperature on radial growth is not highly significant. Despite that, high temperatures occurring with low amounts of rainfall during summer and early autumn are the limiting factor for latewood formation, due to water stress because high temperatures increase evapotranspiration and soil-water evaporation (Campelo et al. 2006). *P. pinea* can be considered a drought-tolerant Mediterranean species that continues growing during the dry season (Piraino et al. 2013), reducing photosynthetic activity when water stress occurs (Lipshitz et al. 1984), as commonly observed in summer and early autumn (Teobaldelli et al. 2004). An increase of evapotranspiration may have contrasting effects on tree growth depending on site conditions, the forest type, and the amount of precipitation received. In drought-stressed areas, an increase in the evapotranspiration rates will lead to a negative influence on tree growth (Pasho et al. 2011). A few studies have been conducted to assess the variability of the species in growth responses to climate according to contrasting site-specific climatic patterns, as different drought conditions. In Portugal, climatic responses of *P. pinea* radial growth were higher in the inland area, characterized by a more severe summer drought, lower winter temperatures and lower water-holding capacity of the soils compared to the coastal area (Campelo et al. 2006). However, the limiting factors of tree-growth can be very different on the Mediterranean and the Atlantic coasts. Indeed, the Mediterranean climate shows the geographical transition between the wet mild domain of the mid-latitudes and the arid and desertic area of the tropical anticyclone belt. Moreover, the highly geographic complexity of the Mediterranean basin diversifies its general climatic regimes, yielding a great variety of atmospheric behaviours, mainly pluviometric, with many subregional and mesoscale features (Lionello et al. 2006; Martin-Vide and Lopez-Bustins 2006).

Different studies indicate that our understanding of the drought impact on growth of tree species at different time scales and across contrasting site conditions is still very limited (Pasho et al. 2012). The analysis of tree-ring networks is a helpful tool for detecting tree responses to contrasted environmental factors within the tree–climate–site complex, highlighting the local interactions between site and climate conditions (Tardif et al. 2003). The aim of the present study is to identify the main climatic factors driving variability in growth responses to contrasting climate conditions at local and regional scales, using tree-ring analysis.

2 Materials and methods

2.1 Study sites

Our research spanned a geographical area ranging from 39° to 42° N in latitude and from 8° to 12° E in longitude, and was conducted in six healthy even-aged pine forests along four coastal areas of Italy. The sampling sites were selected according to contrasting site-specific climatic patterns, especially with regard to drought conditions. All of the pinewoods are located inside protected areas: (1) Alberese (ALB), Maremma Regional Park (Tuscany), (2) Castel Fusano (CFU) and Castelporziano (CPO), Natural Reserve of the “Roman coast” (Latium), and (3) Bidderosa (BID), Is Arenas (ISA), and Arborea (ARB), Sites of Community Importance (SCI) located on the eastern and western coasts of Sardinia (Fig. 1). Sites from Tuscany and Latium will be considered throughout the manuscript as sites from the Tyrrhenian coast. The sampled plots are located within each pinewood, to avoid the influence of coastal erosion and the exposure of crowns both to salty winds and surfactants in marine aerosols, all factors that could affect pine growth (Raventós et al. 2001; Raddi et al. 2009).

The climate ranges from Mediterranean subtropical to continental, with a dry summer in which June, July, and August are the driest months. Drier conditions are present in Sardinia, with significant differences in late summer–early autumn rainfall amounts and autumn–winter temperatures.

Sites from the Tyrrhenian coast (ALB, CFU, CPO) lie on alluvial soil derived from alluvial deposits with inclusions of metamorphic rocks; soil moisture and temperature regime are xeric and thermic. The site from the eastern coast of Sardinia (BID) lies on shallow soil derived from intrusive igneous rocks, partially metamorphic rocks, and limestone; soil moisture and temperature regime are xeric and dry xeric, locally udic and thermic, locally mesic. The sites from the western coast of Sardinia (ISA, ARB) lie on alluvial soil originating from alluvial deposits and locally limited by acidity, salinity, and calcareous crusts (Costantini et al. 2014). Soil moisture and temperature regime are dry xeric and thermic, and the area is affected by strong winds.

The three stands from the Tyrrhenian coast are characterised by a dominant layer of *P. pinea* with holm oak (*Quercus ilex* L.) and other typical broadleaf maquis shrubs that dominate the subcanopy. The composition of Sardinian stands was monospecific. All the six stands were managed primarily for the consolidation of sand dunes, and for protective and recreational purposes (Cutini et al. 2013).

2.2 Dendrochronological analysis

At each site, two cores per tree of between 12 to 27 selected trees were extracted with a 5-mm diameter increment borer at breast height on the cross-sides of the trunk; only healthy

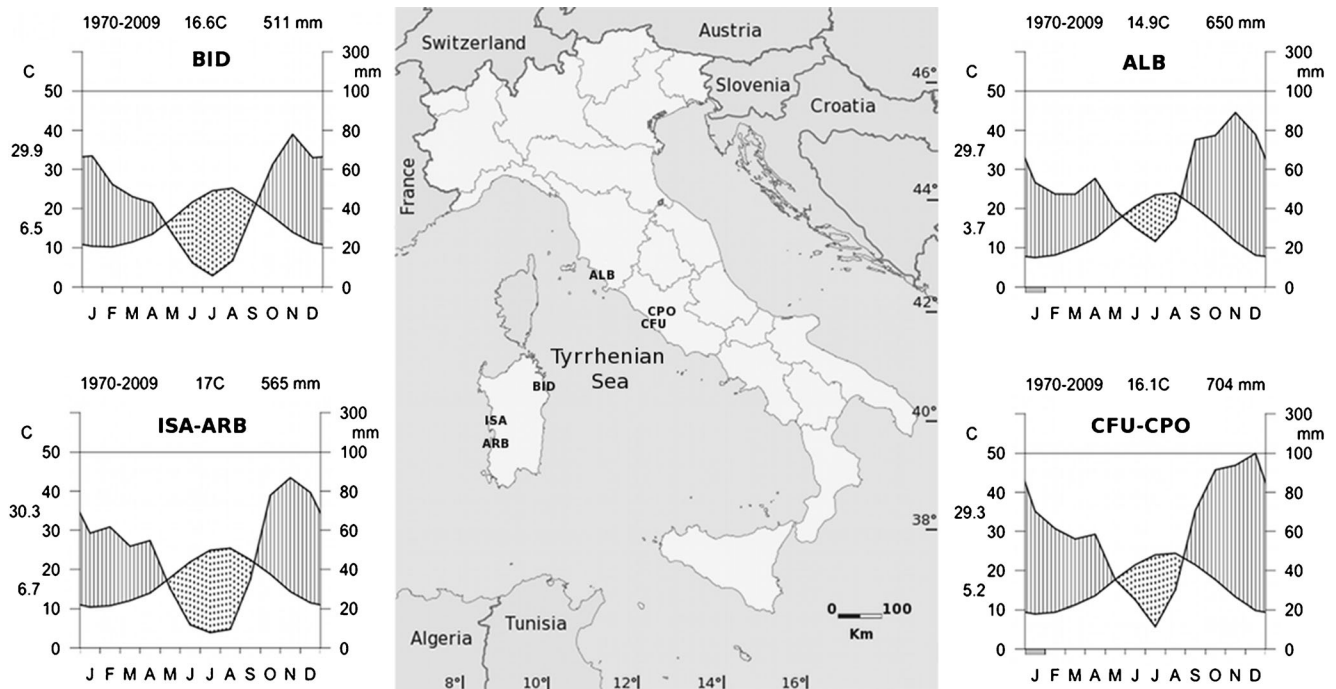


Fig. 1 Location and Walter & Lieth climatic diagrams of the study sites. On top are reported the average annual temperature and the total annual rainfall and beside the left y-axis the mean maximum temperature of the

warmest month and the mean minimum temperature of the coldest month. The dotted area indicates seasonal water deficit. Site codes are shown in Table 1

dominant or co-dominant straight trees with a symmetric crown were selected. The increment cores were mounted on wooden supports, air-dried, and sanded with progressively finer sandpaper (200P and 600P) to obtain a smooth surface, and ring width was measured from bark to pith with a precision of 0.01 mm using a Velmex measuring system. The raw series of ring widths were visually and statistically checked for cross-dating and measurement errors using the dendrochronology program library in R (dplR) (Bunn 2010). The standardisation procedure used to develop the mean site chronologies was conducted in two analytical steps. To remove the influences of local site characteristics on tree growth, we first standardised each tree-ring chronology by dividing it by the mean width of that particular chronology (Sarris et al. 2011). In detrending the tree-ring growth (age-dependent trend), we used the age-band decomposition method (ABD) (Briffa et al. 2001), which is based on decomposing the tree-ring width data into age classes. This method reveals additional climatic information retained in the chronologies of relative growth changes compared to the “classical” indexed tree-ring chronologies. In this second step, we standardised each age-banded tree ring series (10-year bands) by dividing each band by the mean of the tree ring widths of all trees within that age band. Finally, by averaging all the age-band series together, we produced the final time series of the tree-ring widths (Mazza and Manetti 2013; Sarris et al. 2011).

2.3 Spatial variability in growth patterns

Common growth patterns were explored with a principal components analysis (PCA) and hierarchical cluster analysis (HCA) of the tree-ring chronologies to evaluate the shared variance for the time period covered by all the series. The PCA transformed the tree ring indices into a new set of variables (PCs; principal components), calculated from the covariance matrix of the original data. The hierarchical clustering algorithm, based on Ward’s method and applying the squared Euclidean distance between variables as the distance or similarity measure, produced a dendrogram showing groups of similar tree-ring indices. In this method, clusters are joined such that the increase in within-group variance is minimised. All the data analysis was performed using the R software environment (R Development Core Team 2008).

2.4 Climate data

Due to the lack of representative meteorological data for the whole period covered by our chronologies, we used datasets from the Climate Research Unit (CRU), University of East Anglia, UK, for mean temperature and total precipitation in the period 1901–2009, and for Palmer drought severity index (PDSI) in the period 1901–2002 (CRU self-calibrating PDSI), gridded on a 0.5×0.5 degree network. The chosen climate

data, corresponding to the closest grid point to the four coastal areas in which the pinewoods are located, were taken from the website of the Royal Netherlands Meteorological Institute (<http://climexp.knmi.nl/>).

The PDSI uses air temperature, cumulated rainfall and field water-holding capacity to compute a standardised measure of soil moisture ranging from -6 to 6 , which corresponds to extremely dry and wet soil conditions respectively (Dai et al. 2004).

We also use the Standardised Precipitation–Evapotranspiration Index (SPEI) at 1-month time-scale in the period 1901–2009. The SPEI is a new multiscalar drought index based on monthly precipitation and potential evapotranspiration from the CRU datasets, with a spatial resolution of 0.5° (Vicente-Serrano et al. 2010; Beguería et al. 2010 - <http://sac.csic.es/spei/>).

To assess the presence of climatic trends, we applied the Mann–Kendall non-parametric test (Brunetti et al. 2006; Hamed 2008).

2.5 Climate-growth relationships

The influence of climate on tree-ring growth at 1-month time-scale was investigated using a correlation function (CF) analysis (Fritts 1976) based on Pearson's correlation coefficient. We used 52 independent monthly climate variables sequenced from October of the year prior to growth ($t - 1$) to October of the year of growth (t), assuming that the cambial activity still continues during autumn because of the favourable climate conditions, as was observed in our sampling sites. Pearson's correlation coefficients were tested for significance using the 95 % percentile range method after a bootstrap process with 1,000 replications using the "bootRes" package in R program (Zang and Biondi 2013). Standardized coefficients were obtained by dividing the mean correlations by their standard deviations after the bootstrap replications (i.e., considering each test as independent).

Climate–growth relationships at a seasonal scale were investigated using the Pearson's correlations after testing the normal distribution with the Kolmogorov–Smirnov and Shapiro–Wilk tests. We also tested the correlations using the Spearman rho (ρ) non-parametric correlation coefficients when precipitation data were not normally distributed. Significant coefficients were found with both types of correlations; therefore, only Pearson's correlation coefficients (r) are provided in all cases.

Seasonal climate–growth correlations were checked from September–October–November (SON) of the previous year to September–October–November (son) of the current year of ring formation, using 13 rotating seasonal periods (e.g., September–October–November, SON; October–November–December, OND; November–December–January, NDj; etc..) for all the climatic variables.

Seasonal climate–growth correlations were also tested over a common period in which the growth rate of each chronology

(expressed as the 5-year average of the standardised TRW) was stabilised and characterised by a lower variability. The aim of this further analysis was to reduce the influence of site characteristics on tree-growth variability, especially during the establishment phase typical of the first years of growth, where the climatic signal is not well-recorded (e.g., due to a strong competition with understory vegetation).

3 Results

3.1 Spatial variability in climate variables

The distribution of climatic variables showed similar regional features, typical of the Mediterranean climate (Fig 1). Despite that drier conditions were found along the western and eastern coasts of Sardinia, characterised by significantly [$F(3,232)=7.87$ with $p<0.001$] lower annual precipitation ($566\text{ mm}\pm 131$) compared with those of the Tyrrhenian coast ($650\text{ mm}\pm 137$). This was also the case for summer precipitation ($32\text{ mm}\pm 23$ vs $61\text{ mm}\pm 25$, $F(3,232)=31.83$ with $p<0.001$). Similarly, late summer–early autumn rainfall amounts discriminating the coastal areas were observed.

Autumn was the rainiest season in the Tyrrhenian areas, with rainfall 12 % greater than that occurring in winter, whereas seasonal rainfall values did not vary in Sardinia. Moreover, the dry season in Sardinia extended until September and was characterised by a significant decrease of 37 % in total precipitation [$F(3,232)=13.58$ with $p<0.001$] relative to that of the Tyrrhenian coast.

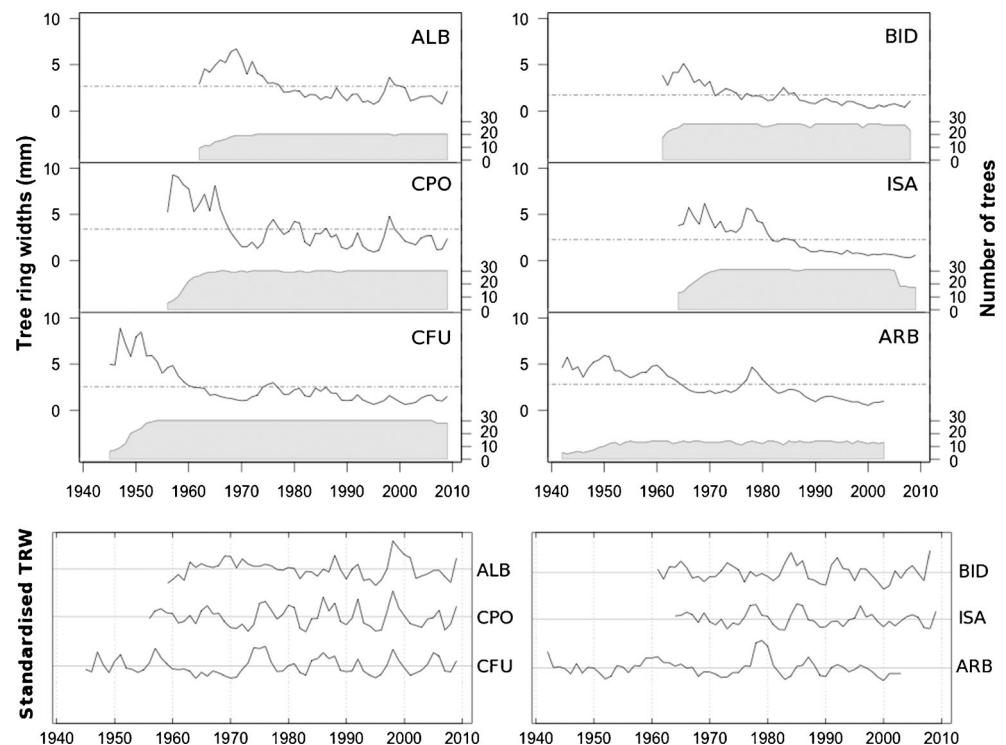
Contrasting spatial patterns of temperature trends were also detected. Annual mean temperature for the Sardinian coasts was 0.9°C higher than that of the Tyrrhenian coast, and this significant difference increased to 1.2°C and 2.1°C during the autumn and winter respectively.

3.2 Spatial variability in tree ring growth

A total of 126 trees and 220 cores were used to compute the site chronologies (Fig. 2 and Table 1). Synchronization between mean site chronologies was highly significant both for the raw and standardised tree-ring width series. At a regional scale (Tyrrhenian and Sardinian stands), the highest values of GLK, Gleichläufigkeit (Schweingruber 1988), was found between the two site chronologies from the Roman coast (CFU vs CPO, 0.85 and 0.75 for the raw and standardised TRW respectively) and the two site chronologies from the Sardinian western coast (ISA vs ARB, 0.69 and 0.67 for the raw and standardised TRW respectively).

Based on the dendrometric measurements (Table 1), CPO and CFU are characterised by the highest site index (which is a measure of a site productivity based on how tall trees will

Fig. 2 Mean raw and standardised tree-ring chronologies for each site. The shaded areas indicate the number of trees



grow over a specified period of time), suggesting much more fertile growing conditions than the other ones. Moreover, the low site index of ALB was closer to the sites sampled in Sardinia, especially BID and ISA.

On the other hand, contrasting results on the spatial variability in tree growth were showed by the clustering techniques after the standardisation procedure. Indeed, the first two principal component (PC1 and PC2) of the loadings plot, that together explained 73.5 % of the common variance, revealed two main groups of tree ring chronologies at a regional scale (Fig. 3a): 1) stands from the Tyrrhenian coast (CFU, CPO, and ALB), and 2) stands from the Sardinian coasts (ISA, ARB, and BID). Moreover, within this two main groups at a regional scale appeared also a difference in radial growth patterns at a local scale between ALB (Tuscany) and Roman coast stands (CFU and CPO), and between the east and west coast stands on Sardinia (BID vs ISA and ARB). The

dendrogram produced by the hierarchical cluster analysis confirmed the same grouping (Fig. 3b).

The growth rates over time showed a stabilised trend from the early 1980s, with a significant reduction in growth variability both within each chronology and among all sites (Fig. 4).

3.3 Climate–growth relationships

According to the grouping obtained by clustering techniques, the growth responses to climate were tested based on the mean standardised chronologies for each coastal area located within the same grid of climate data. For this reason, we averaged all the individual TRW standardised chronologies from the two pinewoods of the Roman (CFU and CPO: ROM) and western Sardinian coasts (ISA and ARB: ISARB).

Table 1 Main characteristics of the pine stands studied. Mean diameter at breast height (DBH); D range of the dominant / co-dominant trees cored; mean height (H); mean ring width (MRW) and standard deviation (SD), computed on the raw tree-ring series

Chronology/ code	N° cores/ N° trees	Time span (n° years)	Tree density ($n \text{ ha}^{-1}$)	Mean DBH (cm)	D range (cm)	MRW±SD (mm)	Basal area ($\text{m}^2 \text{ ha}^{-1}$)	Mean H (m)
Alberese ALB	28/14	1958–2010 (53)	118	35.3	28.3–43.9	2.56 ± 1.70	16.2	11.6
Castel Fusano CFU	50/25	1945–2009 (65)	226	41.7	30.8–50.4	2.19 ± 1.86	30.8	18.3
Castelporziano CPO	48/26	1957–2009 (53)	92	48.5	33.1–53.6	3.28 ± 2.19	20.7	17.5
Bidderosa BID	38/22	1961–2008 (48)	462	25.6	22.7–36.3	1.70 ± 1.26	23.7	9.8
Is Arenas ISA	40/27	1964–2009 (46)	430	25.7	22.1–37.9	2.26 ± 1.87	22.3	10.8
Arborea ARB	18/12	1942–2003 (62)	283	33.5	26.5–42.3	2.56 ± 1.99	24.2	11.8

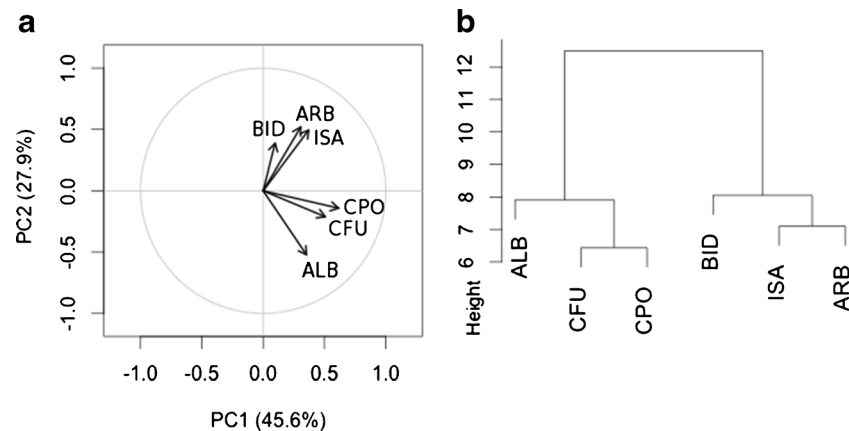


Fig. 3 Loadings plot (**a**) and cluster dendrogram (**b**) of mean standardised site chronologies. **a** Axis labels report the percentage of variance explained by the first two components; each *arrow* corresponds to one of the analysis variables projected onto a two-dimensional plane

Over the whole common period (1961–2008), both monthly and seasonal climate–growth correlations showed almost the same results, while for the period 1980–2008 only the seasonal correlations were performed, due to the time span length being too short for the classical bootstrapped CF analysis.

Precipitation appeared to reveal one of the the main common geographical-scale pattern in tree growth responses to climate, confirming the variability displayed by the clustering methods. The shift of the main precipitation inputs from previous autumn–early winter to current late winter–early spring period distinguished the chronologies of the Tyrrhenian and Sardinian coasts, both for the two periods analysed (Fig. 5a and b).

Indeed, the chronologies from the Tyrrhenian coast (ALB and ROM) were positively correlated with precipitation sum

and proportional to its component loading. **b** The height values on the y-axis indicate the squared Euclidean distance between variables according to the clustering algorithm, based on Ward's method

up to January, while the chronologies from the eastern and western coasts of Sardinia (BID and ISARB) up to March–April.

Spring and summer temperature was influential only in the Sardinian coast, showing from the early 1980s also common negative correlations during late spring (Fig. 5b).

The SPEI represented water availability, and the linear dependence on precipitation was higher in the Tyrrhenian coastal areas than in the Sardinian ones, and ranged from R^2 adjusted=0.88 vs 0.71 during the autumn–winter period to R^2 adj=0.56 vs 0.42 during summer ($p<0.001$). Maybe for this reason, growth responses to SPEI showed similar correlations to those found using precipitation, especially during the stabilised growth rates period (Fig 5b). Although this index revealed a macroclimate signal common to all sites (OND), it summarised also the negative effect of late spring–summer temperature mainly in the Sardinian stands (Fig 5a). In fact, negative correlations were found between BID and late summer–early autumn temperatures of the current year (aso), and between ISARB and late spring–summer temperature (mjj and jja).

An even more remarkable difference in growth responses to climate was found when considering the drought conditions expressed by PDSI, especially at a local scale.

Growth responses to PDSI were positive at each site, and increased with the increase of drought conditions. ISARB resulted the most sensitive site to drought. The main geographical pattern appeared to be the common and positive

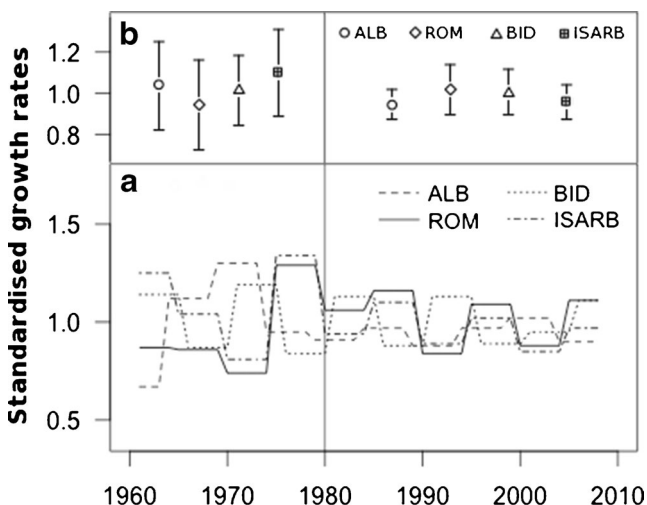
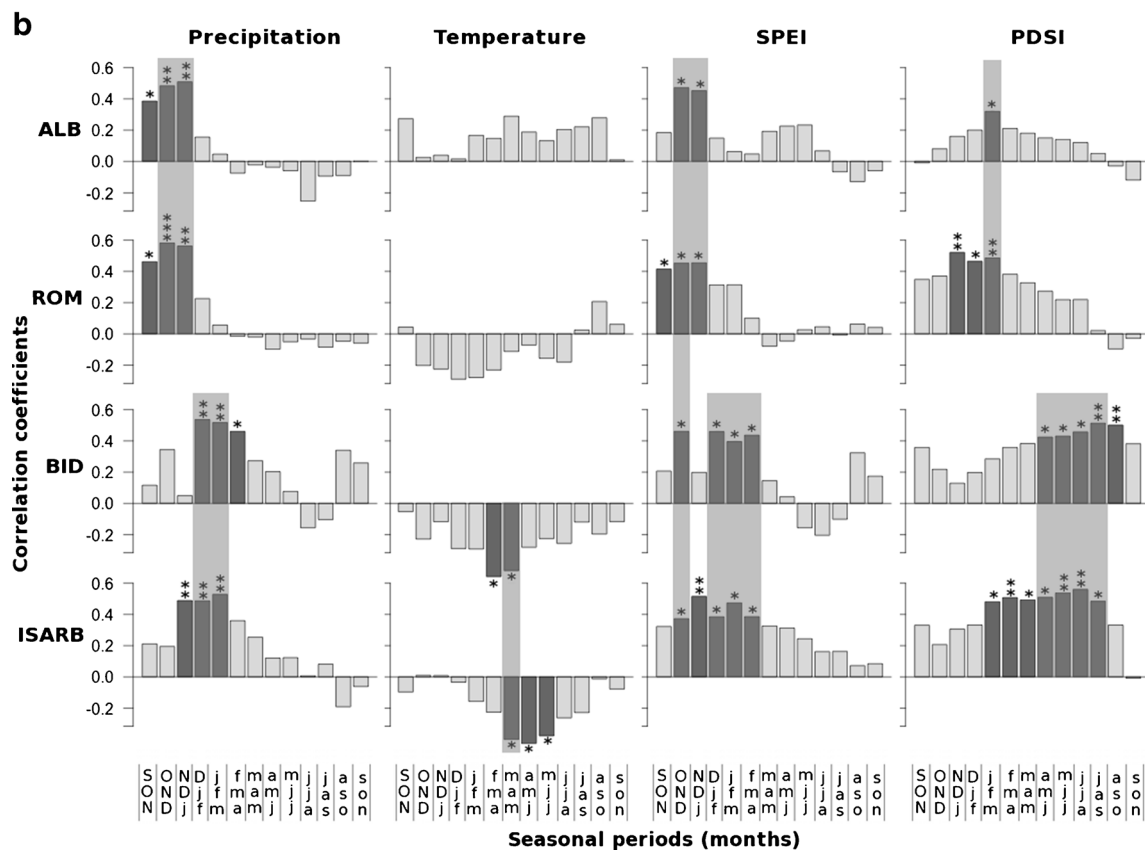
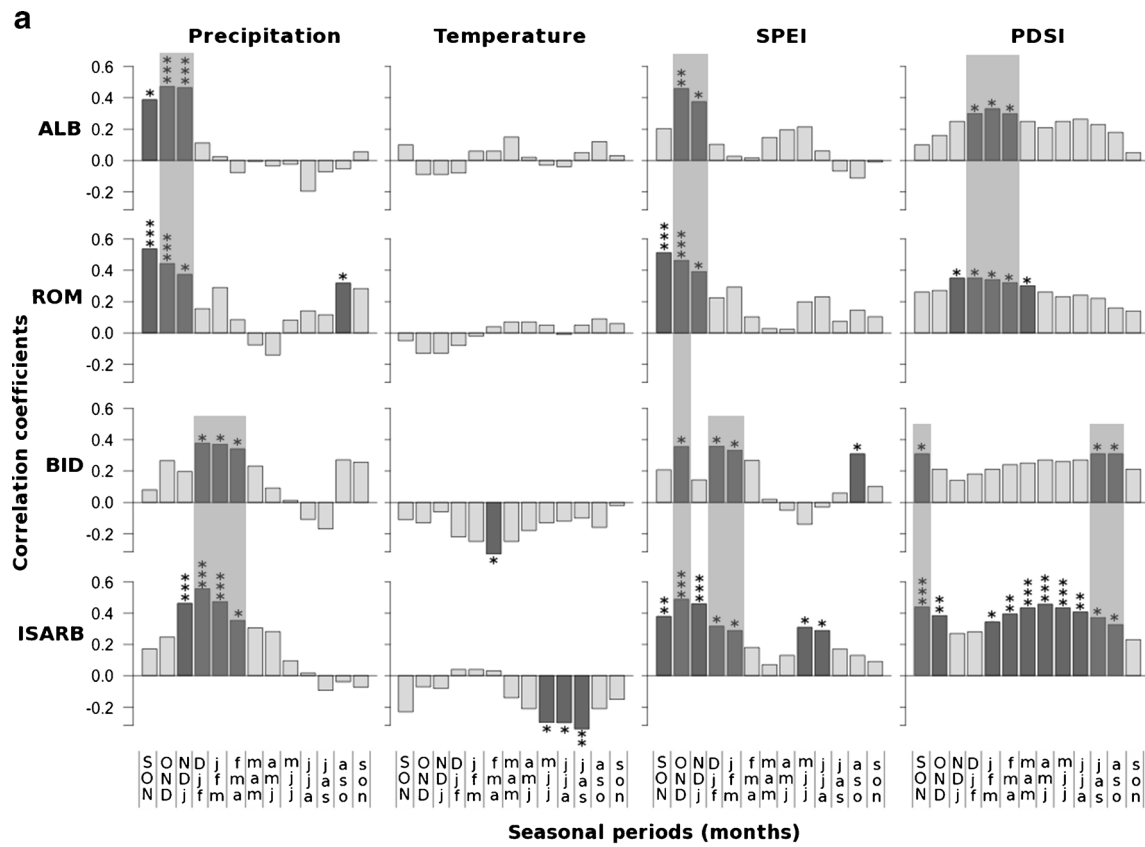


Fig. 4 Growth rate trends represented by the 5-year average of the standardised tree ring widths (**a**) and growth rates average±standard deviation for each site (**b**), during the two periods analysed

Fig. 5 Pearson's correlation coefficients between standardised TRW and climate variables at a seasonal scale during the whole common period 1961–2008 (**a**) and from the 1980s (**b**). The *dark bar charts* indicate significant values. *: $p<0.05$; **: $p<0.01$; ***: $p<0.001$. The *shaded areas* indicate the common climatic predictors driving radial growth at monthly and seasonal scale



response to late summer values of PDSI (jas) of the eastern and western coast chronologies on Sardinia, remaining significant also after the 1980s (Fig. 5a and b). Moreover, from the 1980s in the Sardinian stands, the PDSI influence was significant for all late spring–summer months (Fig. 5b).

The northernmost site along the Tyrrhenian coast (ALB) was positively correlated with PDSI from winter to early spring, while ROM extended the sensitive to PDSI for the whole spring season (Fig. 5a). From the 1980s in the Tyrrhenian stands, the common growth response to PDSI remained significant only for the late winter–early spring period (jfm — Fig. 5b).

4 Discussion

Within the Mediterranean basin, the influence of climate on *P. pinea* growth was analysed in most cases at local scale (Akkemik 2000; Campelo et al. 2006; Cherubini 1993; De Luis et al. 2009; Galli et al. 1992). Our chronologies were constructed from a representative range of pine forests in sites characterised by different drought conditions at regional and local scale. Therefore, this tree-ring network can provide significant growth responses to climate, displaying a spatial trend of increasing drought conditions.

Indeed, although the productivity of ALB site seems to be closer to the Sardinian ones, after the standardisation procedure the climate–growth relationships showed clear spatial patterns according to site-specific climatic conditions.

The principal climatic differences were the lower summer–early autumn precipitation (resulting in an extension of the dry summer season until September) and the higher autumn–winter temperatures on the Sardinian coast relative to those of the Tyrrhenian areas. Moreover, autumn is the rainiest season at the Tyrrhenian sites. In contrast, no significant differences between autumn and winter precipitation were found in the drier sites of Sardinia. The high amounts of autumn–early winter rainfall in the Tyrrhenian sites reflected the high positive correlations with 3-month precipitation sums from September of the previous year to January, highlighting its importance on water availability due to soil recharge (Campelo et al. 2006). The water supplied by these precipitations is not stratified on the top layer, especially in the sandy soils. Consequently, this water pool is used by pines' deeper roots, typical of the mature trees, resulting in the principal water input for tree growth at the beginning of the next growing season. Moreover, pine roots in the first 15 cm of the ground surface were rare and tended to increase below 20 cm; on the contrary, shrub roots tended to pick in the first 5 cm (Frattegiani et al. 1994). Therefore, the capacity to use water from deeper soil horizons allows the pines to avoid the very strong competition exerted by Mediterranean shrubs, characterised by a dense and shallow root system, near the soil surface.

Previous studies in semiarid sites showed that the correlations between precipitation and growth increased when considering the cumulative precipitation over a period of consecutive months (De Luis et al. 2009; Linares et al. 2010). Our results based on cumulated 3-month seasonal periods showed in addition a shift of the main significant precipitation inputs from previous autumn–winter to current early–spring when increasing drought conditions.

Although a true winter dormancy has been observed in response to low temperature (Liphshitz et al. 1984), the higher January–February temperatures recorded in the Sardinia sites could represent an early interruption of winter dormancy, which would result in an extension of the growing season. Most likely for this reason, the Sardinian chronologies showed also significant correlations with the late winter–early spring precipitation sum from December to March–April.

The northernmost site chronology (ALB) was mainly limited by water stress prior to the growing season, with characteristic positive effects of moister autumn–winter. This growth pattern was also shared by the Roman coast chronology, revealing in addition a sensitivity to spring water deficit. On the other hand, Sardinian chronologies seemed to experience drought conditions both during spring and summer–early autumn periods, as shown by the negative responses to temperature and positive responses to both SPEI and PDSI. Moreover, considering the coupled effect of the two drought indexes, trees from Sardinian sites showed a bimodal pattern of sensitivity to water availability, characterised by significant correlations both during winter–early spring and summer–early autumn periods. This result may suggest that water deficit limits *P. pinea* growth also during early spring and late summer months in sites with higher drought conditions. Indeed, drought restricts some physiological processes that occur during this period, such as shoot elongation, cone development, bud lengthening, and phloem growth (Liphshitz et al. 1984; Mutke et al. 2003; Piraino et al. 2013). Hence, the expected reduction in summer soil moisture across the Mediterranean basin caused by decrease in precipitation, along with more severe evapotranspiration processes, might induce a decline in *P. pinea* radial growth and favour more xerophilous pine species as *Pinus halepensis* and *Pinus brutia*. Indeed, these species elude unfavourable conditions related to water deficit during summer drought by stopping growth and closing stomata (Aussenac and Valette 1982; Vila et al. 2008).

Growth responses to climate have largely been attributed to the geographical-scale variability in climate patterns, but also structural stand variables, such as mean DBH, could influence tree ring widths and consequently climate–growth relationships. The first standardization step applied here, which was based on dividing each TRW chronology by the mean width of that particular chronology, allowed us to minimize the size-mediated climate–growth relationships. Moreover, other

possible sources of bias involving the selective trees sampling were unlikely because the social ranking is strongly conserved in pine stands (Vila et al. 2008).

Our findings revealed contrasting climatic signal retained in tree-ring widths depending on the increase in dry conditions, especially in winter–early spring and late summer. This contrasting climatic signal supports the hypothesis that tree growth on dry sites was effectively more controlled by climate than on humid sites (Lebourgeois et al. 2012).

Because water stress is one of the main factors limiting the growth of the species, detecting differences in growth responses to site-specific climate patterns may allow selection of more appropriate mitigation and conservation strategies. Therefore, under predicted climatic scenarios including summer droughts of increasing severity in Mediterranean basin, silvicultural management can guarantee a greater flow of under-canopy water, increasing soil-water availability and improving stand growth rates (Aussenac and Granier 1988; Mazza et al. 2011).

5 Conclusions

The influence of climate on *P. pinea* tree growth showed a clear spatial grouping related to regional variation in climatic features. The primary role of precipitation represented a common macroclimatic signal, but different responses strongly dependent on geographical variability in rainfall inputs were highlighted during the periods that most influence tree ring formation. The decrease in winter–early spring rainfall, occurring with the upward trends of temperatures recorded in the last decades and summer drought conditions, appeared to be the principal climate-driven growth patterns, distinguishing the chronologies of the Tyrrhenian and Sardinian coasts. Consequently, the greater difference in tree growth between these two groups may be linked to a strengthening of water stress during the beginning of the growing season when a large part of a tree-ring is formed. In addition, summer drought constraints may drive some physiological processes in drier sites, resulting in a reduction of radial growth.

Future studies should consider climate-driven growth patterns along drought-gradient conditions at a bigger geographical scale within the Mediterranean basin, with the aim to investigate growth responses to recent climate change of natural and artificial populations of the species across most of its present range.

Acknowledgments This research was funded by the Municipality of Rome project “Management of stone pine (*Pinus pinea* L.) pinewood within the National Natural Reserve of the Roman Coast” and partially financed by the Italian Ministry of Agricultural and Forestry Policies project Ri.SELV.ITALIA – 3.1.1 “Management and conservation of stone pine coastal stands”. The research was also funded by Ente Foreste della Sardegna within the research project “Aboveground biomass and carbon

equations of stone pine in Sardinia”. We are grateful to the personnel from Castelporziano Presidential Estate, Azienda Regionale di Alberese and Maremma Regional Park, and Ente Foreste della Sardegna for site access and collaboration. We also wish to thank the colleagues from the Forestry Research Centre (CRA-SEL) that helped in the field work and the two anonymous reviewers for their useful comments.

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