

Growth rate and climate responses of *Pinus pinea* L. in Italian coastal stands over the last century

Gianluigi Mazza · Maria Chiara Manetti

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Abstract Sensitivity to climate change and anthropogenic disturbance is a typical feature of Mediterranean forests, which grow under dynamic and manipulated environmental conditions. In this study, we examine stone pine (*Pinus pinea* L.) along the Tyrrhenian coast of Italy to analyse the tree-growth variability on a temporal scale and to evaluate the radial growth response to climate trends over the last century. The analysis of tree ring widths at the decadal and multidecadal scale, which were standardised to remove the age trend, showed primarily significant downward trends and time periods with lower growth rates. Characterised by a clear decline in tree ring widths, the two periods of 20 years from the mid-1920s and the early 1970s appeared to be the least favourable for tree growth. Precipitation was the main factor driving growth, and the effect was cumulative over consecutive years because of the increase in soil water content. Including the current year of ring formation, correlations between decline in precipitation and tree growth were greatest with 3-year precipitation sums. The shifting influence of winter rainfall on tree ring growth toward not significant values during the last decades, together with the lack of significant correlation between the current year's precipitation and growth decline from the 1970s, might suggest an increasingly dependence on long periods of water supply to utilise the water content stored due to the previous rainy years. The negative effect on tree-growth decline of summer and early-fall temperatures appeared as a forcing influence related to long-term changes in climate rather than high-frequency climate fluctuations.

1 Introduction

Climate change is one of the major challenges for forestry in the coming decades since it is expected to drastically modify growing conditions for trees (Resco de Dios et al. 2007). Although forest stands show some plasticity to deal with unstable environmental conditions, ecophysiological processes are affected by changes in timing and duration of water stress.

The phenology of Mediterranean coniferous forests is mainly driven by water availability, and significant drought periods can affect the leaf area index for several years because fewer and shorter needles will reside for several years on the tree after a drought period (Kramer et al. 2000). Consequently, longer and more severe dry seasons and associated water shortages could

G. Mazza (✉) · M. C. Manetti
Consiglio per la Ricerca e la Sperimentazione in Agricoltura,
Forestry Research Centre, Viale S. Margherita 80, 52100 Arezzo, Italy
e-mail: gianluigi.mazza@entecra.it

seriously affect tree growth and reduce the net primary productivity of the stands (Osborne et al. 2000).

Global climate models project a decrease in precipitation in most of the Mediterranean basin and changes in the pattern of precipitation distribution (Brunetti et al. 2006; Dünkeloh and Jacobeit 2003; Gibelin and Dèquè 2003; IPCC, WG I 2007). When considering the Italian average over the 1865–2003 period, there has been a decrease of 5 % per century in the annual precipitation amount (Brunetti et al. 2006). Central Italy, which comprises the coastal areas of the Tyrrhenian Sea, is the region with the most evident negative trends in total and seasonal precipitation: a decrease of 10 % per century on a yearly basis, and 20 % and 13 % decreases per century in the spring and summer, respectively.

The Mediterranean area is especially sensitive to climate change because it represents a transition zone between the humid western and central European domain and the arid North African desert belt. The climate of this region include a high variability of precipitation on monthly, inter-annual and inter-decadal time scales (Dünkeloh and Jacobeit 2003), which strongly influences the interrelations between the water resources and water availability and the ecosystem functions and land-use changes. Consequently, we need to know how the trees might react to climate change and increasing variability in the climate. Stone pine (*Pinus pinea* L.) is one of the most important Mediterranean pine species. This species is characteristic of the Italian coastline, and its plantation dates back to the Roman period. It has traditionally been cultivated for timber and pine nuts, and in the last few decades it has acquired a high recreational and landscape value. The extensive root system and the large crown make the species resistant to strong winds; for these reasons, stone pine has been used for the consolidation of sand dunes and to protect soil from erosion in exposed coastal areas. Moreover, the multi-layered root system permits the mature trees to obtain water from different levels of the soil profile and from various sources of water: precipitation, soil water and the water table (Fratteggiani et al. 1994).

In most cases, stone pine stands have become densely overgrown, reducing the flow of under-canopy water reaching the ground, particularly in the driest months and for lower amounts of precipitation (Mazza et al. 2011). Consequently, several years of drought affect growth more severely than each year independently (Kramer et al. 2000), reducing the water content stored due to previous rainy years. Thus, as precipitation decreases, it might be the case that *P. pinea*, like other Mediterranean pines (e.g., *P. halepensis* s.l.), responds by becoming increasingly dependent on moisture from deeper soil horizons that has not been exhausted during previous years (Sarris et al. 2007).

Several studies have demonstrated the stone pine's high sensitivity to autumn and winter precipitation (Campelo et al. 2006; Cherubini et al. 2003; De Luis et al. 2009; Perez-Antelo and Fernandez-Cancio 1992; Raddi et al. 2009) by highlighting its growth responses to soil water recharge. Therefore, if precipitation is the main growth-driving factor for stone pine, then the expected drought effects and associated increase in water demand for human activities (tourism, agriculture, high rate of urbanisation) could affect the availability of water for the pinewoods and induce a severe growth decline and tree dieback.

By comparing tree-ring widths for similar age periods of younger and older pine chronologies grown under different climate conditions, this paper examines the growth rate of *P. pinea* in Italian coastal stands and how that rate is related to the climatic trends over the last century.

To detect climate driven patterns and climate sensitivity to low and high frequency signals in tree-ring growth at temporal scale, a detrending approach based on decomposing tree ring width time series into age classes is also conducted for capturing long-timescale variability (Briffa et al. 2001). This method reveals additional climatic information retained in the chronologies of relative growth changes, integrating the classical moving correlation function analysis.

2 Materials and methods

2.1 Study sites and climate data

The research was conducted in three important and typical pine forests of the Tyrrhenian coast, derived by plantation, along two coastal area of central Italy (Fig. 1): 1–Alberese, 42°39' N, 11°03' E, which is inside the Maremma Regional Park (Tuscany), and 2–Castel Fusano (41°43' N, 12°19' E) and Castelporziano (41°42' N, 12°24' E), which are both inside the Natural Reserve of the “Roman coast” (Latium). We selected these two sampling areas for the presence of pine stands characterised by several age classes, with the oldest approximately 150 years old. The study sites are located on the sand dune ecosystem within each pinewood, at least 1 Km from the shoreline 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 pines growth. These pinewoods are characterised by a dominant crop layer of *Pinus pinea* with holm oak (*Quercus ilex* L.) and other typical broadleaf maquis shrubs (*Phyllirea* sp., *Arbutus unedo* L., *Pistacia lentiscus* L., *Rhamnus alaternus* L., *Erica multiflora* L., *Myrtus communis* L.) that dominate the subcanopy, and have not had regular silvicultural management.

The soils are primarily made of stabilised old dunes and contain a free water table. The rainfall represents the only available input of freshwater for these sand surfaces over which the pines grow.

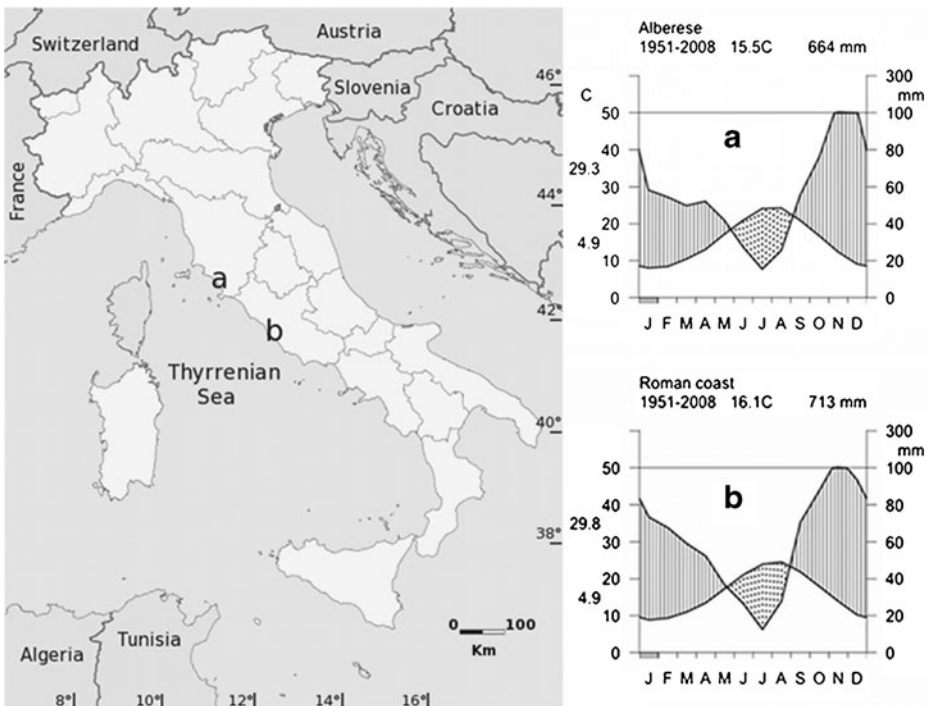


Fig. 1 Location and Walter & Lieth climatic diagrams of the study sites: **a**–Maremma Regional Park (Alberese pinewood) and **b**–Natural Reserve of the “Roman coast” (Castel Fusano and Castelporziano pinewoods). The dotted areas indicate the season with water deficit

Due to the lack of representative meteorological long-term dataset, we used the datasets of the Climate Research Unit (CRU), University of East Anglia, UK, for mean temperature and total precipitation in the period 1901–2006, gridded on a $0.5 \times 0.5^\circ$ network. To assess the presence of climatic trends, we applied the Mann-Kendall (τ) non-parametric test (Brunetti et al. 2006; Dünkeloh and Jacobeit 2003; Hamed 2008). The climate of the two areas is typically Mediterranean, with limited yearly precipitation concentrated in the period from late autumn to early spring and a dry summer in which July is the driest month (Fig. 1). This climate can be described as mesothermic and can comprise the dry-subhumid and semiarid classes.

2.2 Trees sampling and dendrochronological analysis

At each site, we selected only healthy dominant or co-dominant straight trees with a symmetric canopy without any visual injuries to the crown and stem. Two cores per tree were extracted with a 5-mm diameter increment borer at breast height on the cross-sides of the trunk. The increment cores were prepared according to the following standard dendrochronological procedures (Fritts 1976; Schweingruber 1989): the cores were mounted on channelled wood holders, air dried and sanded with progressively finer grade abrasive paper (with 200P and 600P sand paper) to produce a polished surface on which tree-ring boundaries were clearly visible under magnification. In the laboratory, the tree-ring widths were measured from bark to pith with a 0.01-mm precision by a computer-linked mechanical platform under a stereoscope. Each ring-width series was first visually checked and then statistically checked for cross-dating and measurements errors using the dendrochronology program library in R (dplR) (Bunn 2010). The series weakly correlated with the master site chronology were corrected when possible or discarded. The age of cores containing the pith was determined by counting the calendar years assigned to the tree-rings from bark to pith.

Then, trees were classified into three age classes: young (Y–13 trees; <55 years), medium (M–19 trees; 56–90 years) and old (O–17 trees; >100). Due to the same grid box of climate data and the high degree of synchrony over time, the chronologies of the two Roman coast pinewoods were averaged. Descriptive statistics of the tree-ring chronologies are indicated in Table 1.

2.3 Standardization and chronologies computation

In detrending the tree ring growth (age-dependent trend), we used two methods: 1) the age band decomposition method (ABD) (Briffa et al. 2001), which is based on decomposing the tree ring

Table 1 Main statistics of the tree-ring chronologies (old: O; medium: M; young: Y)

Chronology	N° trees/N° cores	Time span (n° of years)	MRW (mm)	SD (mm)	AC(1)	MS	rbar.bt/N° trees	EPS
Alberese O	22/42	1861–2010 (150)	1.30	0.94	0.058	0.310	0.55/18	0.95
Alberese M	26/49	1924–2010 (87)	1.66	1.18	–0.095	0.270	0.54/22	0.98
Alberese Y	10/20	1962–2010 (49)	2.56	1.70	0.115	0.257	0.78/10	0.98
Roman coast O	37/63	1843–2009 (167)	2.46	2.64	0.083	0.235	0.64/31	0.98
Roman coast M	30/53	1945–2009 (65)	2.19	1.86	0.083	0.239	0.62/28	0.98
Roman coast Y	30/55	1957–2009 (53)	3.28	2.19	0.174	0.352	0.80/29	0.99

Mean ring width (MRW) and standard deviation (SD), computed on the raw tree-ring series; first-order serial autocorrelation (AC1), mean sensitivity (MS), mean correlation between trees (rbar.bt) and expressed population signal (EPS), computed on the indexed tree-ring series

width data into age classes with the aim of comparing similar life periods of young, medium and old tree chronologies (Sarris et al. 2011), and 2) the “classical” approach, which is based on indexes of tree-ring data obtained by fitting each series with the typical functions that retain the high-frequency climatic information, according to standard dendroclimatic procedures. These two different detrending methods were used with the aim to detect both low and high frequency climatic signals in tree-ring chronologies.

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). To remove the age trends, we standardised each age-banded tree ring series by dividing each band by the mean of the tree ring widths of all trees within that age band. For all the tree ring chronologies, we used a narrower banding up to 100 years old (10-year bands) to account for the faster rate of change in TRW with tree age (Briffa et al. 2001). Wider bands (20 years) were used after this threshold (e.g., a 140-year-old chronology produced ten 10-year bands and two 20-year bands). Finally, by averaging all the age-band series together, we produced the final time series of the tree ring widths. This final time series was used to compare the same age classes of the younger and older chronologies independent of the calendar year. Significant differences between the TRW decadal and the multidecadal means of these age classes were detected using the analysis of variance (ANOVA) and the Tukey HSD test for multiple comparisons of averages. Both the ANOVA and Tukey tests were applied to the standardised tree-ring data after testing the normal distribution with the Kolmogorov-Smirnov and Shapiro-Wilk tests.

In the “classical” approach, the individual TRW series were used to compute a mean chronology for each area in a two-step standardization procedure using the *dplR* library (Bunn 2008) and the “*detrendeR*” package. To remove the decreasing trend in the series that resulted from the tree circumference increase with time, each tree-ring series was first standardised by fitting a negative exponential curve to the measured data series. The smoothing spline closely follows the “*n*-year spline” approach first described by Cook and Peters (1981) was used as second standardisation procedure. The expected growth (G) at time t was calculated as a spline with a 50 % frequency response of 20 years. Flexible cubic spline curves guarantee the removal of most non-climatically related variances, such as biological trends or the effect of localised disturbance events always present in the course of forest dynamics, by preserving high-frequency climatic information (Cook and Peters 1981). The indices were calculated as ratios between the actual and fitted values. The index values were then prewhitened using an autoregressive model selected on the basis of the minimum Akaike information criterion and combined across all series using a bi-weight robust estimation of the mean to exclude the influence of the outliers (Cook et al. 1990). The mean correlation between trees (r_{bar}) was computed to assess the synchronization in the annual growth patterns among sampled trees and the common signal strength indicated by the mean growth chronologies.

The chronologies reliability was tested using the Expressed Population Signal (EPS) (Briffa and Jones 1990; Wigley et al. 1984). This statistic quantifies the degree of year-by-year growth variations shared by trees in a population of the same site. Only those series with a high common signal ($\text{EPS} \geq 0.85$) were included in the analysis.

2.4 Climate-growth relationships

For the 1901–2006 period, the influence of climate on tree-ring growth was investigated using a correlation function (CF) analysis (Fritts 1976) based on Pearson’s correlation coefficient. We used 26 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.

To detect and assess the stationarity and the trend of the correlation functions over time, we computed moving correlation functions (MCF) for the same monthly variables using a 50-year window progressively shifted over the last century. This analysis allowed us to detect time-dependent changes in the significance of the tree-ring growth–climate relationships. Pearson’s correlation coefficients were tested for significance using the 95 % percentile range method after a bootstrap process, adopting 1000 replications with the “bootRes” package in R programme. For MCF, the ‘false discovery rate’ approach (Benjamini and Hochberg 1995; Carrer et al. 2010), implemented in the R package “fdrtool”, was applied for multiple test correction of the correlation coefficients.

The decline of tree-growth was also related to the precipitation and temperature during the same calendar period using the Spearman rho (ρ) non-parametric correlation coefficients, due to the non-normal distribution of climate data. To evaluate any possible effects of previous rainfall years on tree growth, we tested the annual precipitation (from December to October of the current year) and precipitation cumulated over 1–3 years prior to the year of tree ring formation (from October $t-n$ to October t , with n ranging from 1 to 3 previous years, according to the correlation functions predictors). The Bonferroni method was used for multiple comparisons correction of the significance levels.

3 Results

3.1 Growth rate trend over the last century

Decomposition of the tree ring widths produced 14 age bands. Both mean chronologies of Alberese and Roman coast indicated a significant decline of tree growth from the 1920s (Fig. 2). The growth rate, which was expressed as the mean standardised TRW, decreased at the multidecadal scale (50 years) during the first and second half of the twentieth century when compared with the previous half century, 1850–1900 (21.0 % and 28.2 %, $p < 0.001$, respectively). When compared with the period 1900–1950, a significant decline was also observed during the second half of the twentieth century (9.3 %, $p < 0.05$). At the decadal scale, the mean growth rate indicated a similar trend.

By averaging all of the age-band time series, standardised by site effects and age trend, a significant and common decrease in the tree ring widths was detected during the first half of the twentieth century (ranged from $\tau = -0.58$ to $\tau = -0.72$, $p < 0.01$), and again beginning in the middle 1960s (from $\tau = -0.35$, $p < 0.05$, to $\tau = -0.44$, $p < 0.01$).

When analysing the early life-phases of tree growth (1–20 and 21–40 year periods of each age class chronology), we found significant differences between the average tree growth of the three age classes for both decades (Fig. 2). The last decades of the twentieth century appeared to be the least favourable for tree growth and were characterised by a clear decline of tree ring widths in all sites examined. The growth rate indicated by the younger chronology during the 1–20 year period (1956–1975) significantly decreased (20.4 %, $p < 0.05$) when compared with the growth rate indicated by the medium chronology during the same life period (1914–1933). When considering the second two decades (21–40 year period), which corresponded to the period 1976–1995 for the younger chronology, a second significant decrease was observed (22.3 %, $p < 0.01$) when it was compared with the decrease indicated by the older chronology during the same life phase (1860–1879).

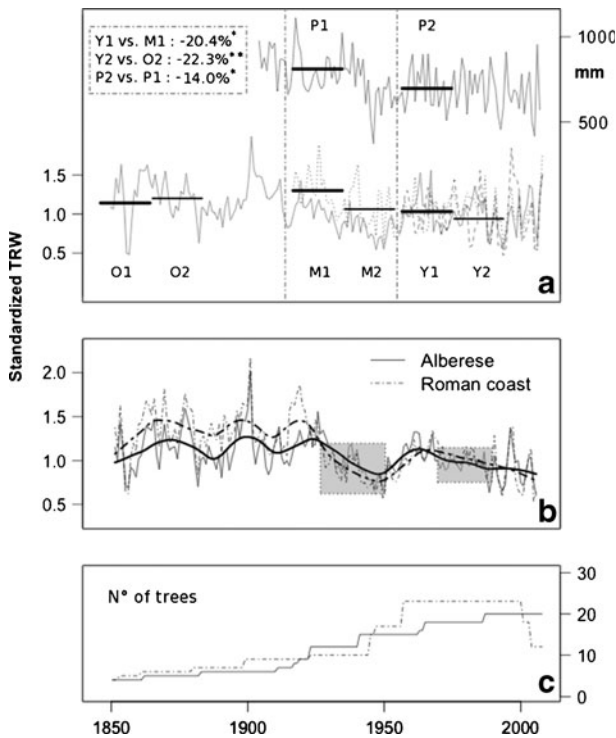


Fig. 2 **a** Standardised tree ring widths chronologies for old (O), medium (M) and young (Y) age classes, and annual precipitation (P) combined at all of the sites. *Horizontal lines* represent the average tree ring widths for two decades in the three age class chronologies when compared during their same youth life periods: 1–20 years (*bold line*) and 21–40 years (*thin line*). The *legend box* indicates the significant multiple comparisons; *: $p < 0.05$; **: $p < 0.01$. **b** Standardised TRW, smoothed by a Loess non-parametric function, of the two coastal areas combined at all of the class chronologies. The *shaded areas* indicate the life periods with a significant decline in tree growth. **c** Total number of trees

3.2 Climate influence on tree growth decline

The precipitation and tree ring chronology time series indicated similar trends (Fig. 3). During the first half of the twentieth century, the period characterised by tree growth decline was correlated with the decrease in annual precipitation, for both the Alberese and Roman coast sites ($\rho = 0.65$ and $\rho = 0.61$, $p < 0.05$, respectively). Including the current year of ring formation, correlations between precipitation and tree growth increased when considering the precipitation amount accumulated during the previous years. The higher correlation coefficients were found with the precipitation cumulated over 2 years ($\rho = 0.80$ and $\rho = 0.75$, $p < 0.001$, respectively). In the second period of tree growth decline, from the mid 1970s to the late 1990s, significant correlations were achieved only with precipitation cumulated over 2–3 years (Table 2). On the other hand during the period with higher growth rates, characterised by wetter climatic conditions, no significant correlations were found.

Precipitation also indicated negative trends during the early life-phase of tree growth and was characterised by a significant decrease in tree ring widths when compared at the decadal scale. In fact, rainfall from 1956 to 1975 (corresponding to the first two decades of the

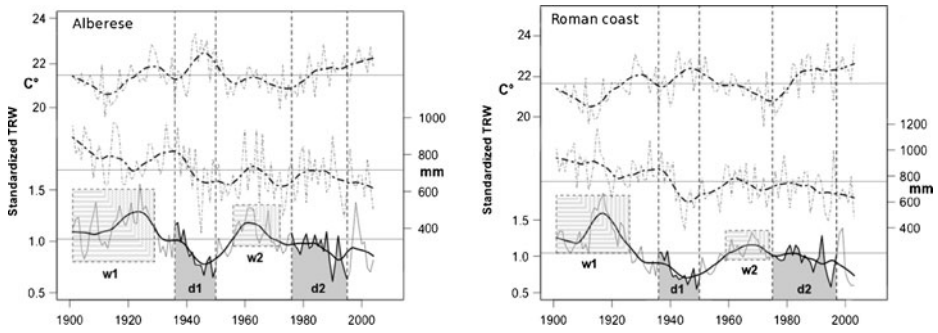


Fig. 3 Trends of the standardised TRW, smoothed by a Loess non-parametric function, and climatic variables (annual precipitation and June–October temperature) at each coastal area. The shaded and dotted areas indicate the life periods with lower and higher growth rates, corresponding to drier and wetter climatic conditions, respectively

Young age class chronology) demonstrated a significant decrease of 14.0 % ($p < 0.05$) when compared with the period 1914–1933 (the first two decades of the Medium chronology).

Considering the mean temperature, both periods analysed showed upward trends ($\tau = 0.38$ and $\tau = 0.36$, $p < 0.01$, respectively) (Fig. 3). Although this similar climatic pattern, the influence of temperature on the decrease in tree-ring widths showed contrasting correlations over the century. Considering the summer and early-fall period, significant and negative correlations with tree growth decline were found only during the first half of the twentieth century ($\rho = -0.69$ and $\rho = -0.62$, $p < 0.05$, for Alberese and Roman coast sites, respectively).

3.3 Climate-growth relationships

After detrending was conducted using the classical approach, the expressed population signal (EPS) value was 0.98, which suggests that the year-to-year growth variation shared

Table 2 Correlation coefficients during the drier (d) and wetter (w) periods between the standardised TRW and climatic variables: the sums of previous precipitation years (Pre), ranged from October $t-n$ to current October (with n ranging from 1 to 3 years prior to ring formation), and mean temperature (Tm) from June to October of the current year

ρ (Spearman)	Climatic variables	Time periods			
		d1	d2	w1	w2
Alberese	Pre (t)	0.65*	0.07	-0.03	0.08
	Pre (t+1)	0.64*	0.55*	-0.15	0.01
	Pre (t+2)	0.80***	0.56*	-0.31	0.36
	Pre (t+3)	0.76***	0.36	-0.24	0.30
	Tm (Jun–Oct)	-0.69*	-0.10	0.14	0.46
Roman coast	Pre (t)	0.61*	0.03	0.11	-0.05
	Pre (t+1)	0.59*	0.58*	0.09	0.12
	Pre (t+2)	0.75***	0.60*	0.18	0.20
	Pre (t+3)	0.62**	0.41	0.19	0.36
	Tm (Jun–Oct)	-0.62*	-0.14	-0.28	-0.44

Bold type coefficients are significant at: * $p < 0.01$; ** $p < 0.001$; *** $p < 0.0001$, after the Bonferroni correction for multiple comparisons

by the trees was high. The correlation functions calculated between each tree-ring chronology and climate series indicated the primary climate factors influencing tree growth (Fig. 4). Precipitation appeared to be the most important factor, and the growth responses to the autumn and last-winter precipitation were highly and positively significant. The November precipitation of the year prior to the ring formation ($t-1$) was the monthly climate variable primarily correlated to growth, in both areas (Fig. 4a).

The MCF profiles confirmed the previous results (Fig. 4b). This confirmation highlights the importance of autumn precipitation over the twentieth century. October and November $t-1$ precipitation was the common and significant climate-sensitive signal (for Alberese and Roman coast pinewoods, respectively), exhibiting a stationary response over time. On the other hand contrasting growth responses to winter precipitation were found over the century. The MCF profiles indicated that the significance of winter precipitation (from December to February) on TRW shifted over time, and was negligible during the last few decades.

4 Discussion

4.1 Tree-growth over the last century

The analysis at the decadal and multidecadal scales of tree ring widths, highlighted the significant downward trends and the time periods with lower growth rates. The growth trend analysis over time conducted in this study used a similar approach based on the age band decomposition method adopted in Briffa et al. (2001) and Sarris et al. (2011) and showed a

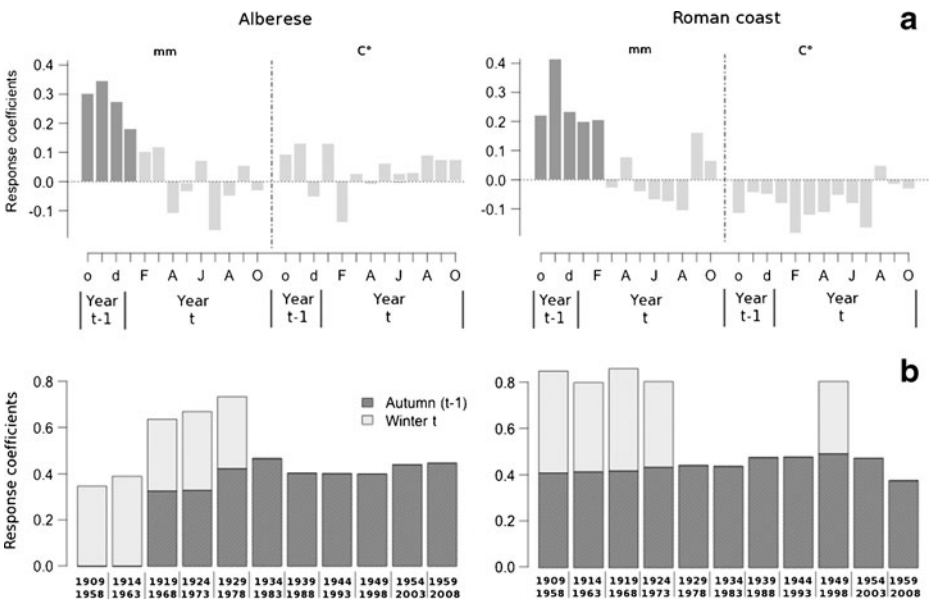


Fig. 4 Regular (a) and moving (b) correlation functions (computed using a 50-year moving window) between the tree-ring indexed chronologies and the total monthly precipitation and mean monthly temperatures for the previous (October to December) and current (January to October) growth year, for the period 1901–2006. **a** The dark bar charts indicate a 95 % bootstrapped significant values. **b** The average of the significant correlation coefficients, adjusted according to the ‘false discovery rate’, for Autumn (October and November $t-1$) and Winter (December $t-1$ and January–February t), were displayed

clear decrease in tree ring widths during two separate periods of the twentieth century. The second half of the century was characterised by lower growth rates when compared with past growth. In this period the decrease in tree ring widths ranged from 21 % at the decadal scale to 28 % on a larger time scale, when using a multidecadal mean of standardised TRW.

During the first years of life, the even-aged stands of *Pinus spp.* have high radial growth rates. These high rates are induced only by shrubs and understory vegetation competition because of the light-demanding behaviour typical of the pioneer species. Although the competition in planted pinewoods was not as strong as in naturally regenerating pines, the climatic signal in this establishment phase was not well recorded. When considering that *P. pinea* was usually planted using 1- to 2-year-old plants (Bussotti 1997) and that the first few years of tree growth are not counted when coring at breast height, the establishment phase was avoided. Thus, when comparing similar life periods of the three age class chronologies irrespective of the calendar year, the early life-phases of the younger chronology showed lower growth rates than the rates of the Medium and Old tree age classes. Compared with the same life periods of the two other age class chronologies that dated back to the beginning of the twentieth century and the second half of the nineteenth century, the tree ring decadal means of the Young age class decreased significantly from 1956 to 1975 and during the period 1976–1995. Sarris et al. (2011) reported similar trends in the eastern Mediterranean (Greece). That study also showed the growth decline in *Pinus halepensis* Miller tree ring widths during the last decades of the 20th century, thus suggesting a significant influence on tree growth of recent climatic change across the Mediterranean basin.

4.2 Precipitation as the primary growth driving factor

The influence of precipitation on the growth responses of *P. pinea* along the Mid-Tyrrhenian coast of Italy was clear during the two periods of the 1900s analysed in this study. Significant negative growth responses to the decrease in precipitation have been found in the second half of the twentieth century. This result was determined by comparing the early life-phases of the tree age classes at the decadal scale. In our analysis during the two periods 1956–1976 and 1976–1995, both of which were characterised by lower decadal means of the standardised TRW, the annual mean precipitation decreased by 13.6 % and 15.9 %, respectively.

When considering the annual mean precipitation from October $t-n$ to October t , with n ranging from 1 to 3 years prior to the year of ring formation, the tree growth decline indicated significant correlations with downward trends of precipitation. The higher correlation coefficients were found during the first period of decrease in tree-ring widths, especially with 3-year accumulated precipitation. From the mid 1970s, no significant correlation with the current year's precipitation was found, and the previous rainy years influenced significantly only up to 2 years prior to the ring formation. These results might suggest an adaptation to the precipitation reduction from the mid-twentieth century and, consequently, an increasingly dependence on long periods of water supply to utilise the water content stored due to the previous rainy years.

After the late 1970s, a clear drought impact on tree growth was also found in the eastern Mediterranean (Greece), where the decrease in precipitation was significantly associated with the reduced tree ring width in *Pinus brutia* (Ten.) (Sarris et al. 2007). Along the Tyrrhenian Sea in Tuscany, another study confirmed the influence of precipitation cumulated over consecutive years on tree growth (Raddi et al. 2009). These authors found, at a monthly scale, the highest correlations between a tree growth index and precipitation in June, November and December, or only November and December, cumulated over 3 years.

The primary role of precipitation on tree growth responses to climate was also highlighted by correlation functions (CF). The tree ring widths indicated a positive correlation with precipitation from October ($t-1$) to January–February (t), thus suggesting the importance of late autumn and

winter precipitation on water availability at the beginning of the next growing season because of the recharging of soil.

Our results are in agreement with other studies on *P. pinea* that were conducted in the Mediterranean basin and showed that a large part of a tree-ring is formed during the late winter and spring. These findings reflect the behaviour of evergreen conifers that grow in regions with mild winters and are characterised by a photosynthetic activity during winter that produces carbohydrates for early wood formation in the following year (Kozłowski et al. 1991). At the monthly scale, the highest correlation coefficients were found with November precipitation of the previous year, which was the rainiest month of the year during the whole climate data time series, having an annual mean of approximately 112 mm. The influence of November $t-1$ precipitation on tree growth appears significant in other studies performed also in areas with a more limited annual mean precipitation than the study areas, e.g., 274 mm in Spain (De Luis et al. 2009) and 538–581 mm in Portugal (Campelo et al. 2006).

The moving correlation functions indicated more detailed and dynamic trends of the growth responses to climate over the last century. The shifting significance of the influence of winter precipitation on tree rings growth toward not significant values during the last decades, might explain the lack of significant correlation between the precipitation of the current year and tree growth decline from the mid 1970s, due to the decreased water supply stored during the winter months. This freshwater reaches the highest piezometric surface in the late winter-early spring period (Gandolfo 1999). Thus, the decrease in precipitation, which represents the only available input of freshwater, reduced soil water content above the water table. At the same time, the expansion of tourism and transportation infrastructures during the last decades caused the progressive depletion of the ground water levels (Teobaldelli et al. 2004), deteriorating the growth conditions of the pinewoods.

The influence of temperature on tree growth was significant at lower frequencies compared with the typical high-frequency climatic information detected using the classical standardization methods. The negative effect on tree-growth of summer and early-autumn temperature, founded with the age band decomposition approach, appeared as a forcing influence related to slow changes in climate. This influence showed a contrasting trend over the twentieth century. Significant and negative growth responses to the significant increase in temperature have been found only in the first period with lower growth rates, during the first half of the twentieth century. High temperatures occurring with low amounts of precipitation during summer and early autumn are the main limiting factor for latewood formation. Consequently, the not statistically significant influence of summer and early-autumn temperature on tree-growth decline from the mid 1970s, might indicate that trees increasingly utilise the water supply stored due to the previous rainy years to deal with drier conditions compared with that of the first half of the century.

Although the precipitation resulted the primary explanatory variable of tree growth decline, the negative influence of temperature might be due to water shortage because higher temperatures increased the evapotranspiration and soil water evaporation (Campelo et al. 2006). Thus, the significant increase in temperature during the less rainy years may impose overall growth limitations through water stress where water availability is a stronger limiting factor than heat, as observed in other studies on Mediterranean pine forests (Sarris et al. 2011).

5 Conclusion

The growth rate responses of *P. pinea* to climate over the last century suggested the influence of precipitation as the main factor driving trees growth decline. The decrease and changes in the distribution patterns of precipitation have influenced the availability of water resources

that are closely dependent on precipitation. Stronger and significant correlations between tree ring widths and precipitation, especially for precipitation cumulated over consecutive years prior to the ring formation, confirmed that pine trees can obtain water from the soil by intensively exploring the ground at different levels.

The higher water stress induced by an increase in air temperature and a decrease in rainfall for successive years could seriously affect the tree growth of Mediterranean pine species, despite their drought-tolerant behaviour. Such conditions reduce soil water content during the growing period and also inhibit the water table's recharge, that, during the last decades, was strongly influenced by anthropogenic impact, especially in terms of the water demand for urban and/or tourist activities. Our findings help to identify more appropriate mitigation and conservation strategies that have become closely connected with appropriate water resources management and that improve stand stability and resilience in the coastal environments of the Mediterranean basin.

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