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A DENDROCHRONOLOGICAL ANALYSIS OF *PINUS PINEA* L. ON THE ITALIAN MID-TYRRHENIAN COAST

SERGIO PIRAINO[1], SERGIO CAMIZ[2], ALFREDO DI FILIPPO[3],
GIANLUCA PIOVESAN[3] and FRANCESCO SPADA[4]
[1]Laboratorio de Desertificación y Ordenamiento Territorial (LADyOT), IADIZA, CCT-CONICET-Mendoza, Avda. Ruiz Leal s/n, Parque Gral. San Martín, CC 330, PO Box 5500 Mendoza, Argentina.
[2]Dipartimento di Matematica "Guido Castelnuovo", Università degli Studi di Roma "Sapienza", Piazzale Aldo Moro 5, 00185 Roma, Italy
[3]DendrologyLab, DAF, Università degli Studi della Tuscia, Viterbo, Italy
[4]Dipartimento di Biologia Ambientale, Università degli Studi di Roma "Sapienza", Piazzale Aldo Moro 5, 00185 Roma, Italy

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Abstract: In order to assess the response of the radial growth of *Pinus pinea* L. to climatic variability in Central Italy, dendrochronological and dendroclimatological analyses were carried out on five different populations scattered along the Tyrrhenian coasts of the peninsula. The aim of this study is to contribute to the understanding of the ecological demands of this species, particularly in the study area.

For each site total ring, early-, and late-wood width chronologies were developed.

Multidimensional analyses were performed for the three tree-ring datasets in order to analyze the relations between sites chronologies. Both Principal Component Analyses and hierarchical classifications highlighted an important difference of one site in respect to the other, probably due to site characteristics.

Correlation functions were performed to infer the main climatic factors controlling the radial growth of the species. For a comparative study, we limited our attention to the common interval 1926-2003 (78 years) in which the response of the tree-ring chronologies to climate at both local and regional scale was investigated.

Positive moisture balance in the late spring-summer period of the year of growth is the climatic driver of *P. pinea* radial growth in the study area. Moreover, this study shows how low summer temperatures strongly favor the radial growth of the species.

Keywords: Mediterranean, dendroclimatology, tree-ring, early-wood, late-wood, multidimensional analysis, principal component analysis, hierarchical factor classification.

Corresponding author: S. Piraino
e-mail: spiraino@mendoza-conicet.gov.ar

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1. INTRODUCTION

Pinus pinea is a widespread tree in the Mediterranean regions, covering 380,000 ha, 19,000 of which in Italy, mostly located in coastal areas (Moussouris and Regato, 1999), where its forests represent an important environmental and historical value. Large stands have been planted or managed along the coast since antiquity for timber and cone production, and in recent times to prevent erosion of the coastline (Gabbrielli, 1993; Ayrilmis *et al.,* 2009). Nevertheless, natural stands of *P. pinea* are very rare along the Mediterranean coasts, while the bulk of its range is located on the Atlantic side of the Iberian Peninsula. Relic disjunct stands occur far East in Lebanon and Northern Turkey (Trapezun district: see Critchfield and Little, 1966). The few natural stands in Italy grow under Mediterranean climatic conditions, characterized by summer drought and high inter-annual variability of precipitation and temperature (Walter 1973), where summer drought is the crucial factor in limiting plant growth. At the Iberian Peninsula, the widespread stands are influenced by the oceanic climate, with a higher frequency of relatively cool summers; thus, plant growth is not limited by the classic Mediterranean climate constraints. The disjunct pine stands on the slopes of the Lebanon mountains and the Southern coasts of the Black Sea benefit in locations where the local mesoclimate provides more oceanic conditions than the ones provided by the generally drier macroclimate ruling along the Mediterranean coasts (Zohary, 1973; Richardson, 1996), apparently favourable to more xerophilous species of pines (*P. halepensis, P. brutia*). Hence, we can infer that the species needs cooler and wetter summers for its successful radial growth than the one provided by the Mediterranean type climate (Ashmann 1973).

Tree-ring analysis is a powerful tool for the identification of the most important relations between tree radial growth and climate in the present (Fritts, 1976). In conifers the intra-annual responses of radial growth to local climatic variations have been successfully assessed through the study of the relation between total ring, early-wood (the part of the annual ring formed in the spring-early summer period) and late-wood (formed during late summer-autumn period) widths (Kaennel and Schweingruber, 1995) with climatic data (e.g. Campelo *et al.*, 2006; Bogino and Bravo, 2008).

A close relation between radial growth and climatic factors in *P. pinea* has been detected analyzing the influence of climate on radial growth, however only at a local scale (Cherubini, 1993; Akkemik, 2000; Campelo *et al.*, 2006; De Luis *et al.*, 2009). The development of tree-ring networks can provide a more accurate ecological description of trees, and contributes to improve the knowledge of their ecological demands and bio-geographical assessment. Moreover, the analysis of the relation between growth indices and climatic variables at the regional scale can help to predict how the species can behave in a climatically unstable scenario.

Therefore, the objectives of this work are: *i*) to develop a tree-ring network for *P. pinea* along the coasts of Central Italy regarding total ring, early-, and late-wood widths, and *ii)* to study the adaptation of the species to its environmental envelope through the analysis of the effects of climatic patterns on the radial growth at both local and regional scale.

2. MATERIAL AND METHODS

Sites description

The study area is located on the Western coast of Central Italy, between 41.30° and 43.72° N, 10.31° and 13.03° E (**Fig. 1**). Five different sites were selected: *San Rossore*, *Cecina*, *Duna Feniglia* in Tuscany, and *Castelporziano* and *Circeo* in Latium (**Table 1**). All these sites lie close to the coastline. The stands grow under Mediterranean climatic conditions, locally characterized by a summer drought ranging from one to three months (**Fig. 2**). In these sites the species grows on sandy soils. The stands of *San Rossore*, *Cecina,* and *Circeo* have been planted on areas which were claimed during the first half of the 20th century. The population of *Duna Feniglia* is also originated by earlier plantations and grows on Holocene dunes close to a brackish lake. At *Castelporziano* the pine stands were planted in the 18-19th century on former late-Quaternary dunes, where a previous mixed deciduous-evergreen forest had been destroyed.

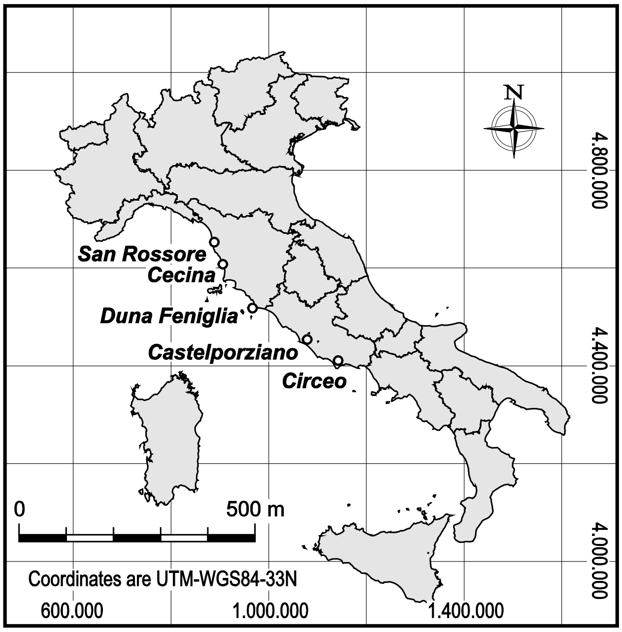

Fig. 1. *Geographical location of the studied sites.*

Table 1. *Characteristics of the sampled sites. Lat = Latitude, Long = Longitude; Trees = Number of sampled trees per site; DBH = range of the sampled logs diameters at breast height; Time span = time range of the sampled populations.*

Site	*Lat (°N)*	*Long (°E)*	*Trees*	*DBH (cm)*	*Time span*
San Rossore	43.72	10.31	19	56-82	1861-2003
Cecina	43.31	10.52	17	41-57	1851-2003
Duna Feniglia	42.44	11.22	19	35-76	1925-2003
Castelporziano	41.74	12.40	21	60-76	1897-2003
Circeo	41.31	13.03	31	55-84	1878-2004

At each site, we studied pure stands of this species, with only rare arboreal associates in the understorey, i.e. evergreen (*Quercus ilex*, *Q. suber*) and deciduous oaks (*Q. pubescens s.l., Q. cerris*) and a scanty thicket of sclerophyllous treelets and shrubs of the Mediterranean "*maquis*".

Tree-ring chronology

Tree-ring chronologies were developed from wood samples using standard dendrochronological procedures (Stokes and Smiley, 1968). At each site, 15-20 trees were sampled at breast height (about 1.3 m from the ground; Fritts, 1976) and one sample *per* tree was extracted with incremental borers. Additionally, 14 individual series (6 for *San Rossore* and 8 for *Circeo* sites) developed by Biondi (1992) were downloaded from the *ITRDB* web page (The International Tree-Ring Data Bank: http://www.ncdc.noaa.gov/paleo/treering.html). Wood samples were put on core mounts and surfaced with the use of a scalpel. Tree-ring widths (*TRW*) were measured in a radial direction, from the bark to the pith to the nearest 0.01 mm using the sliding stage micrometer *CCTRMD* and recorded through the *CATRAS* program (Aniol, 1983 and 1987). Due to the clear distinction between the early to late-wood transition, we also measured early- (*EWW*) and late-wood (*LWW*) widths in the same way as the *TRW* measurements. Each measure was cross-dated and checked both visually (via *CATRAS*) and statistically (via *COFECHA* program; Holmes, 1983). Statistical parameters commonly used in dendrochronology were calculated: 1) the mean sensitivity (*MS*) which is the mean percent change from each measured yearly ring value to the next; and 2) the first order autocorrelation (*AC1*), the correlation of each value in a time series with the value of its predecessor with a time lag of one year (Fritts, 1976). These parameters indicate the sensitivity of the species to environmental factors.

The cross-dated raw series were transformed by removing the age-related trend usually present in the raw ring width measurements by using the program *ARSTAN40c* (Cook and Krusic, 2006). A negative exponential function was fitted to the raw data and then the original values were subtracted by the fitted ones. Standardized indices used in dendrochronology are often calculated as ratios between the measurement and the fitted

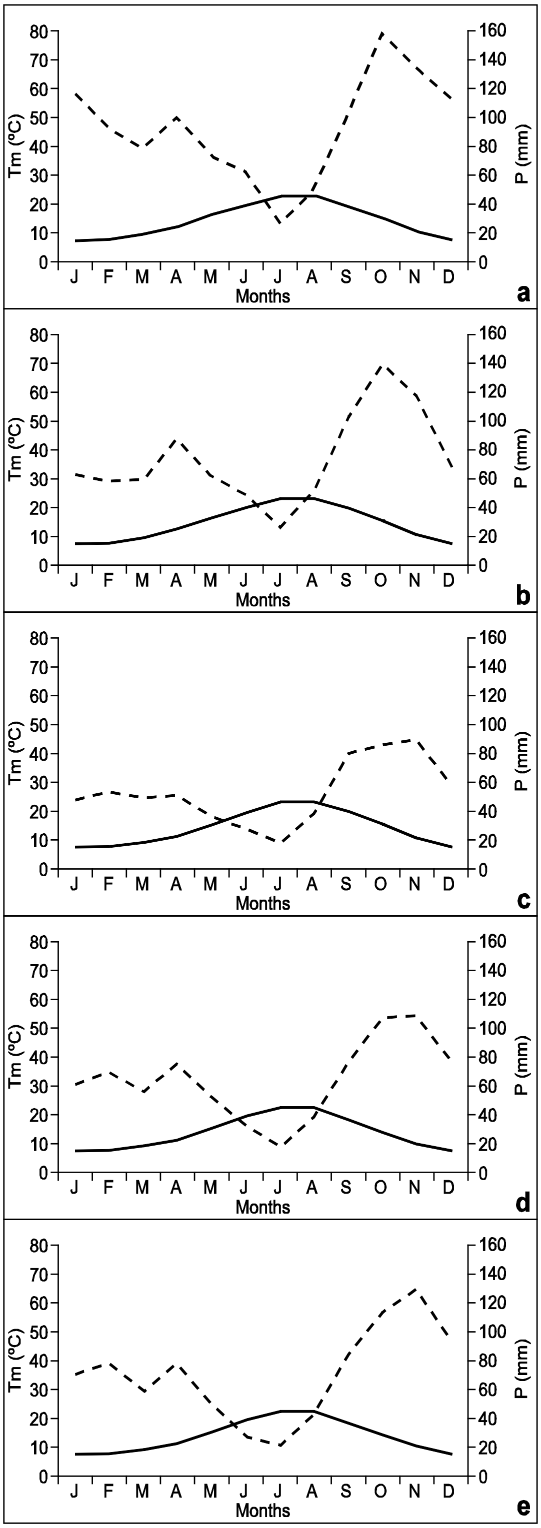

Fig. 2. *Ombrothermic diagram of a) Sarzana -San Rossore; b) Pisa-Cecina; c) Grosseto-Duna Feniglia; d) Ciampino –Castelporziano; and e) Latina -Circeo for the period 1971–2000, according to Bagnouls and Gaussen (1953). Data of the Military Air Force - National Centre of Meteorology and Climatology (available at http://clima.meteoam.it/downloads.php). Tm = monthly air temperature; P = monthly total rainfall. Solid line refers to monthly air temperature, dot line to monthly total rainfall.*

curve value. Since ratios can inflate the tree-ring index, the use of residuals was chosen to avoid possible overestimations in the standardization process (Cook and Peters, 1997; Helama *et al.*, 2004).

The Expressed Population Signal (*EPS*), a measure of how the mean chronology derived from the sampled trees represents a hypothetical infinitely replicated chronology, was used to evaluate the reliability of each chronology (Wigley *et al.*, 1984). In the following analyses, the period 1926–2003 (78 years), common to all chronologies, has been taken into account.

Multidimensional analysis

Relations between the tree-ring chronologies were explored with both ordination and classification multidimensional analyses (Whittaker, 1973; Tukey, 1977, Camiz *et al.*, 2006). For the ordination, the classical *Principal Component Analysis* was run (*PCA*; Orlóci, 1978; Jolliffe, 1986; Legendre and Legendre, 1998). According to the Kaiser-Guttman's rule (Guttman, 1954), we decided to take into account the principal components whose eigenvalues are larger than 1.

For the classification of the series, we ran the *Hierarchical Factor Classification* (*HFC*; Denimal, 2001). At each step, a node is composed by merging two already existing groups and to it *HFC* associates a factor plane where to represent both aggregated variables and units. Thus, *HFC* acts simultaneously as both classification and factor analysis tools (Camiz *et al.*, 2006; Camiz and Pillar, 2007). Indeed, at each step, given a node, the associated first principal component represents what the variables of the merging groups have in common, whereas the second one represents the main differences between the groups (Camiz *et al.*, 2006). As the latter is adopted as hierarchy index, its value suggests the cut-point to identify the partitions. Indeed, a value larger than one would mean that the second principal component of a node has the same weight of an original variable, that is to say that the node clusters two nodes whose differences are too large to reasonably gather them. According to both Guttman (1954), Jolliffe (1986), and the practice, we considered questionable to merge groups at fusion levels higher than 0.8.

For this work, *PCA* was run through the *SPAD* package (Lebart *et al.*, 1999) and *HFC* through *Clahfac* program (Denimal, 2001).

Climate-growth relation

The tree radial growth/climate relations were analyzed through correlation functions (Fritts, 1976). The climatic data were extracted from the data set of the project *CLIMAGRI* assessed according to a grid of 1°×1° cells of geographical coordinates covering the whole Italy (Brunetti *et al.*, 2006). A set of 19 climatic monthly time-series was selected, from May of the year preceding the ring formation to November of the current year of growth. Site standard chronologies were matched against monthly total precipitation (*P*), monthly mean maximum air temperature (*Tmax*), and monthly mean minimum air temperature (*Tmin*) time-series.

To describe the climatic signal shared by these Tyrrhenian populations, the correlation functions were calculated for the tree-ring, early- and late-wood width chronologies as well as for the three chronologies represented by the first principal components (*PC1*) of *PCA* performed on the three dendrochronological datasets. For the latter analysis, we built a regional series of climatic data, averaging the values for each grid cell. In addition, correlation functions were performed between *PC1s* and monthly Palmer Drought Severity Index (*PDSI*; Palmer, 1965) to analyse the influence of drought at regional scale. The *PDSI* index takes into account precipitation, evapo-transpiration, and soil moisture conditions, all of which are indicators of drought. *PDSI* monthly series for the study area were derived from the Dai *et al.* (2004) 2.5°×2.5° gridded data set.

The correlation values were computed and tested for significance with the program *DENDROCLIM2002* (Biondi and Waikul, 2004), by applying the bootstrap method (Guiot, 1991).

3. RESULTS

Characteristics of the tree-ring network

107 wood samples were used to build 15 site chronologies, 5 for *TRW*, 5 for *EWW*, and 5 for *LWW*. The populations were of different ages (**Table 1**), ranging from 79 years at *Duna Feniglia* to 153 years at *Cecina*. The mean correlation among trees (*MC*) ranks from 0.424 (*Cecina LWW*, 153 years) to 0.763 (*Castelporziano TRW*, 107 years), all at least at 5% significance level (**Table 2**). Statistical parameters (*MS* and *AC1*, **Table 2**) indicate homogeneous values within the 15 chronologies, with the *LWW* showing the highest values of *MS* and lowest of *AC1*. For each site, the *EWW* is about 70-80% of the total tree-ring width. *Castelporziano*, *Duna Feniglia* and *Circeo* show the highest percentage of late-wood (**Table 2**). The *EPS* for all pre-whitened site chronologies is higher than the critical value of 0.85 on the common period 1926–2003 (**Table 2**).

Multidimensional analysis

Three *PCAs* were run separately on each of the three datasets (*TRW*, *EWW* and *LWW*; **Fig. 3**). It is well known that the most relevant numerical result of *PCA* is the percentage of inertia as a measure of the importance of a component. In the *TRW* analysis, the first principal component explains 43.83% of the total inertia and the second one, not negligible, contributes up to 65.88%. For *EWW*, the first principal component explains 41.42% and the other adds up to 62.36%; in *LWW*, the first contributes with 40.07% and the second adds up to 64.59%. Thus,

Table 2. *Statistical parameters of the sampled sites: MC = mean correlation between trees, MS = Mean Sensitivity, AC1 = First order Autocorrelation, Corr = Correlation between site chronology and first principal component; EPS = Expressed Population Signal. % = Percentage of early-wood and late-wood in the whole ring.*

Site	*Total-ring Width*					*Early-wood*					*Late-wood*				
	MC	*MS*	*AC1*	*Corr*	*EPS > 0.85*	*MC*	*MS*	*AC1*	*Corr*	*%*	*MC*	*MS*	*AC1*	*Corr*	*%*
San Rossore	0.490	0.244	0.904	0.873	1894-2003	0.490	0.246	0.933	0.872	80	0.692	0.429	0.704	0.760	20
Cecina	0.472	0.277	0.916	0.436	1892-2003	0.500	0.329	0.910	0.485	78	0.424	0.384	0.720	0.650	22
Duna Feniglia	0.578	0.254	0.980	0.109	1926-2003	0.575	0.277	0.866	-0.076	72	0.611	0.354	0.835	0.484	28
Castelporziano	0.763	0.240	0.924	0.850	1901-2003	0.753	0.269	0.877	0.833	71	0.703	0.390	0.676	0.657	29
Circeo	0.527	0.220	0.897	0.710	1878-2004	0.509	0.233	0.866	0.613	75	0.539	0.340	0.743	0.580	25

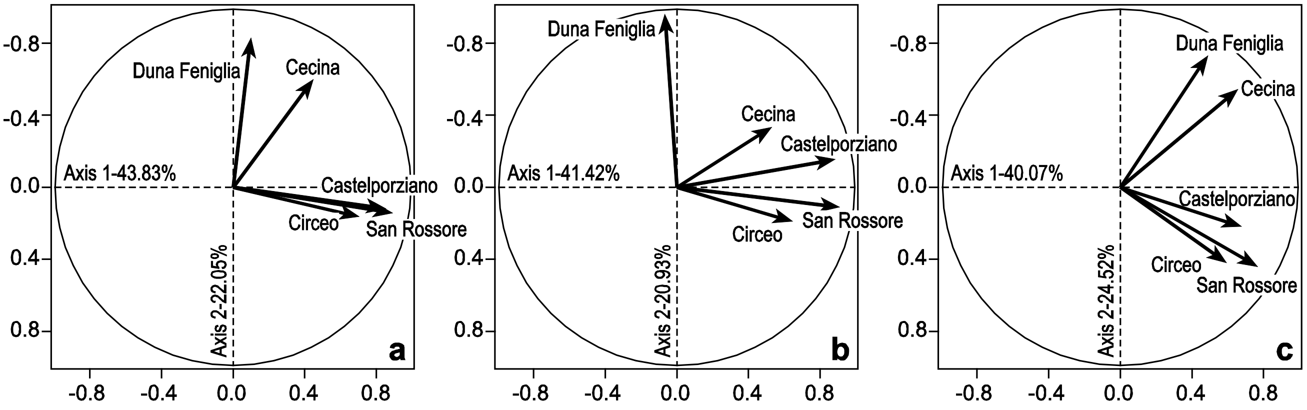

Fig. 3. *The pattern of the chronologies on the planes spanned by the first two principal components of PCAs: a = Tree-rings, b = Early-wood, c = Late-wood.*

two principal components seem to be important to describe sufficiently well the five chronologies independently from the kind of wood taken into account.

Considering the numerical results of the *HFC*, the fusion level is a measure of the diversity of the groups obtained by cutting the dendrogram at each level: here the *TRW* chronologies dendrogram (Fig. 4) suggests either two or three classes (with fusion levels 1.09 and 0.83, respectively), depending upon whether to consider *Cecina* and *Duna Feniglia* to be clustered or no. The dendrogram of the *EWW* suggests three groups (1.00 and 0.86, respectively), with *Cecina* and *Duna Feniglia* clearly separated, whereas the *LWW* one shows two groups (1.20) only, with these two chronologies clearly aggregated. The other three chronologies are always clustered together, with *Circeo* joining the other two at a higher level.

Radial growth-climate relations

The correlation function analysis performed for the *TRW* site chronologies indicates that radial growth is almost always positively correlated to the spring-summer moisture (from March to September) of the current year, with the exception of the *Duna Feniglia* chronology (Fig. 5). Radial growth is also positively influenced by precipitation and negatively by temperatures (that is, the growth is favored by high precipitation and low temperature) of the late

Fig. 4. *The dendrograms created by HFC of the chronologies of the whole tree-rings, early-wood and late-wood widths.*

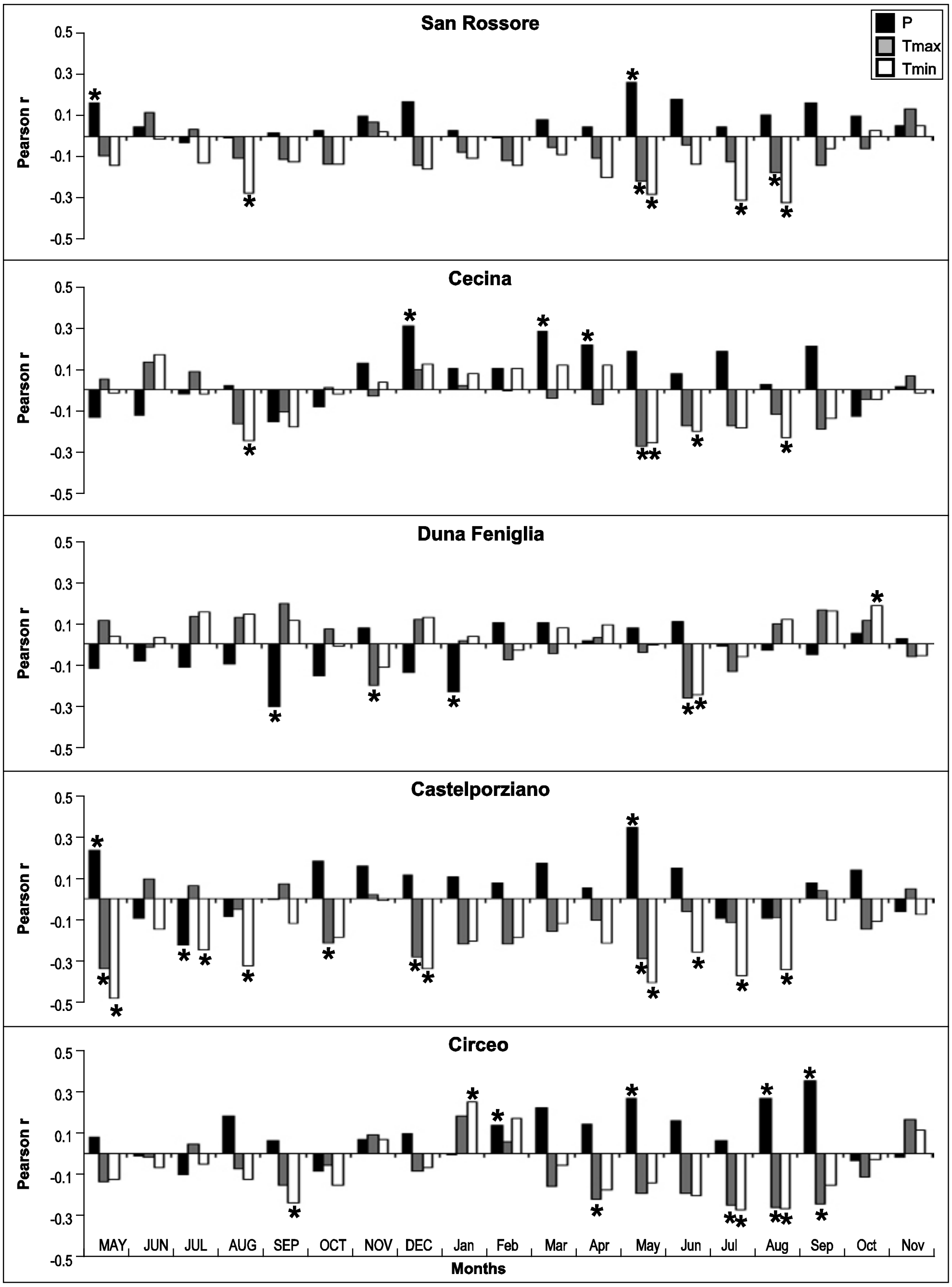

Fig. 5. *Correlation functions between standardized total ring width site chronologies and monthly total amount of precipitation (P = black bars), mean monthly maximum (Tmax = gray bars) and minimum temperature (Tmin = white bars). Upper case = months of the preceding year. Lower case = months of the current year. The black asterisks indicate months whose correlation is significant at least at p<0.05.*

autumn-winter period of the previous year, with a special characterization by high precipitation at *Cecina* and low temperatures at *Castelporziano*. The correlation function calculated for the *EWW* site chronologies confirm the results previously reported. Then, the development of the early-wood width is favored, at the site scale, by positive moisture in the spring-summer season (**Fig. 6**). Again, the *Duna Feniglia* chronology does not seem to respond clearly to the climatic variability. On the other hand, the analysis of the correlation functions performed for the *LWW* site chronologies shows that the development of this part of the ring is mainly positively influenced by a late summer-autumn period (from August to November) characterized by a positive moisture balance (i.e. abundant rainfall and low temperatures) (**Fig. 7**). In addition, at *Castelporziano* site, the *LWW* formation is negatively

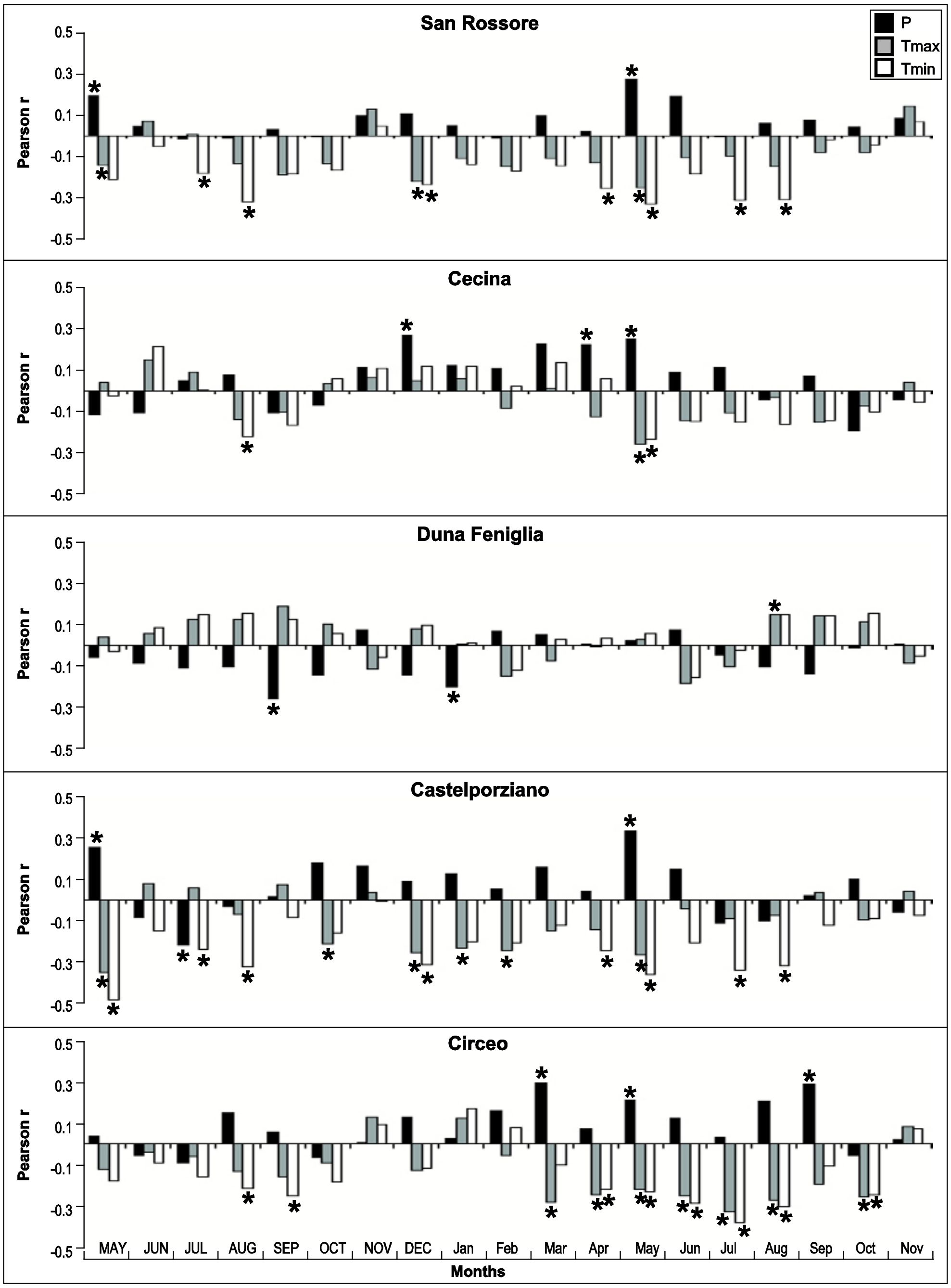

Fig. 6. *Correlation functions between standardized early-wood width site chronologies and monthly total amount of precipitation (P = black bars), mean monthly maximum (Tmax =gray bars) and minimum temperature (Tmin = white bars). Upper case = months of the preceding year. Lower case = months of the current year. The black asterisks indicate months whose correlation is significant at least at p<0.05.*

influenced by temperatures of the preceding year (May, July, August, October, and December).

The correlation functions performed for the first component (*PC1*) of *TRW* (**Fig. 8**) confirm the positive influence of precipitations (May and August) and the negative one of temperatures (from May to August) in the late spring-summer period of the current year over radial growth at a regional scale. Negative correlations were found for minimum temperatures of the spring-summer period and December of the previous year, and positive relations for precipitation of May of the previous year. The *TRW* is also positively influenced by *PDSI* values of May and June of the previous year, and from October of the previous year to November of the year of growth (**Fig. 9**).

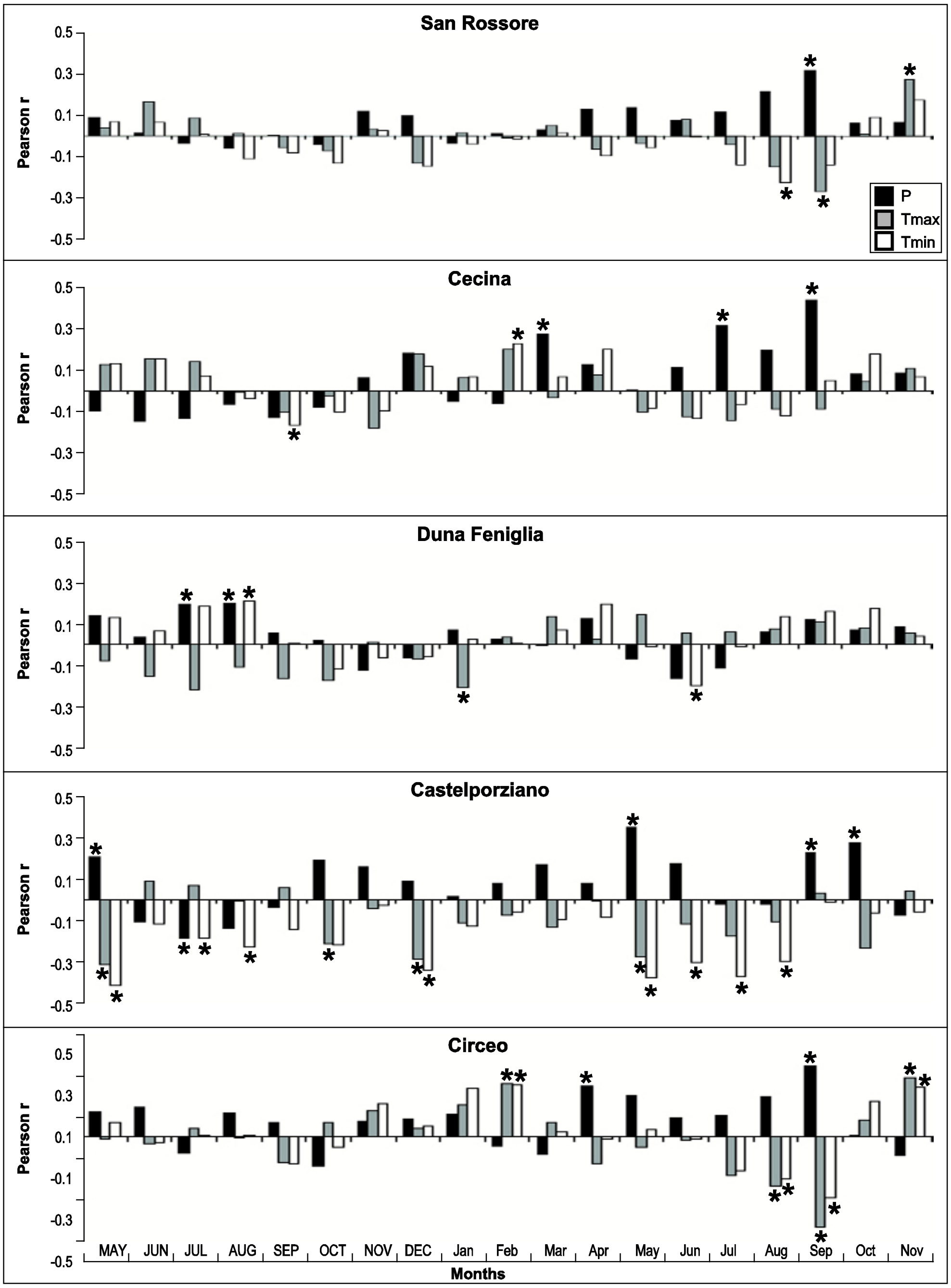

Fig. 7. *Correlation functions between standardized late-wood width site chronologies and monthly total amount of precipitation (P = black bars), mean monthly maximum (Tmax =gray bars) and minimum temperature (Tmin = white bars). Upper case = months of the preceding year. Lower case = months of the current year. The black asterisks indicate months whose correlation is significant at least at p<0.05.*

Considering correlations functions performed for the *EWW* and *LWW PC1s* (**Fig. 8**), the results seem to confirm those of the whole ring. At a regional scale, the growth of the *EWW* is positively influenced by the amount of precipitation in May, and negatively by the temperatures from April to September of the current year. The positive moisture balance in May of the preceding year favors the development of *EWW*, while both the summer minimum temperatures and the December temperatures of the previous year negatively influence the formation of this part of the ring. Moreover, *EWW* shows the same relations as *TRW* with *PDSI* (positive correlations with *PDSI* values of May and June of the previous year and with the values from October of the previous year to November of the year of growth; **Fig. 9**).

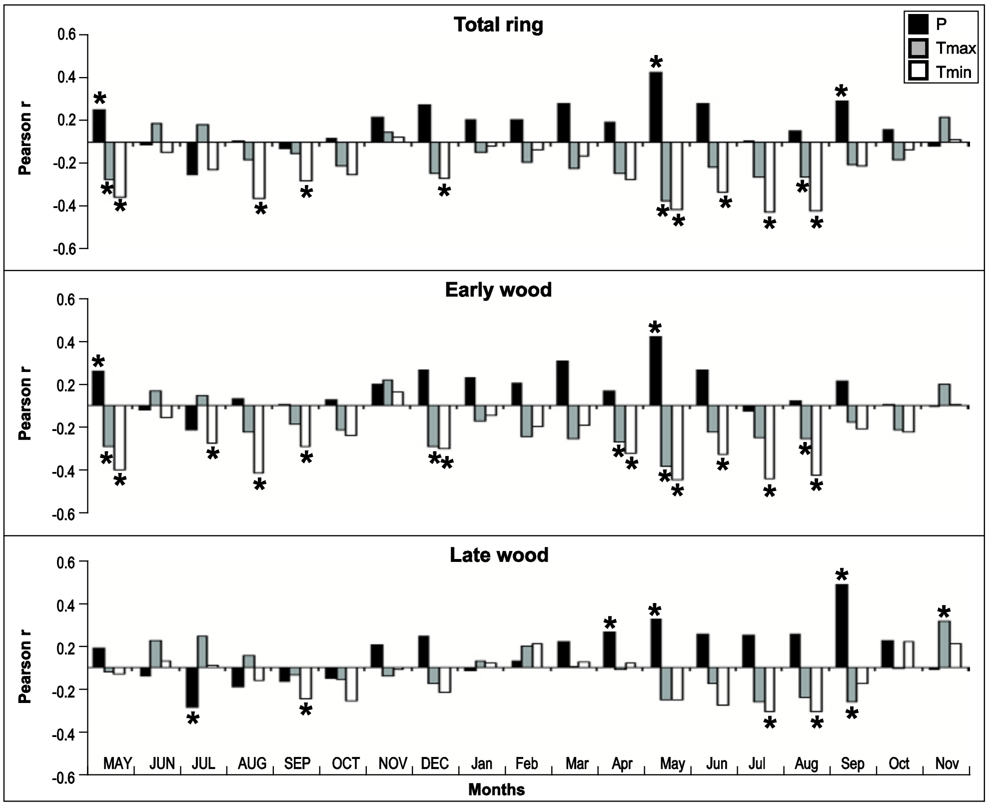

Fig. 8. *Correlation functions between PC1 of the three PCAs on sites chronologies for total ring, early-, and late-wood widths, and monthly total amount of precipitation (P = black bars), mean monthly maximum (Tmax =gray bars) and minimum temperature (Tmin = white bars). Upper case = months of the preceding year. Lower case = months of the current year. The black asterisks indicate months whose correlation is significant at least at p<0.05.*

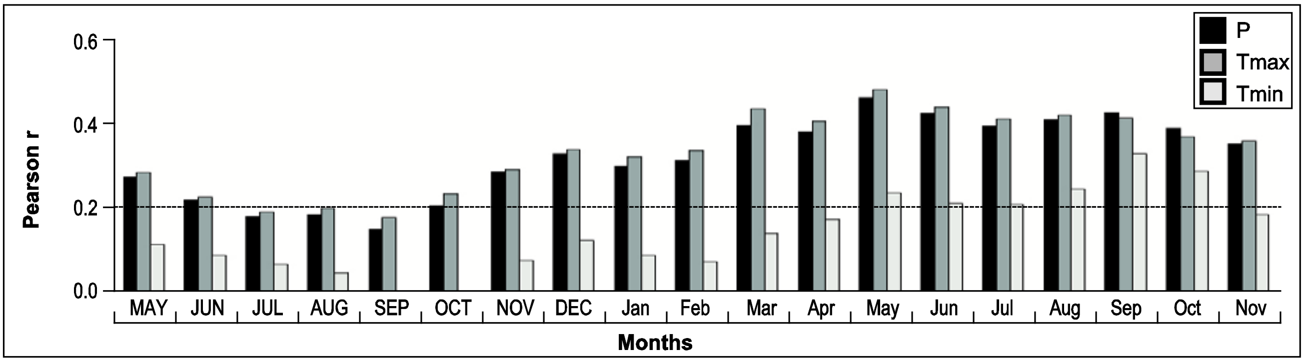

Fig. 9. *Correlation functions between PC1 of the three PCAs on sites chronologies for total ring, early-, and late-wood widths, and mean monthly values of PDSI. Upper case = months of the preceding year. Lower case = months of the current year. The dashed line represents the 95% confidence limit.*

The correlation functions performed for the *LWW PC1* show how the formation of this part of the ring is positively influenced by both spring (April-May) and September precipitations of the current year, with the latter highly correlated to the late-wood development. *LWW* is negatively correlated to summer (June-July) minimum temperatures. Moreover we detected a negative correlation between *LWW* growth and precipitation in July and minimum temperatures in September of the preceding year and a positive relation with maximum temperature of November of the current year. Finally *PDSI* in the May-October period of the year of growth positively influences *LWW*, with the highest correlation values for the *PDSI* index in September and October (Fig. 9).

4. DISCUSSION AND CONCLUSION

Statistical parameters (*MS* and *AC1*) corresponding to the five different sites do not indicate significant differences according to the spatial distribution. Therefore, these parameters do not seem to reflect any particular ecological or climatic gradient. They rather suggest a uniform sensitivity of these pine populations to the environment. On the other hand, the *MS* and *AC1* values of *LWW* suggest that this part of the annual ring is apparently more sensitive to environmental constrains.

In each site and for each tree-ring parameter, a high percentage of inertia explained by *MC* may be considered as a signal shared by all individuals, probably as a consequence of the influence of a dominant environmental (climatic) factor over radial growth. *EPS*, always higher than the 0.85 threshold for the time span in common to all sampled trees in each site (**Table 2**), allows to assume that these chronologies can well describe hypothetical and infinite *P. pinea* populations at each sampling site (Wigley *et al*., 1984).

Two sites, *Castelporziano* and *Duna Feniglia*, show the highest percentage of late-wood, followed by the *Circeo* site. These higher values are statistically significant (one-way ANOVA: DF = 3, F = 13.54, *p* = 0.0348), and may reflect higher water stress conditions. This can be also inferred by the analysis in **Fig. 2**, which shows how these three sites are characterized by three months of drought conditions during the summer period. Indeed, it is well known that a higher late-wood/early-wood ratio can be a strategy of conifers growth in dry climate (Domec and Gartner, 2002).

The multidimensional analyses show that all chronologies, except *Duna Feniglia,* contribute to the first axis: more weakly *Cecina* and more strongly the other three ones. This suggests the existence of a common signal for four chronologies, namely *San Rossore*, *Cecina*, *Castelporziano* and *Circeo*. Indeed, in all analyses, *Cecina* contributes (with different weights) to the second axes as well, axes to which *Duna Feniglia* contributes most. This reflects the non-significant correlations of *Duna Feniglia* with the other chronologies for both the *TRW* and the *EWW* and significant with *Cecina* for the *LWW*. This behavior of *Duna Feniglia* is also reflected in a lack of signals connected to climatic influence (with the exception of a negative influence of July temperatures over annual radial growth). The reason can be that this population was planted in 1911 on a narrow sandy strip of dunes separating the sea from a lagoon with brackish water (Gabbrielli, 1993). The lagoon itself is located on a flat isthmus connecting the promontory of Monte Argentario (632 m.a.s.l.) with the Tuscanian coast. The water-table is apparently affected by salty water on both sides of this sandy narrow strip. The action of salts on roots and on the absorption of phreatic water is known to be detrimental to the growth of *P. pinea*, especially during periods of lower precipitation (Teobaldelli *et al*., 2004). Consequently, the location of *Duna Feniglia* might bias the relation with the climatic parameters that influence the other sites. Moreover, since the isthmus is exposed to both Northern and Southern quadrants dominating winds (Bellarosa *et al.*, 1996), the negative effects of enhanced evapotranspiration can be suggested in the interpretation of the observed pattern.

From a physiological viewpoint*, P. pinea* is known to reduce photosynthesis when water stress occurs, a mechanism that has been observed in this species during summer and early autumn, and does not show any summer quiescence (Liphschitz *et al*., 1984; Awada *et al*., 2003; Teobaldelli *et al*., 2004). It can therefore be considered as a drought-tolerant Mediterranean species that continues its growth, albeit reduced, during the dry season (Specht, 1981; de Lillis and Fontanella, 1992).

Our analysis shows that the radial growth of *P. pinea* (*TRW*, *EWW* and *LWW*) along the western coast of middle Italy is mainly favored by positive moisture of the late spring-summer period of the current year and, more slightly, negatively influenced by the previous year winter temperatures. During the spring-summer period (March to September of the year of growth), the *cambium* activity takes place (Liphschitz *et al*., 1984). Then, the tree is highly dependent upon the amount of water stored in the soil for the construction of the ring (Campelo *et al*., 2006).

The April-May period represents a crucial moment for the radial growth of the species. The negative relation found for the *EWW PC1* with April temperatures, associated with the positive relation with precipitation for the *LWW PC1* in the same month, may be explained considering that for this species the cambial activity begins during March (Liphschitz *et al*., 1984). Then, positive moisture favors the development of the ring at the beginning of the growing season. Radial growth is also favored by the positive moisture balance during May of the year of growth, outlined by the correlation functions performed for both site chronologies and *PC1* of *TRW* and *EWW*. This signal is strengthened by the positive correlation found for precipitation and *LWW PC1* chronology. The same climate-radial growth signal was reported for the species in Turkey and in the Iberian Peninsula (Akkemik, 2000; Campelo *et al*., 2006; De Luis *et al.*, 2009).

These results suggest severe constraints of summer drought on the species growth. Indeed, drought restrains some physiological processes that take place during this period, as shoot elongation, bud lengthening, cone development and phloem growth (Liphschitz *et al*., 1984; Mutke *et al*., 2003). Furthermore, drought conditions during late spring can provoke xylem embolism (Oliveras *et al*., 2003). Thus, in this period the tree physiology and growth are strictly dependent on climatic variability.

The *LWW* formation is negatively influenced at a regional scale by high precipitation of July of the previous year. Since low precipitation can cause the cone abortion

(Mutke *et al.*, 2005), it may be hypothesized that the carbohydrates not used in the cone development during the previous year will be used in the *LWW* formation during the year of growth.

High maximum temperatures during November of the current year favor the construction of the *LWW*, suggesting that in Mediterranean regions photosynthesis can take place also during a mild autumn, by producing carbohydrates necessary for the ring formation (Kozlowski *et al.*, 1991). Low December temperatures of the previous year favor both *TRW* and *EWW* formation, probably reducing the evapo-transpiration processes that can negatively influence the recharge of the soil water-table (Campelo *et al.*, 2006).

The analysis of correlation functions between radial growth and *PDSI* values confirms the importance of a positive moisture balance during the growing season for *P. pinea* radial growth, previously reported for the combined influence of precipitation and temperatures. *PDSI* index takes into account precipitation, temperature, evapo-transpiration and soil moisture. For this reason, it is considered a key indicator of drought conditions (Cook and Jacoby Jr, 1977; Meko *et al.*, 1993).

Several works have analysed the dendroclimatology of different Mediterranean *Pinus* species. In southern Italy and in France, bioclimatic models show that the annual radial growth of *P. halepensis* is mainly sensitive to soil water availability during the growing season (Attolini *et al.*, 1990; Rathgeber *et al.*, 2005). In Greece, for the same species it was found that *TRW* is enhanced by a high amount of winter and spring precipitations and negatively influenced by high temperatures of the spring months (Papadopoulos *et al.*, 2009). In the Iberian Peninsula, the growth of *P. halepensis* is mainly favoured by abundant precipitations of the spring season (Olivar *et al.*, 2012). In the stands of central Spain, the annual radial growth of *P. pinaster* is favoured by high precipitations in the spring-early summer season (Bogino and Bravo, 2008). The *TRW* of *P. pinaster* is enhanced by a positive moisture balance during spring on the coasts of north-western Portugal (Vieira *et al.*, 2009). In southern Spain, the radial growth of *P. halepensis* is positively influenced mainly by the amount of precipitation during the spring-early summer season (De Luis *et al.*, 2009).

Regarding *P. pinea*, the species has been previously studied using dendroclimatological methods in the two core areas of its natural range in the Mediterranean Regions (Akkemik, 2000; Campelo *et al.*, 2006; De Luis *et al.*, 2009). In Turkey, only the precipitation regime influences the radial growth at a significant level, since the development of the *TRW* is positively influenced by the rainfall amount in the spring-summer period (May, June and August) of the current year (Akkemik, 2000). In southern Portugal, the winter precipitations of the preceding year and in May and June of the year of growth positively influence both *TRW* and *EWW*, while the amount of precipitation in October positively influences the *LWW* development. Concerning the temperature effect, *TRW* exhibits a positive response to high temperature in the previous December, whereas the high temperatures in August have a negative effect on the *LWW* formation (Campelo *et al.*, 2006). In the semiarid coastal area of southern Spain, the amount of precipitation in the growing season (March trough September) positively influences the annual radial growth of the species, while high March temperatures negatively influence *TRW* (De Luis *et al.*, 2009).

Summarizing, the previously reported dendroclimatological analyses indicate that the positive moisture balance in the spring season is the dominant climatic factor favouring the radial growth of *Pinus* spp. in the Mediterranean regions. This is true as well for *P. pinea* at both the eastern and western districts of its natural range. Furthermore, this species seems to present also a strong dependence on summer climatic conditions, since abundant rainfalls and low temperatures enhance the development of the ring width.

Our study indicates that the positive moisture balance in late spring-summer of the year of growth is the crucial climatic driver that enhances the radial growth of *P. pinea* in the coastline populations in the mid-Tyrrhenian area. This analysis also shows how temperature too influences the radial growth of the species in the study areas, since low temperatures during the growing season favor the ring-growth. Our results add new information about the role of climatic variability over the radial growth of the species, suggesting that *P. pinea* seems to exhibit some differences in the response to the Mediterranean climatic constraints compared to other Mediterranean pine species such as *P. halepensis*. Indeed, the radial growth of the species apparently follows the pattern of a colder and wetter climate than the one ruling the Mediterranean region (Liphschitz *et al.*, 1984).

This information becomes particularly relevant considering that all over the Mediterranean regions, while annual precipitation is at present decreasing, temperature is increasing (Giorgi, 2006; IPCC WG I, 2007). Since some analyses show an ongoing increase also in winter temperatures (García-Herrera *et al.*, 2007), *TRW* and *EWW* formation might be severely affected. The magnitude of this climate shifts is exemplified by an increase of the daily temperature in a range of 0.56 °C during the period 1961-2004 and by a decreasing trend of monthly precipitation over the last 140 years, mainly related to the spring season (Toreti and Desiato, 2008; Brunetti *et al.*, 2006).

A decrease in precipitation along with more severe evapo-transpiration processes will probably reduce the summer soil moisture in the whole Mediterranean area (Lavee *et al.*, 1998). All these events might therefore turn detrimental for the radial growth of the species, inducing a reduction of natural and artificial populations across most of its present range.

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