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ORIGINAL ARTICLE – Conservation of Nature

Spring-Summer Drought Induces Extremely Low Radial Growth Reactions in North-Tyrrhenian *Pinus pinea* L.

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Abstract

Climate projections predict shifts in environmental conditions, with cascade effects on forest growth dynamics. As such, *Pinus pinea* L., an ecologically important low-elevation Mediterranean tree, can be threatened by drought events. The occurrence of negative stem growth anomalies ("negative pointer years", or NPY) and its relation to climatic conditions were analyzed, as well as the influence of extreme dry spells upon the species growth. NPY were temporally independent among the analyzed forest stands, likely due to local factors. We observed that NPY depended on dry and hot conditions during the spring-summer period at both sites, while differences in the NPY-climate reflected the species medium term dendroclimatological signal. Extremely dry years directly reduced stem growth rates. Water stress differentially affected growth at each site, likely reflecting local adaptation to droughts. Because of the increasing drought trend expected for the Mediterranean basin, our findings must be considered regarding the conservation and management of these forests.

Keywords: Mediterranean; pointer year analysis; ring width; umbrella pine; water stress.

1. INTRODUCTION AND OBJECTIVES

During the last decades, climate change has been increasingly recognized as an influencing factor upon natural systems and human society (Walther et al., 2002). In this sense, changing climatic conditions already triggered the growth, survival and distribution of tree species around the globe, inducing forest die-off and decline in tree productivity (Allen et al., 2015; Walther et al., 2002).

The Mediterranean basin is considered a climate change hotspot, where shifts in climatic variability occurred recently (Diffenbaugh & Giorgi, 2012). Further changes in average conditions are predicted for this area, with consequent modification of the frequency, severity and nature of anomalous climatic episodes (e.g. heat waves, droughts) (IPCC, 2014). As alterations in weather anomalies may have greater influence on the tree growth dynamics than gradual shifts in average conditions (Jentsch & Beierkuhnlein, 2008), understanding the ecological impact of past anomalous episodes may contribute to improve forest conservation and management plans in an unstable environmental scenario.

Dendrochronology is a powerful tool in analyzing the relationship between environmental stress and plant growth (Speer, 2010). Commonly, this method relies on continuous time series, for example matching annual radial increment with monthly or seasonal climate variables. On the other hand, tree-ring research allows the identification of anomalous growth events, either anatomically based or defined comparing extreme peaks in the width of tree rings in relation to their average development. False rings/intra-annual density fluctuations, for example, may reflect drought tolerance in trees (e.g. Campelo et al., 2006). Pointer years, expressed as particular widths of the total ring, in early or latewood portions, can be related to specific environmental conditions (Schweingruber et al., 1990). Extreme growth can thus reflect the occurrence of climatic anomalies, representing

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a relevant source of information concerning tree sensitivity to climate change (Ols et al., 2016).

Pinus pinea L. (umbrella pine) is one of the most characteristic trees of the low-elevation Mediterranean forests (Mutke et al., 2012). Along the Tyrrhenian Italian coastline, umbrella pine has been planted since Roman times, performing important ecological, environmental and recreational functions up to this day (Teobaldelli et al., 2004). From a physiological point of view, *P. pinea* is considered a drought-tolerant species (Liphschitz et al., 1984; Teobaldelli et al., 2004). Nevertheless, drought-driven damage in the species canopy, along with declining stem growth rate related to decreasing precipitation trends, suggest the sensitivity of umbrella pine to extremely dry climatic conditions (Busotti et al., 1995; Mazza & Manetti, 2013). This assumption is indirectly confirmed by the species natural distribution, where *P. pinea* grows in areas (east and west ends of the Mediterranean basin) characterized by relatively cooler and wetter summers than those of the classical Mediterranean climate (Richardson, 1996).

The climate-growth signal of *P. pinea* stands has been extensively addressed (e.g. De Luis et al., 2009; Mazza & Manetti, 2013; Mazza et al., 2014; Piraino & Roig-Juñent, 2014; Piraino et al., 2013). Nevertheless, the relation between umbrella pine radial growth anomalies and climatic factors is still poorly documented (Campelo et al., 2006; Nabais et al., 2014; Novak et al., 2011; Toromani et al., 2015). To fill this gap, this research examined the radial growth of planted *P. pinea* woodlands located in the north-Tyrrhenian coasts of the Italian peninsula, aiming to answer the following questions: (i) are extremely narrow rings related to climatic factors? (ii) How are drought episodes expressed in the species stem growth?

2. MATERIALS AND METHODS

2.1. Sites description and sampling

Two populations, namely San Rossore and Cecina, were sampled during the autumn of 2003 along the western Italian coastline (Table 1 and Figure 1).

Table 1. Geographical and dendrometric settings of the sampled sites.

Site	Latitude (°N)	Longitude (°E)	DBH (cm)
San Rossore	43.72	10.31	59
Cecina	43.31	10.52	44

DBH: diameter at breast height values of the cored trees.

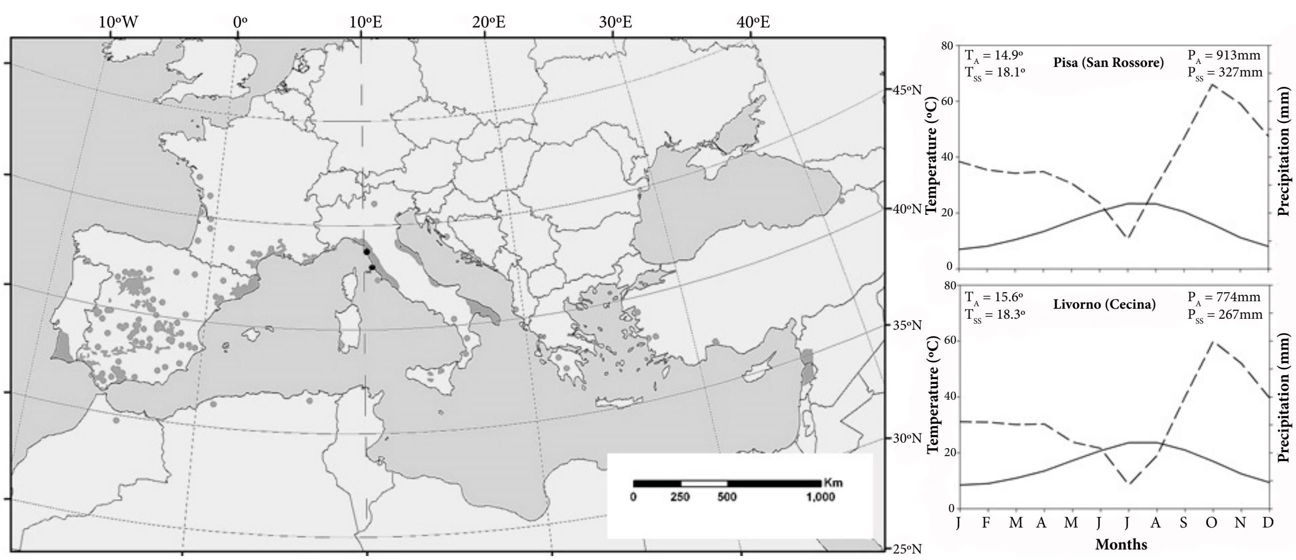

Figure 1. On the left: sampled sites (black dots) located on the *Pinus pinea* L. On the right: ombrothermic diagram of the analyzed forest stands for the period 1951-1994.
TA: annual temperature; TSS: spring-summer temperature; PA: total annual precipitation; PSS: total spring-summer precipitation.
Source: left: Euforgen, 2009; right: Settore Idrologico Nazionale, 2011.

Both forest stands belong to the thermo-Mediterranean subhumid class, with one (San Rossore) and two (Cecina) months of summer drought, respectively (Figure 1). Both woodlands are pure and even age forest plantations, where trees grow on sandy-loamy (San Rossore) and sandy (Cecina) soils (Cambi et al., 2017; Raddi et al., 2009). Literature for the San Rossore and Cecina stands reports densities of respectively 200-565 and 200-377 trees/ha, and approximated ages of

100-120 and 80-100 years (Cambi et al. 2017; De Micco et al. 2007; Maetzke & Travaglini, 2005; Raddi et al., 2009).

Sampled sites were selected avoiding managed (e.g. thinned) areas, thus minimizing the possible effect of disturbance upon tree growth dynamics. Classical dendrochronological procedures were adopted (Speer, 2010). As pinewood belonged to protected areas, at both sites only one sample per tree was extracted at breast height (about 1.3 m from the ground) from 13 dominant individuals with an increment borer. Samples were mounted on wooden supports and surfaced with a scalpel. Tree-rings were dated, then had their widths measured from bark to pith to the nearest 0.01 mm using the sliding stage micrometer CCTRMD and recorded through the CATRAS program (Aniol, 1983).

2.2. Tree-ring chronology development and environmental-growth analyses

The tree-ring measurements were visually cross-dated and then checked through statistical control (COFECHA program) (Holmes, 1983). During the chronology building process, individual series showing correlation with master chronology $r < 0.4$ were discarded. Dendrochronological statistical indexes were considered: MS (Mean Sensitivity), which refers to the relative year-to-year change in tree-ring widths; EPS (Expressed Population Signal), an estimation of the reliability of a finite-sample chronology in representing the theoretical infinite-sample population; RBAR, a measure of the common variance between the single series in a chronology (Speer, 2010; Wigley et al., 1984). EPS and RBAR were calculated for a 20-year window with a 19-year overlap. Statistical indices were obtained through the COFECHA and ARSTAN40c software (Cook & Krusic, 2006; Holmes, 1983).

A two-step process was adopted in analyzing the relation between anomalous radial growth patterns and environmental factors. Previous research showed that at the medium-term frequency the species' ring development at both forest stands mainly depended on positive moisture balance of the current spring-summer season (Piraino et al., 2013). Therefore, total precipitation, average temperature and drought index values for the March-August period of the current year were used as climatic variables. Drought conditions were evaluated through the self-calibrated Palmer Drought Severity Index (scPDSI) (van der Schrier et al., 2006). Climate data was obtained from the database of KNMI Climate Explorer web page (http://climexp.knmi.nl/). Precipitation and temperature were downloaded from the E-OBS analyses v14.0 dataset (period 1950–2016), with a resolution of 0.25° × 0.25°. The scPDSI data was extracted from the CRU self-calibrating PDSI dataset (period 1901-2016) with a resolution of 0.5° × 0.5°.

Superposed Epoch Analysis (SEA) (Holmes & Swetnam, 1994), a nonparametric technique, was performed to disentangle the origin of reduced *P. pinea* ring growth rates, as well as the influence of drought upon the species ring development. Two separate analyses were run, differing in the established background series. In the first SEA, total precipitation and mean temperature represented the background time series, and pointer years corresponded to notorious narrow rings. In the second SEA, drought episodes represented event years, while standardized (age-detrended) annual growth was considered as background series.

Concerning the first SEA, narrow rings were defined considering negative pointer years. Positive pointer years were not computed, since we aimed to reconstruct the temporal occurrence of anomalous growth rates related to water stress, which are most likely expressed as extremely narrow rather than wide ring widths. NPY were calculated upon raw ring data following the "normalization in a moving window" (Cropper, 1979). A 5-year-long timeframe was selected, and NPY were recorded when at least 75% of the analyzed trees exhibited a reduction in growth of at least 50%. The common period 1942-2003 was considered, excluding the years of juvenile radial growth and their possible influence upon NPY development. The WEISER software was run for the identification of NPY (Gonzalez, 2001). Regarding the second SEA, drought episodes were established following Drobyshev et al. (2013), thus selecting those years when annual drought index fell in the lowest 10% percentile of the historical series (1944, 1945, 1949, 1973 and 2000). In this analysis, the age effect upon raw ring widths was removed through standardization procedure with the aid of the ARSTAN40c program (Cook & Krusic, 2006). To this end, individual chronologies were built fitting a negative exponential function to the raw ring series. Then, annual measured ring widths were divided by the expected value. Finally, individual standardized series were averaged producing a mean chronology for each sampled population.

For both SEA, a 5-year window (2 years before and 2 years after the event) was established. This window was selected based on previous analyses showing the sensitivity of the species radial growth to climatic conditions up to two years before ring development (Mazza & Manetti, 2013; Raddi et al., 2009). For each event, windows were superimposed and averaged. The mean climatic and ring-width patterns for the selected event years were statistically examined for significance (95% bootstrap confidence intervals) through 1000 Monte Carlo random simulations (Mooney & Duval, 1993). SEA was performed through the EVENT software (Holmes & Swetnam, 1994).

3. RESULTS

Twenty-two individual series contributed to the two tree-ring chronologies (Table 2 and Figure 2). Chronologies spanned similar periods, with San Rossore pinewood being slightly older than Cecina (Table 2). Mean annual ring width, mean correlation among series and mean sensitivity were higher at Cecina stand, whereas EPS and RBAR values were greater at San Rossore (Table 2).

Table 2. Characteristics of the tree-chronologies.

Site	Period	MV (mm)	MC	MS	EPS	RBAR
San Rossore	1890-2003	2.38	0.57	0.24	0.91	0.51
Cecina	1923-2003	2.71	0.58	0.27	0.89	0.45

Period: time span of the developed chronologies; MV: mean ring width annual value; MC: mean correlation among series; MS: mean sensitivity; EPS: expressed population signal; RBAR: average correlation between all series; EPS/RBAR: mean indexes values.

Pointer year analysis showed the occurrence of six (San Rossore) and nine (Cecina) negative growth anomalies, respectively (Figure 3). At the San Rossore stand, NPY occurred during 1950, 1951, 1956, 1964, 1994, and 2000 (Figure 3a). At Cecina, narrow rings corresponded to 1945, 1949, 1957, 1970, 1973, 1987, 1990, 1997, and 1999 (Figure 3b). No temporal coincidence in NPY emerged among the two studied woodlands.

Superposed Epoch Analysis, calculated selecting NPY as event years, showed a close relation among narrow ring formation and climatic factors. At the San Rossore forest stand, NPY are associated with dry conditions during the preceding year followed by high spring-summer temperatures during the current year (Figure 3a). On the other hand, negative growth anomalies at the Cecina population are related to March-August period of the current year characterized by low precipitation (Figure 4). Finally, SEA performed considering standardized ring widths as background time-series revealed that extreme drought translated into reduced species growth during the current year at both woodlands, and in the following year at the San Rossore stand (Figure 5).

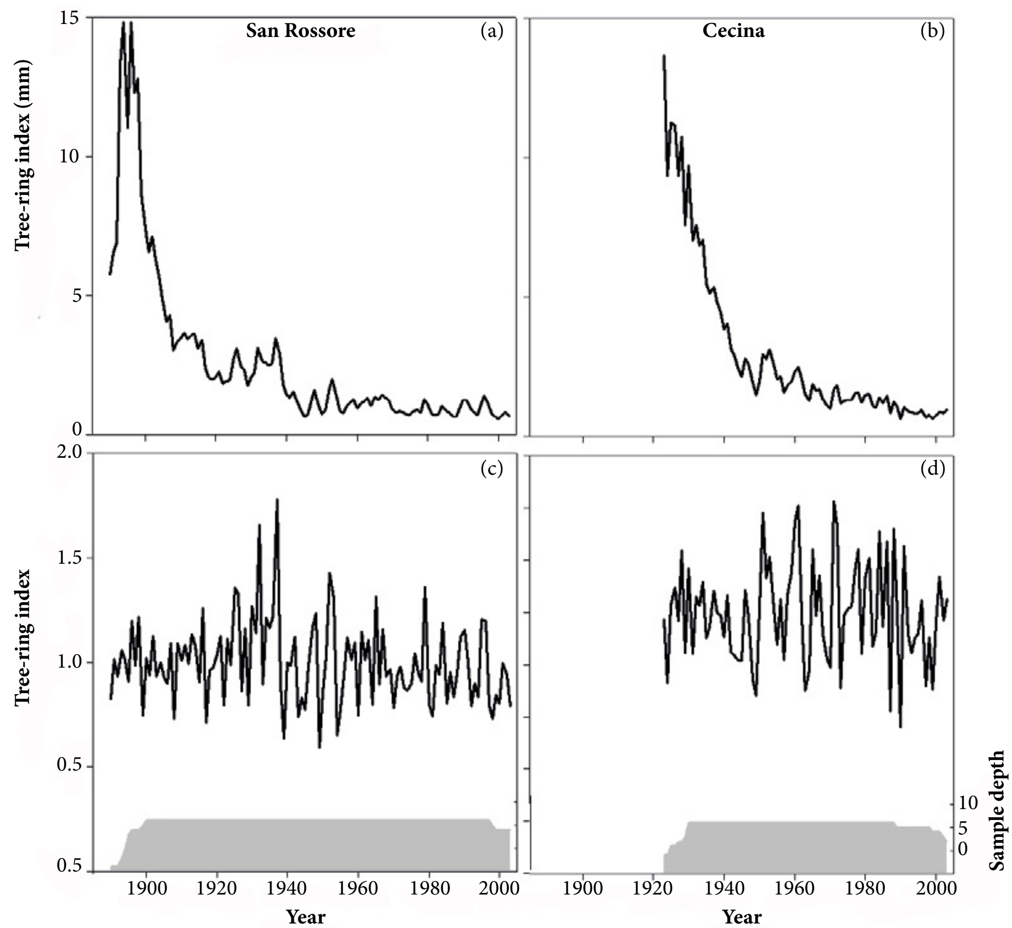

Figure 2. Site raw ring-width chronologies (top), residual tree-ring ch ronologies (middle), and sample depths (bottom) of the sampled umbrella pine populations.

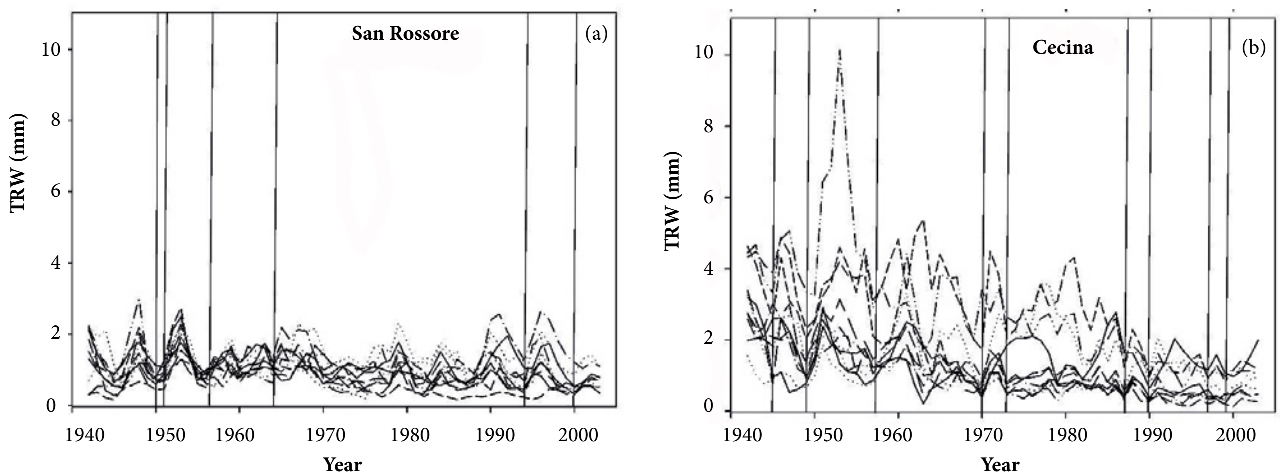

Figure 3. Raw ring-width series of the analyzed trees showing negative pointer years (vertical lines) at the examined forest stands for the common period 1942–2003.

TRW: tree-ring width.

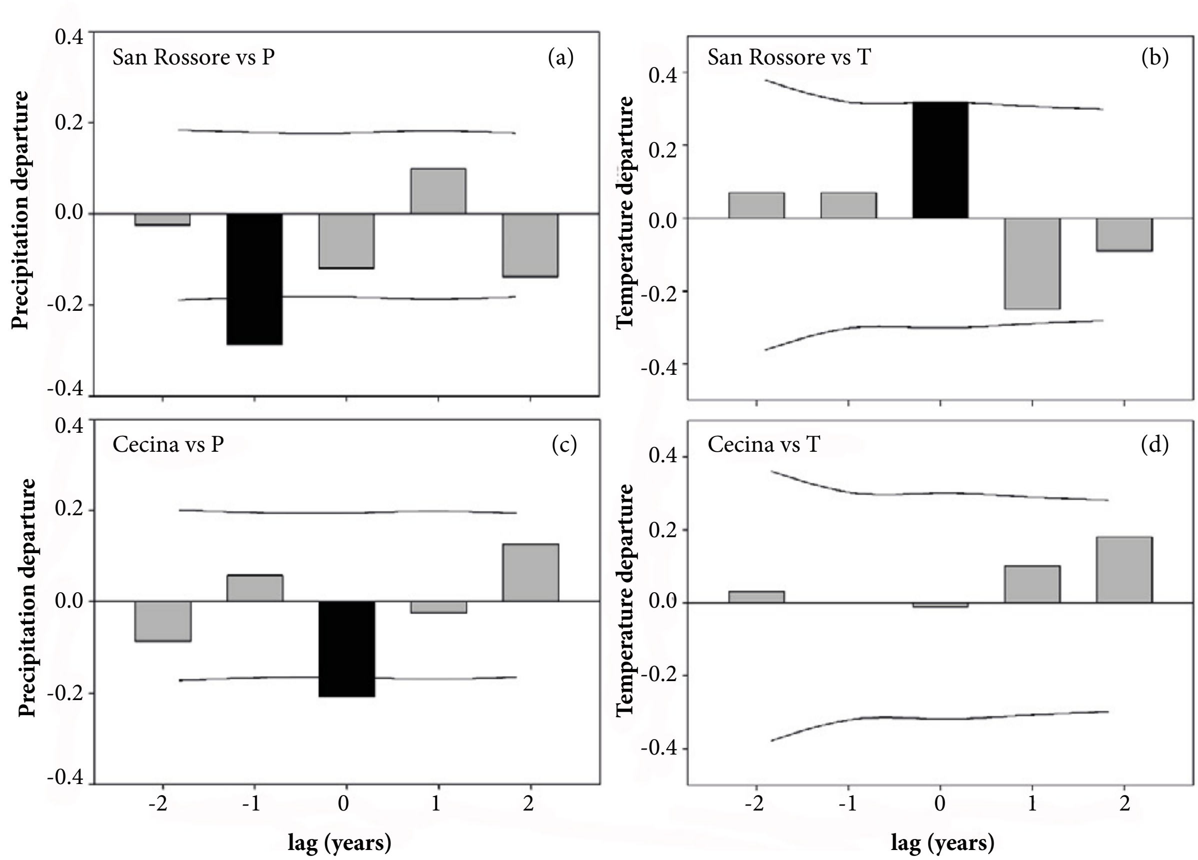

Figure 4. Superposed epoch analysis (SEA) comparing spring-summer season precipitation and temperature departures during the growth event-years, corresponding to negative pointer years.

The X-axis represents a 5-year window, starting 2 years previous and ending 2 years after the growth event (year 0). The time intervals used to run SEA analysis were 1950-2003. Dotted lines: 95% confidence interval

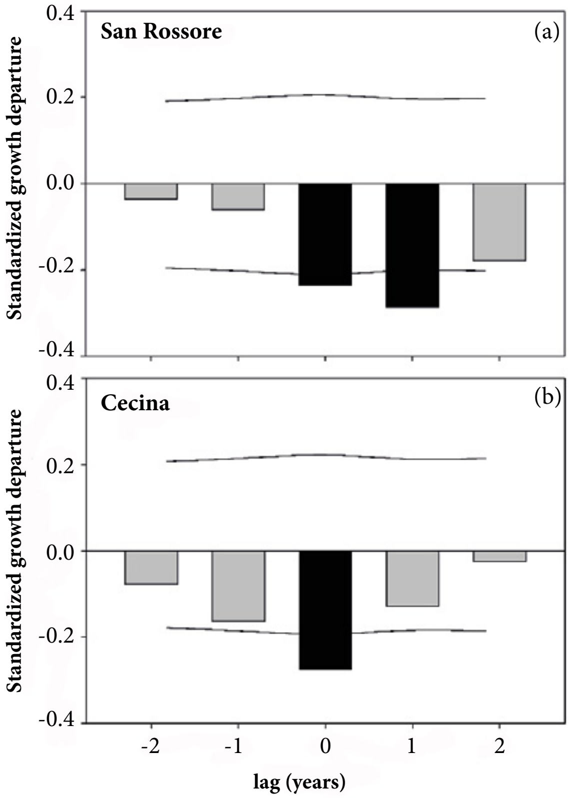

Figure 5. Superposed epoch analysis (SEA) comparing standardized ring growth departures during the event-years, corresponding to extremely drought years.

The X-axis represents a 5-year window, starting 2 years previous and ending 2 years after the event year (year 0). The time intervals used to run SEA analysis were 1942–2003. Dotted lines: 95% confidence interval.

4. DISCUSSION

Regarding the statistical indices examined in this work, the relatively high values of MC for both chronologies are likely related to a common factor influencing the stem growth, possibly depending on local climate conditions (Speer, 2010). Most important, the high EPS values, above the 0.85 critical threshold indicate that, despite the relatively low sample depth developed in this research, our findings could be extended to the whole woodlands where sampled trees grew (Wigley et al., 1984).

Interestingly, NPY emerged at the analyzed forests during different years, suggesting that narrow ring formation was unlikely driven by a regional environmental factor. Pointer years can either reflect large-scale climatic variability or more local environmental characteristics (Schweingruber, 1996). Although not measured in this work, it is well known that insect outbreaks, masting events, stand factors, and local climatic conditions may be potential NPY drivers (Schweingruber, 1996). Further research should help to disentangle the origin of local NPY for the analyzed north-Tyrrhenian umbrella pine populations.

Superposed Epoch Analysis establishing NPY as event years revealed that extremely narrow ring development is climatically driven. Differences emerged among the selected stands, which seem to reflect the medium-term dendroclimatological signal at the studies sites (Piraino et al. 2013). In this sense, previous research showed a strong relation between Cecina ring growth and spring-summer rainfall of current year, whereas at the San Rossore stand, radial growth reflected amount of precipitation of preceding years as well (Piraino et al., 2013).

Physiologically, the lagged response of radial growth to rainfall at the San Rossore stand may be related to the detrimental effect of reduced precipitation upon carbohydrate storage (Pallardy, 2010). On the other hand, high temperatures during spring-summer of current year (San Rossore) can enhance evapotranspiration processes, while low precipitations (Cecina) may reduce photosynthesis (Campelo et al., 2006; Oliveras et al., 2003). Both climatic conditions can negatively affect carbohydrate production, thus promoting NPY occurrence (Liphschitz et al., 1984). The presented results agree with researches performed for *P. pinea* woodlands distributed in coastal Albania, showing that negative pointer years are tightly coupled to dry climatic conditions during the spring-through-autumn period (Toromani et al., 2015).

Further information is provided by SEA calculated considering extremely low scPDSI values. At the San Rossore and Cecina woodlands, tree-ring decreased in drought years, suggesting that although no common NPY occurred, stem growth at both stands is sensitive to extremely dry conditions during the year of ring formation. On the other hand, plasticity in the species response to drought emerged, expressed by the impact of the dry spell in the San Rossore pinewood. Variability in the species response to extreme drought could reflect either genetic variation in provenance or phenotypic plasticity. Although our research did not address this particular topic, the low genetic polymorphisms of umbrella pine suggested that this result is unlikely to be an expression of differences in genetic provenances (Fallour et al., 1997). Therefore, local adaptation to climatic conditions possibly explains the different response of the analyzed forests to drought events. San Rossore could be considered, by a bio-climatological point of view, a transitional area located at the northern border of the Mediterranean bio-climate, characterized by the presence of Central European plant species lacking at southern latitudes along the Tyrrhenian coasts (Vagge & Biondi 1999). In this sense, the San Rossore stand is under the influence of the orographic effect of the

Apuan Alps, with consequent higher rainfall amounts than Cecina, where climate is modulated solely by the presence of the Tyrrhenian Sea (Rapetti, 1997; 1999). Additionally, hydroclimatic balance during dry years is more negative at Cecina than at San Rossore, suggesting more arid conditions at the former pinewood site (Rapetti 1997; 1999). The data presented in this research further supported these assumptions (Figure 1). Indeed, temperatures are similar between the sampled areas, whereas trees located at San Rossore grow under wetter regional climatic conditions than those of Cecina site at both annual and seasonal (spring-summer) timescales (Figure 1). Differences are more marked during the late-summer period, when pines growing at Cecina stand experienced a longer water deficit (Figure 1). For the abovementioned reasons, we could hypothesize that umbrella pines growing at San Rossore stand may experience a greater physiological stress during dry spell than those located at the Cecina site, where trees could probably be better adapted to water shortage episodes (De Luis et al., 2013).

Previous researches highlighted the effects of drought upon the species radial growth along the Mediterranean area. In the Iberian Peninsula, more arid conditions experienced by umbrella pine increased inter-annual variability in the species growth, suggesting an amplified sensitivity of ring development to water shortage (Natalini et al., 2015). Regarding *P. pinea* populations distributed in the Italian coastline, decreasing annual rainfall amount during the mid-1920s and the early 1970s induced significant downward trends in the species stem growth (Mazza & Manetti, 2013). On the other hand, the synergic action of reduced rainfall and expansion of tourism translated into less stored soil water, which likely deteriorated the growth conditions of mid-Tyrrhenian pinewoods (Mazza & Manetti, 2013).

5. CONCLUSION

This research explored the relationship between *P. pinea* radial growth anomalies and environmental conditions. Previous research concerning the analyzed pine stands dealt with the species dendroclimatological signal, but only at the medium-term frequency, thus not considering the occurrence of extreme radial growth (Piraino et al., 2013). Furthermore, to our knowledge there are no studies that directly addressed the response of the species radial growth to drought events. Our findings highlighted the site-dependent stem growth response to dry spells, apparently modulated by local climatic conditions. In this sense, drought-related effect was more evident at the San Rossore woodland. This result is relevant considering that the San Rossore pinewood is among the most important productive plantations of *P. pinea* in Europe, characterized by long tradition in high-quality production of pine nuts exported globally (Peruzzi et al., 1998). Our findings further demonstrated that the expected drying trend for the study area will be detrimental for the *P. pinea* growth dynamics, warning about the need to enact conservation and management policies in these forest resources.

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