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Original Article

A long-term chronology of *Pinus pinea* L. from Parco della Versiliana (Pietrasanta, Italy) derived from treefall induced by a windstorm on March 4th-5th, 2015

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ABSTRACT

Pinewoods are distinctive environmental elements in the Mediterranean coastal area and have both natural and historical significance. From the evening of March 4th to the morning of March 5th, 2015, a severe and unusual windstorm occurred in the Tuscany region of central Italy with wind gusts over 120 km/h. The windstorm caused vast damage to the anthropic and natural environment and wounded numerous trees in the renowned pinewoods of *Parco della Versiliana* in the Tyrrhenian coastal area. The meteorological calamity provided the opportunity to i) date the onset of the artificial plantation of the present Italian stone pine (*Pinus pinea* L.) forest to the 1820s, ii) build a long-term tree-ring chronology of the Italian stone pines in the area and iii) analyze the climate-growth relationship of the Italian stone pine in the study area. The resulting Versiliana chronology was derived from 60 trees and spanned from 1828 to 2014 (187 years), representing one of the longest living Italian stone pine forests on the Italian Peninsula. Finally, the climate-growth analysis highlighted that at this site the latewood width is positively influenced by summer temperature, a peculiarity worthy of further investigations.

1. Introduction

Italian coastal pine forests mainly have anthropogenic origins. These forests were initially planted to consolidate sandy soils and to protect internal crops from erosion and salty winds, and they were then used to produce wood, resin and nuts. Over time, they have become intimately inherent to the coastal landscape and represent valuable sites of naturalistic interest for animal and plant species conservation (Bianchi et al., 2005; Maetzke and Travaglini, 2005). On the Tyrrhenian coast of Italy, several pine forests have remarkable historical and ecological value and represent evocative, characteristic and symbolic elements of the coastal landscape (Agrimi et al., 2002; Ciancio et al., 2008, 1986; Del Perugia et al., 2017; Di Filippo et al., 2014). Woods of Mediterranean pine species cover more than 448 ± 39 km^2 in Tuscany and have become, over time, a significant environmental and historical part of the coastal ecosystem (Bernetti, 1987). The most representative species are maritime pine (*Pinus pinaster* Aiton.) and Italian stone pine (*Pinus pinea* L.), occupying 264 ± 31 and 112 ± 20 km^2, respectively, which have been planted since the 16th century (Del Perugia et al., 2017; Gasparini and Tabacchi, 2011). Their relevance involves cultural and touristic aspects, and their management and conservation are imperative issues to promote their preservation as areas of public interest (Bianchi et al., 2005; Maetzke and Travaglini, 2005).

The forest ecosystems in Europe and the Mediterranean region in particular are largely affected by climate change due to regional summer warming and the concurrent reduction in summer precipitation (IPCC, 2018; Lindner et al., 2010; Schelhaas et al., 2003). Severe damage has occurred due to extreme meteorological events that are becoming more frequent over time; in particular, windstorms are increasing in frequency and intensity, impacting the structure and composition of forests (Ulanova, 2000) at various scales.

On March 4th, 2015, a strong and unusual pressure gradient built between central Europe and the Tyrrhenian Sea. The pressure values in France and central Italy ranged between 1038 − 1042 hPa and

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997 − 1000 hPa, respectively. This steep gradient caused one of the most powerful and blasting windstorms ever observed in the Tuscany region and lasted approximately 16 h, reaching its highest intensity between late night and morning. The storm-related winds peaked at 150 − 170 km/h in the northern plains and 120 − 140 km/h in the central-northern coastal areas. This extreme weather event caused extensive damage to buildings, infrastructure and forests. It was calculated that the windstorm affected an area of 20.17 km^2, equal to 5.7 % of the forested territory in Tuscany (Bottalico et al., 2016; Chirici et al., 2016). *Parco della Versiliana*, a renowned pine forest on the Tyrrhenian coast, was severely damaged by this meteorological event as a large number of trees were felled by the storm.

The availability of stumps and logs provided the opportunity to conduct an extensive sampling campaign. The intention was that all woody material would be removed in a short period of time by the municipalities for security reasons, although this removal would entail the loss of valuable dendrochronological data. The aim of our work was to construct the first chronology of Italian stone pine from *Parco della Versiliana*, to evaluate the response of these trees to climate (Fritts, 1976) and to preserve part of this material from destruction.

2. Materials and methods

2.1. Study area

Parco della Versiliana (43° 56' 34" N, 10° 11' 27" E) is a historical park located near the town of Marina di Pietrasanta in the municipality of Pietrasanta in the province of Lucca. The front of the park extends over 1 km along the Tyrrhenian coast, and it currently covers a total area of approximately 0.83 km^2 (Fig. 1), lying on sandy beach ridges and interdune wet areas (Baroni et al., 2015).

The history of this park, as well as other coastal pinewoods in Tuscany, is closely related to the development of land tenure in coastal areas. A natural forest, named *Macchia di Marina,* mainly composed of oaks and alders, occupied the study site in the 18th century (Nepi and Mazzei, 2001). The forest was used by local communities for harvesting wood and grazing, and its conservation was regulated by precise disposals of the Grand Duke of Tuscany (Gabbrielli, 1993). The aim of this political preservation was to protect inland cultivation from sea winds; moreover, it was believed that the forest provided protection from malaria that infested the more internal marshy areas (Rombai, 2019). In the second half of the 18th century, measures to reclaim the marshy areas were taken, giving way to the gradual cutting of wood and the concession of lands for farming. Old forests were gradually reduced for property development, except in the area closest to the sea, which was saved because the sandy soils were unsuitable for cultivation, and the forest provided a protective barrier against the salty winds (Bernetti, 1987). Anthropic plantings of Italian stone pine in this area started in the second decade of the 19th century; in 1828, Grand Duke Leopoldo II granted landowners the use of new lands that had emerged due to sea retreat on the condition that they sowed a protective belt of Italian stone pines to consolidate sandy dunes and protect inland cultivation (Eckenwalder, 2009; Farjon and Filer, 2013; Nepi and Mazzei, 2001). Until the middle of the 20th century, the forest was intensively used for the production of pine nuts and harvesting wood (Maetzke and Travaglini, 2005; Rombai, 2019). In 1953, the park was declared an area of public interest due to its high recreational, touristic and landscape value (D.M. n. 94 of 26/03/1953, http://www.regione.toscana.it/piano-paesaggistico/vincoli-per-decreto/lucca (accessed on 06 August 2019) following the provincial committee minutes for the protection of the natural beauty of Lucca Province performed on 29 December 1947). In 1980, the municipality of Pietrasanta bought the park and declared it public area; in 2004, the park was declared a protected landscape (Art. 136 of the Italian D.Lgs. n. 137 of 22/01/2004, https://www.camera.it/parlam/leggi/deleghe/testi/04042dl.htm accessed on 21 May 2020).

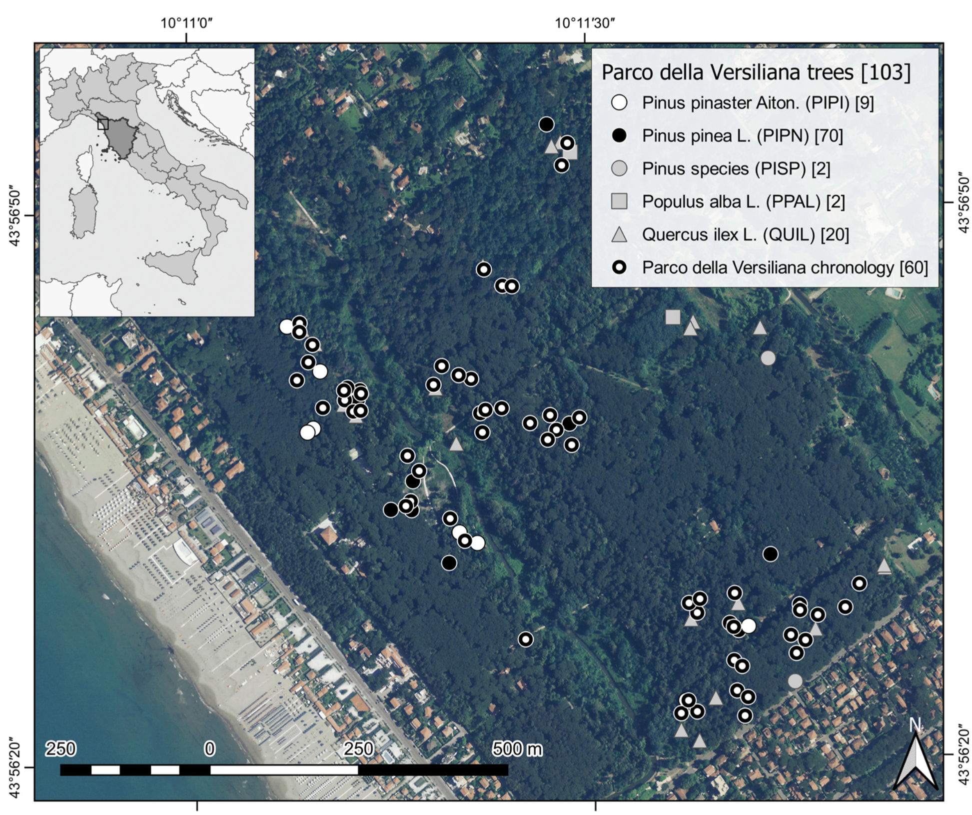

Fig. 1. Sketch map of the study area. The basemap is a Tuscany Region Web Map Service colored orthophoto of 2007 (http://www502.regione.toscana.it/wmsraster/com.rt.wms.RTmap/wms?map=wmsofc, accessed December 18, 2019).

Currently, the pinewoods are mainly dominated by Italian stone pine, with holm oak (*Quercus ilex* L.) and maritime pine in small areas. White poplar (*Populus alba* L.) and black alder (*Alnus glutinosa* Gaertner) are also present in the proximity of water channels and pools (Gellini et al., 1986; Maetzke and Travaglini, 2005); the wood is considered "Mesomediterranean dune pine wood of Italian stone pine" as defined by Mondino and Bernetti (1998).

2.2. Climate data

As the local meteorological temperature data spans the last two decades and precipitation data are present from 1955 to 2001 (https://www.sir.toscana.it/, accessed on December 16th, 2019), monthly precipitation and mean monthly temperature time-series data were reconstructed for the period from 1774 to 2014 by compiling long-term meteorological observation time-series data that were available for Italy and interpolating the data for the sampling site using the anomaly method (Mitchell and Jones, 2005; New et al., 2000), as described in Brunetti et al. (2014, 2012) and Crespi et al. (2018). The climatologies, mean temperature and precipitation for each month were calculated using the reference period 1961–90, and they are reported in Fig. 2.

The climate is temperate, with hot and dry summers, and it is classified by the Köppen classification (Peel et al., 2007) as Csa which is characteristic of the Mediterranean area. The yearly precipitation is concentrated from late autumn to early spring; the summer is dry, and July is the driest month. The mean annual temperature is 15 °C, with the cooler months presenting a mean temperature higher than 7 °C (Fig. 2).

2.3. Chronology development and climate/growth analysis

The sampling involved standing trees and trees that were felled by the windstorm. Standing trees were selected as much as possible to be healthy straight trees with a symmetric canopy and without any visual injuries to the crown and stems.

In total, 103 trees belonging to four species were sampled in the park, and sampling was conducted by cutting disks from the felled trees or extracting cores by means of an increment borer from the standing trees. At least two cores per tree were extracted using a double helix500 mm long incremental borer with a diameter of 5.15 mm (Haglöf Sweden AB, Långsele, Sweden).

Considering the number of samples and the sensitivity of Italian stone pine to climatic parameters in other Mediterranean sites (Akkemik, 2000; Campelo et al., 2007; Cherubini, 1993; De Luis et al., 2009; Mazza et al., 2014), we focused on 70 trees of this species (*P. pinea* L.) to construct the tree-ring chronology.

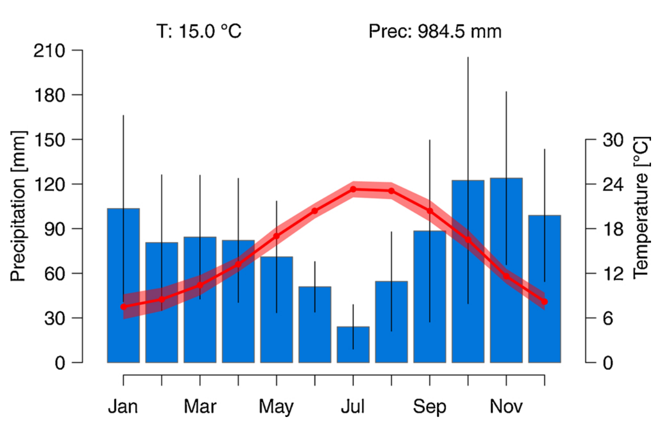

Fig. 2. Climatic diagram of the study site. The climatologies were calculated based on the reconstructed climatic variables for the period 1961–1990. Bars and shaded area identify the standard deviation of the precipitation and temperature, respectively. Reported values refer to the mean temperature and precipitation for the reference period 1961–1990.

The disks and cores were prepared for measurement following standard dendrochronology procedures (Fritts, 1976; Schweingruber, 1988); the samples were sanded with progressively finer sand paper to produce a polished surface and to highlight the ring boundaries. The total tree ring width (RW), earlywood width (EW) and latewood width (LW) were measured with a precision of 0.01 mm using an incremental slide (LINTAB™ mod. 3, RINNTECH®, Heidelberg, Germany), a reflected light optical microscope with a 40x zoom (Leica®, Wetzlar, Germany) and TSAPWin Scientific 4.69 h software (RINNTECH®, Heidelberg, Germany). The distinction between EW and LW was based on visual characteristics of the wood which appears light with a large lumen and thin cell walls in the former and dark with small lumens and thick cell walls in the latter. The border between EW and LW of the same year was identified at the beginning of the transition between the two wood structures.

Each measurement was examined for correct dating using visual and statistical cross-dating, and potential dating errors were checked with COFECHA software (http://www.ldeo.columbia.edu). In the site chronology, we only included individual series with a statistically significant positive interseries correlation value (p-value < 0.05).

To preserve the midfrequency variability (Melvin, 2004), the tree-ring series were standardized as ratios by single detrending by means of a modified negative exponential curve or a negative slope line when the exponential model did not fit the growth trend. This standardization method resulted to be the most suitable, among those that were tested associated to the *Parco della Versiliana* Italian stone pine series (e.g. various length and age-adaptative cubic smoothing splines and modified Hugershoff curve), for dendroclimatic analysis purposes (not shown). The site standard chronology was constructed as a biweighted mean of the standardized tree series, contextually a residual chronology, where part of the autocorrelation that characterizes the tree-ring series was removed, was built averaging the prewhitened tree-ring series. Prewhitening is a process that fits an autoregressive model to the tree-ring series and adds the residuals derived from the model to the series' mean (Bunn, 2008). The interseries correlation values, detrending and site chronology were calculated using the dlpR package in the R statistical environment (package ver. 1.7.0; R ver. 3.6.1; Bunn, 2008; R Core Team, 2019).

To separately analyze the mid- and high-frequency response of tree growth to climate, the site standard chronology and the reconstructed meteorological series were both filtered with a Gaussian filter (window length = 30 years, sigma = 5 years), as this method has been performed on other pine species in alpine environments (Cerrato et al., 2019). The calculated low-pass filtered time-series (called "mid" hereafter in the case of the filtered tree-ring chronology) were used to investigate the response of tree growth to climate variation at mid-frequency, whereas the high-frequency were investigated by means of the residual time-series obtained by subtracting the low-pass filtered time-series from the standard chronology (obtaining the chronology called "hig" hereafter) and from the non-filtered meteorological data. The Gaussian filter was applied to the time-series using the smoother package in the R statistical environment (package ver. 1.1).

The climate/growth relationship was assessed by means of bootstrap correlation analysis. The site-specific monthly variables of temperature and precipitation from May of the prior year of growth to October of the year of growth on the portion of the chronology that showed a subsample signal strength greater than 0.85 were used in the analysis (Buras, 2017). Moreover, two aggregated variables that involved the growing season in the Mediterranean area were considered: a longer season, from March to October, and a shorter season, from March to July. The standard (std) and residual (res) chronologies were correlated to the reconstructed meteorological time-series, whereas the filtered chronologies (mid and hig) were correlated to the filtered meteorological time-series (low-pass and high-pass filtered, respectively). The correlations were computed using the treeclim package in the R

Table 1
Parco della Versiliana chronology statistics.

Chronology	Time span (years) [SSS > 0.85]	μ(r) ± σ [std chronology] [*res chronology*]	MS [std chronology] [*res chronology*]	SSS [std chronology] [*res chronology*]	AR ± σ [std chronology] [*res chronology*]
RW-VERS	1828–2014 (187)	0.389 ± 0.081	0.205	0.95	0.838 ± 0.072
	[1839–2014 (176)]	[0.400 ± 0.080]	[0.204]	[0.94]	[0.732 ± 0.085]
		[*0.428 ± 0.085*]	[*0.110*]	[*0.99*]	[*0.053 ± 0.075*]
EW-VERS	1828–2014 (187)	0.376 ± 0.096	0.223	0.95	0.810 ± 0.096
	[1839–2014 (176)]	[0.397 ± 0.088]	[0.215]	[0.94]	[0.686 ± 0.092]
		[*0.402 ± 0.092*]	[*0.120*]	[*0.99*]	[*0.050 ± 0.075*]
LW-VERS	1828–2014 (187)	0.433 ± 0.102	0.287	0.94	0.715 ± 0.093
	[1839–2014 (176)]	[0.444 ± 0.102]	[0.291]	[0.95]	[0.651 ± 0.115]
		[*0.459 ± 0.100*]	[*0.174*]	[*0.99*]	[*0.014 ± 0.063*]

$\mu_{(r)}$: Mean interseries correlation; σ: standard deviation; MS: mean sensitivity; SSS: subsample signal strength; AR: 1st order autocorrelation.

statistical environment; 1000 bootstrap iterations were applied (Biondi and Waikul, 2004; Zang and Biondi, 2015). As multiple hypotheses were tested (i.e., 18 monthly and two aggregated variables), the significance levels of 5%, 1% and 0.1 % were divided for the number of hypotheses to compensate for the increased occurrence of type I errors following Bonferroni's method.

3. Results

3.1. Chronology statistics

According to the selection criteria, data from 60 out of the 70 Italian stone pines were selected to build the mean site chronology. The resulting RW, EW and LW *Versiliana* (VERS) chronologies spanned from 1828 to 2014 (187 y) with a mean series length of 147 years. Considering the portion of the chronologies with a subsample signal strength greater than 0.85, the site chronologies could be considered statistically reliable from 1839 CE onwards (176 years). The ring-width mean values were equal to 2.14, 1.55 and 0.59 mm for RW-, EW- and LW-VERS, respectively. The interseries correlation values of the standard chronologies ranged from 0.397 of EW-VERS to 0.444 of LW-VERS, whereas the mean sensitivity values were 0.205, 0.223 and 0.287 for RW-, EW- and LW-VERS, respectively. A substantial amount of autocorrelation was retained in the standard chronologies showing values of 0.732, 0.810 and 0.715 for RW-, EW- and LW-VERS, respectively. These values decrease to 0.053, 0.050 and 0.014 when considering the residual chronologies (Table 1). The low- and high-pass filtered chronologies returned slightly higher but comparable values compared with the standard and residual chronologies, respectively (not shown). Summary information of the VERS standard and residual chronologies are reported in Table 1 and Fig. 3.

3.2. Climate/growth relationships

The correlation function analysis performed on the VERS chronologies showed that the midfrequency trend was the most influencing factor. In contrast, the correlation functions performed in the high-frequency domain did not return statistically significant results (Fig. 4). Considering the standard chronologies, the temperature trend for the considered months had a positive influence on tree growth even if the effect could rarely be discerned by chance. Significant correlation values were found for the July temperature of the previous year of growth for all RW-, EW- and LW- chronologies, whereas the temperatures in June and October of the current growing year had a significant effect on LW-VERS. Moreover, the aggregated temperatures from March to October and March to July showed significant positive correlation values that were higher than the single month LW-VERS correlation values, with the latter being higher than the former (Fig. 4). Considering only the mid-frequency domain (mid), correlation values were higher than considering the std chronologies and always significant at the 95 % confidence level, especially considering LW-VERS. Contrarily, the high-frequency chronologies (res and hig) never showed significant correlation values with temperature even if an increase in values was observable considering the aggregated variables (Fig. 4).

The correlation between the chronologies and precipitation was not significant at the study site considering the std, res and hig chronologies. Considering the mid-frequency domain, significant negative correlation values were observable with previous and current summer precipitation (June and July) for the RW- and LW-VERS chronologies, and for aggregate variables considering LW-VERS (Fig. 4). Despite the paucity of significant values, the correlation between the chronologies and the precipitation was almost always negative, with the exception of early spring (April and May) and late summer (August and September), especially observable in RW-VERS and EW-VERS (Fig. 4). Regarding the aggregated variable, the correlations showed positive values in the high frequency and negative values in the midfrequency (Fig. 4).

4. Discussion

The main objectives of this work were the construction of the first tree-ring chronology from *Parco della Versiliana* and the assessment of its suitability for dendroclimatic studies. *Parco della Versiliana* was severely injured by the windstorm on March 4th-5th 2015, and a vast amount of dendrochronological data risked being definitively lost. This scenario was serious because the VERS chronology is one of the longest tree-ring chronologies of Italian stone pine in the Italian western coastal environment; to our knowledge, this chronology is exceeded only by the Pineta di Classe chronology (Ravenna, Italy) on the eastern Italian coast (Buli, 1949). Along the Italian mid-Tyrrhenian coast, several old pine forests of historical and ecological relevance have been investigated for dendroecological and dendroclimatic purposes, and the ages of these forests date back to the mid-19th century. A dendroecological investigation on the ancient forest of Fregene (Fiumicino, Rome) revealed a breast height age of 174 years (Di Filippo et al., 2014), and in the Castelporziano, the oldest trees date back to 1872 CE (Cutini et al., 2015). Piraino et al. (2013) conducted a study on several pinewoods in the Tuscany and Lazio regions, obtaining chronologies spanning from 1851 CE (Cecina) to 1925 CE (Duna Feniglia). The VERS chronology verifies the onset of the cultivation of Italian stone pine in the study site in the second decade of the 19th century that was promoted by Grand Duke Pietro Leopoldo to remedy the degradation of the primary Macchia di Marina, as historical documents report (Galli, 2008; Nepi and Mazzei, 2001). The oldest tree in the VERS chronology (1828 CE) dated back precisely to the beginning of the anthropic plantation of Italian stone pines in the study area that surely began after 1787 CE (Nepi and Mazzei, 2001). By analyzing the ages of the trees included in the chronology, it was determined that *Parco della Versiliana* is an uneven-aged forest (from 90 to 186 years) with a dominant cohort of old trees. This evidence indicates some natural forest renewal, which has been found in other Tyrrhenian sites (Ciancio et al., 1986; Di Filippo

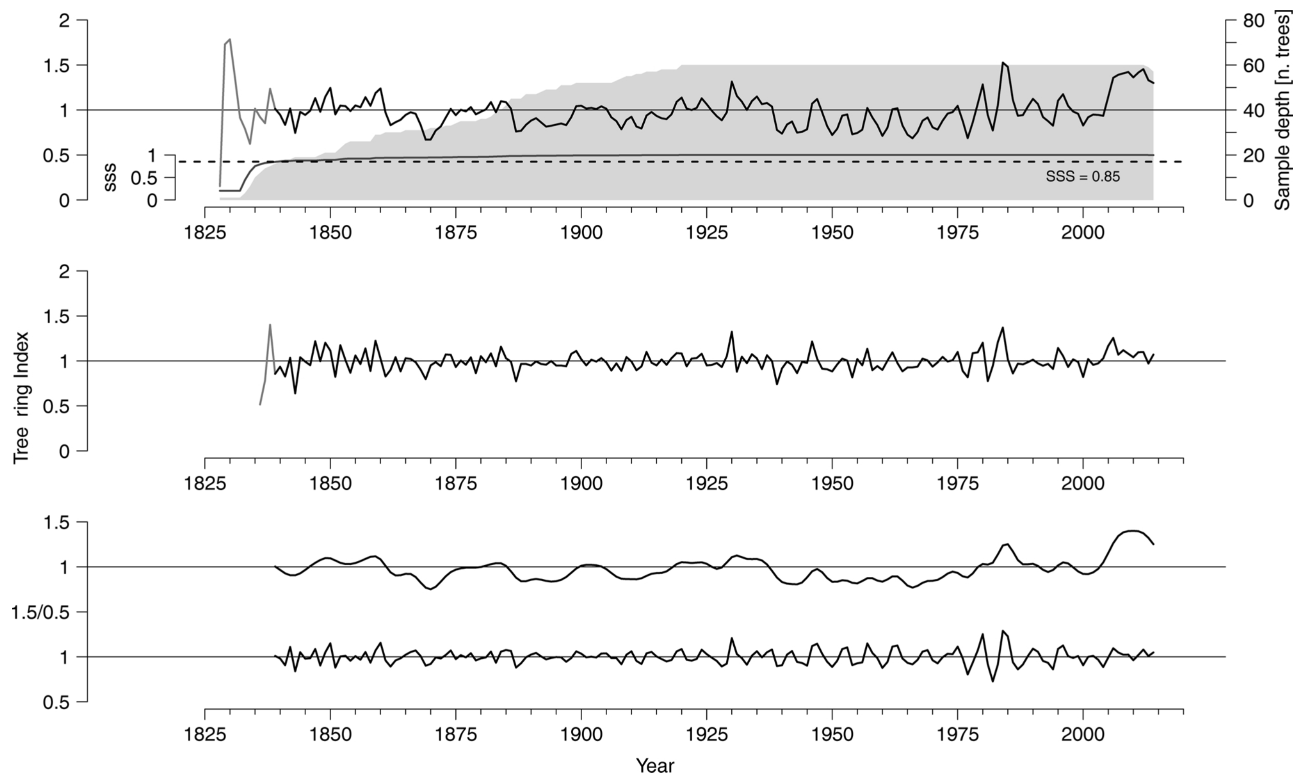

Fig. 3. *Parco della Versiliana* ring-width standard (upper), residual (middle) and 30-years low- and high-pass filtered chronologies (lower panel). The inset in the upper panel identifies the SSS value along the chronology, whereas the gray area identifies the sample depth.

et al., 2014). The majority of the oldest trees included in the VERS chronology survived until the windstorm according to the data obtained from the cores. These results confirm the priceless value of *Parco della Versiliana* not only as an extraordinary landscape element but also for its importance as a natural data archive for the study of environmental changes (Baroni et al., 2015).

The *Parco della Versiliana* chronologies showed relatively low interseries correlations and mean sensitivity values compared with those

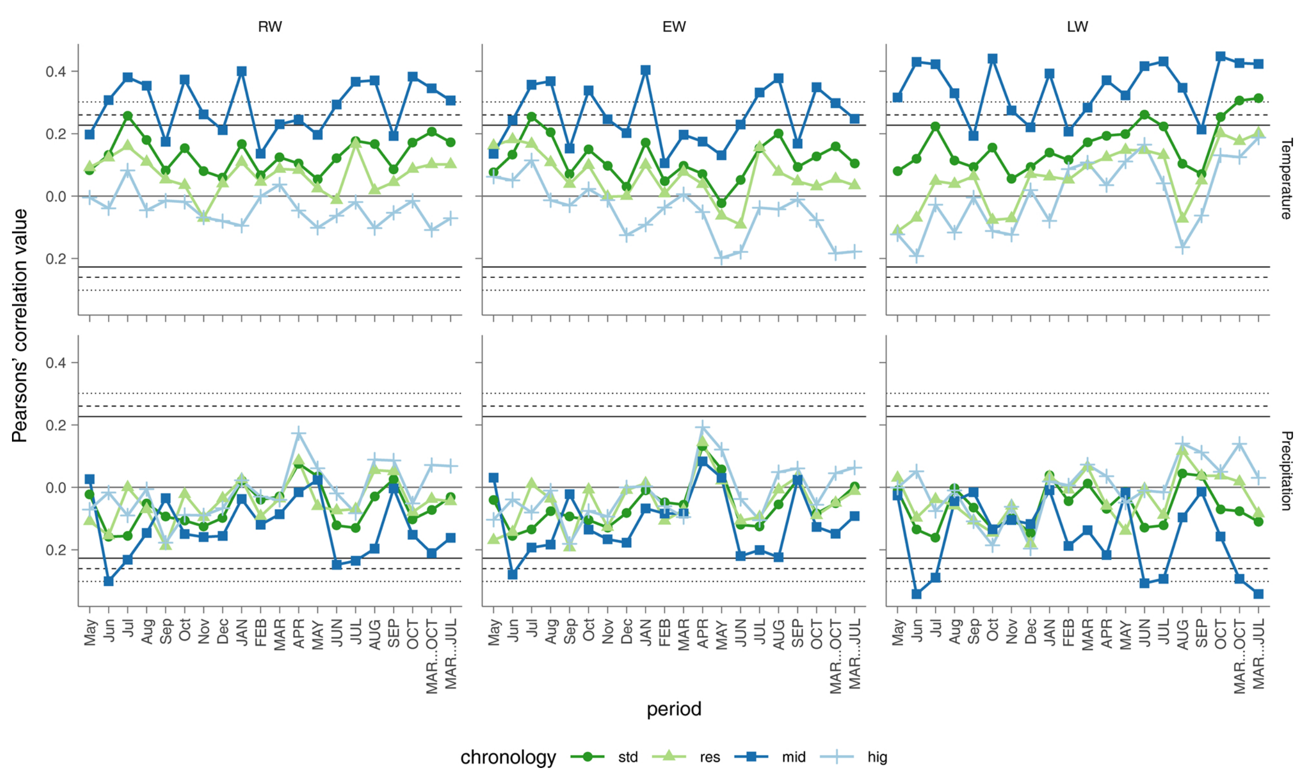

Fig. 4. Results of the climate/growth analyses for the mid (dark) and high frequencies (pale colors). Solid, dashed and dotted lines identify the Bonferroni corrected levels of significance, α = 0.05, 0.01 and 0.001, respectively.

derived from other Mediterranean sites (De Luis et al., 2009; Mazza and Manetti, 2013; Toromani et al., 2015). The low interseries correlation values indicate a lack of a very strong common signal between individuals, and the low mean sensitivity values indicate the relatively standard growth of trees without a large width difference between subsequent years. When analyzing the relationships between radial growth and the climate parameters, a peculiar characteristic of Italian stone pine in *Parco della Versiliana* was shown: their growth seemed to be enhanced by high temperatures during the summer months, revealing a behavior that differs from what is usually reported in other Mediterranean environments (Akkemik, 2000; Campelo et al., 2007; De Luis et al., 2009; Mazza et al., 2014; Toromani et al., 2015). The Italian stone pine has been investigated with dendroclimatological methods in several stands within its natural range in the Mediterranean basin. This species has usually been revealed to be sensitive to drought conditions, with reductions in tree-ring dimensions caused by high temperatures and reduced water availability (Akkemik, 2000; Campelo et al., 2007; De Luis et al., 2009; Mazza et al., 2014; Mazza and Manetti, 2013; Toromani et al., 2015). In contrast, the RW-, EW- and LW-VERS chronologies showed positive correlations with temperature during the summer months, although only those reported for LW-VERS were significant. Moreover, the lack of significant correlation values in the high-frequency domain (for both res and hig chronologies) was in accordance with the low mean sensitivity values recorded and corroborate the idea that only the long-time trend had an important influence on the tree-growth at this site. Contrarily, it seemed that precipitation was not relevant for tree growth; the correlations were almost always negative but not significant (Fig. 4). These results may have been due to the nonsignificant impact of the reduction in precipitation during the dry season due to the conditions at the sampling site, where the presence of water channels and pools could have influenced tree growth, acting as clean water reservoirs during periods of drought stress. This aspect needs to be investigated further following recent dendroecological and dendroclimatological studies on Mediterranean tree species that have focused on some distinctive anatomical wood features, such as intra-annual density fluctuations (Battipaglia et al., 2016; Campelo et al., 2007; Cherubini et al., 2003; Zalloni et al., 2016). Analyses on the number and distribution of intra-annual density fluctuations in our sample will help to better understand the response of these trees to climate.

5. Conclusion

The coastal Italian stone pine forest of the *Parco della Versiliana*, located on the Tyrrhenian coast of Tuscany, was found to be one of the oldest living forests on the Italian Peninsula. In fact, the oldest trees verified the onset of the anthropic plantation of the Italian stone pine forest in the 1820s, soon after the Gran Duke regulation occurred in 1787 CE. Thus, their longevity indicates that some individual trees in the study stand belonged to the first pine plantation and survived following the windstorm.

The climate-growth analyses showed unexpected results, as they differ from what is typically reported for this species. In fact, a significant positive correlation between LW and summer temperature in Mediterranean area was never reported for Italian stone pine before. Further dendroclimatic investigations are needed to better understand whether the growth/climate relationship is influenced by anthropic actions or if the population of pinewood at the study site retains a non-typical climatic signal due to site characteristics.

Nevertheless, considering the length of the chronology and the historical and environmental importance of the study site, which is heavily conditioned by human activities, our results provide new and valuable data about the evolution of this stand. The oldest living Italian stone pines are worthy of consideration and protection as natural heritage. They represent “natural monuments” that retain valuable data about the cultural heritage of this area. For these reasons, the *Parco della Versiliana* needs to be preserved and managed, as this area is widely appreciated as part of the cultural landscape not only in Tuscany but also in the whole Italian Peninsula.

Author contributions

This study was developed with the contributions of all authors: CB and MCS determined the scientific design and participated together with AC and RC in the field activities. The laboratory work and statistical analysis were performed by AC with contributions by RC. The climatological and meteorological time series were provided by MB while GB supplied the wind data. The text was written by AC and revised by RC, MCS, CB, MB and GB. The project was directed, coordinated and founded by CB.

Disclaimer

Any use of trade, firm or product names is for descriptive purposes only and does not imply endorsement by the involved universities.

Declaration of Competing Interest

The authors declare that they have no conflicts of interest.

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F. Pasquetti prepared and preliminarly measured part of the samples presented here in the framework of a Bachelor thesis (University of Pisa, Course of Study in Natural and Environmental Sciences), titled: “*Elaborazione di curve dendrocronologiche di pino domestico (Pinus pinea L.) del Parco della Versiliana, Pietrasanta*”, tutor C. Baroni, co-tutor A. Coppola.

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