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Assessing *Pinus pinea* L. resilience to three consecutive droughts in central-western Italian Peninsula

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Climate projections for the Mediterranean area forecast drier and hotter conditions and increasing trend in extreme climatic events such as drought. Scientific evidences reported that extreme dry spells affected the stem growth of different Mediterranean low-elevational pine forests inducing a decrease in tree resilience, defined as the capacity to resist to environmental stress and to recover pre-disturbance functioning. Despite its ecological and economic importance, thus far no study examined *Pinus pinea* L. (stone pine) resilience to drought events. This research reconstructed stone pine resilience by considering resistance, recovery, and the proportion of trees showing high values of both indexes of several planted stands to three consecutive spring-summer droughts occurred during the second half of the 20th century. Local climatic conditions during dry spells modulated the species resistance and recovery. In this sense, wetter conditions promoted recovery, whereas warmer spring-summer affected stone pine resistance. Moreover, spring rather than summer droughts influenced stone pine resistance and recovery, confirming the species sensitivity to climatic conditions at the beginning of the growing season. Results indicated that while recovery did not significantly changed, the species resistance diminished along the analyzed period. Furthermore, more than 60% of the examined trees were not able to reach pre-drought growth, suggesting a moderate resilience of *P. pinea* to adverse climatic conditions. The results contribute to improve our understanding of stone pine growth dynamics in the climate-change context of increasing aridity actually occurring in the Mediterranean area, providing useful information for the sustainable management of these natural resources.

Keywords: Climate Change, Disturbance, Dry Spell, Tree Growth

Introduction

Extreme climatic events such as drought represent disturbance factors for forest ecosystems, that may induce growth decline, dieback, and mortality from the tree to the stand level (Breda & Badeau 2008, Allen et al. 2010). Forests are considered able to tolerate gradually shifting climatic conditions, whereas weather extremes may cause loss of resilience, intended as a reduction in the capacity to recover pre-disturbance functioning (Breda & Badeau 2008, Lloret et al. 2011). Expected global changes in average climatic conditions will likely modify both frequency and intensity of climatic extremes events, highlighting the need of a deeper understanding of forest resilience to drought (IPCC 2014).

During recent years, tree-ring methods successfully contributed to reconstruct forest resilience to extreme drought in different biomes (Lloret et al. 2011, Gazol et al. 2016). For example, *Juniperus* spp. distributed in the Tibetan Plateau showed an overall increase in resilience to drought in the second half of the 20th century (Fang & Zhang 2019). Temperate forests in Central Europe exhibited age/site-dependent resilience to dry spells during recent consecutive climatic extremes (Zang et al. 2014). In moist tropical forests, resilience to drought would depend on species-specific characteristics (Rahman et al. 2019). Regarding Mediterranean woodlands, several works analyzed resilience to dry spells of low-elevational pine forests dominated respectively by *P. halepensis* and *P. pinaster* (Navarro-Cerrillo et al. 2018, Serra-Maluquer et al. 2018). On the other hand, thus far no study addressed this particular topic for another important Mediterranean pine such as *P. pinea* (stone pine), possibly because of the species drought-tolerant characteristic and its inferred high resilience to dry spells (Oliveras et al. 2003). Nevertheless, it is well known that dry climatic conditions negatively impact stone pine growth (Mazza & Manetti 2013). Furthermore, drought can trigger changes in the species physiology interacting with pollution and surfactants, affecting tree health status and survival (Tani 1991, Bussotti et al. 1995, Fady et al. 2004, Bouachir et al. 2017). Stone pine plantations play important environmental and economic roles, such as dune stabilization and nut production (Mutke et al. 2012). These forests have been long considered as ecological desert, being often undervalued by the scientific community (Bonari et al. 2017). Nevertheless, recent studies demonstrated their utility in maintaining local biodiversity, thus calling for conservation plans of this natural resource (Bonari et al.

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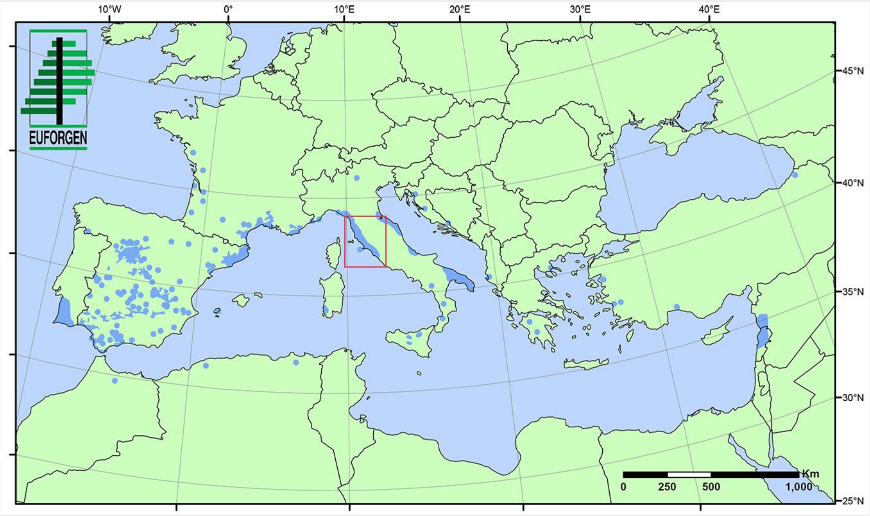

Fig. 1 - Distribution map of Italian stone pine (*Pinus pinea* – Fady et al. 2004). The red rectangle delimits the analyzed area.

2017). A deeper understanding of the stone pine response to extreme drought would provide useful information for sustainable management of these woodlands, a mandatory task in the climatic-change scenario of increasing aridity currently developing in the Mediterranean area (IPCC 2014).

For the abovementioned reasons, this research analyzed several stone pine stands located in the coast of Central Italy aiming to: (i) reconstruct resilience to drought in term of the species resistance and recovery; and (ii) examine if consecutive dry spells cumulatively affected the species resilience.

Materials and methods

Study area and dendrochronological sampling

Eight stone pine stands located along the north to mid-Tyrrhenian coasts of the Italian peninsula were analyzed (Fig. 1, Tab. 1). Woodlands are pure plantations located on sandy soils and growing under typical Mediterranean climate, with summer drought and precipitation concentrated in winter months (Raddi et al. 2009, Piraino & Roig-Juñent 2014).

Six of the 8 examined plantations were sampled during 2003-2004 and earlier versions of these tree-ring chronologies have been presented in Piraino & Roig-Juñent (2014). Ring increment data of the remaining two stands were downloaded from the ITRDB webpage (The International Tree-Ring Data Bank – http://www.ncdc.noaa.gov/paleo/treering.html). The latter consisted of individual ring widths series from Marina di Bibbona (code ITAL030) and Punta Tesorino (ITAL032) sites, both shown in Raddi et al. (2009). Regarding these data, we considered only tree-ring series belonging to forest stands far from the coastline, thus minimizing the possible influence of factors other than drought (*e.g.*, shoreline erosion) on the species resilience. Details about sampling, core preparation and ring width measurements can be found in Raddi et al. (2009) and Piraino & Roig-Juñent (2014).

Tree growth response to drought

Drought was defined through the SPEI index (Standardized Precipitation Evapotranspiration Index – Vicente-Serrano et al. 2010). Based on previous researches (Piraino et al. 2013), a regional time series of August SPEI value with a timescale of 6-months was built for the 1902-2013 period (Fig. 2). Therefore, the March-August period was considered, allowing the analysis of drought effect upon tree growth during the main drought period (summer) and the main growth season (spring). SPEI data were downloaded from the EC&D web page (http://climexp.knmi.nl/). Drought events were established as those years when SPEI index fell in the lowest 10% percentile. As Raddi et al. (2009) ring width series ended in 1996, the three last consecutive droughts considered in this study were 1973, 1987 and 1993 (Fig. 2).

This research considered that tree resilience is expressed by its ability to resist to and to recover from extreme climatic events (Fang & Zhang 2019). Therefore, two different indexes were calculated: resistance (R_t) and recovery (R_c – Lloret et al. 2011). In this sense, according to Lloret et al. (2011), resistance is "considered as reversal of the reduction in ecological performance during disturbance", and recovery corresponds to "the ability to recover relative to the damage experienced during disturbance". The indexes were computed as follows (eqn. 1, eqn. 2):

$$R_t = \frac{BAI_D}{BAI_{preD}} \quad (1)$$

$$R_c = \frac{BAI_{postD}}{BAI_D} \quad (2)$$

where R_t is the resistance index, R_c is the recovery index, BAI_D, BAI_{preD} and BAI_{postD} are, respectively basal area index (BAI) during the drought year, mean BAI for the 3 years before and mean BAI for the 3 years following drought. BAI series were calculated from tree-ring widths through the AGE program (DPL, Dendrochronological Programme Library – Holmes 1999). Additionally to R_t and R_c, the proportion of trees showing high resistance and recovery was calculated (Fang & Zhang 2019). Trees were considered resistant and able to recovery after drought when R_t and R_c values were higher than 1 ($R_t > 1$ and $R_c > 1$).

Statistical analyses

Drought effect upon stone pine growth was assessed at both the individual and stand level. At the tree scale, changes through time of R_t and R_c were examined by the means of ANOVA with *post-hoc* Tukey test (Zar 1984). Since data were not normally distributed, indexes were transformed by the Box-Cox method (Wessa 2016). At the site level, abiotic and tree biometric influence upon R_t, R_c, $R_t > 1$ and $R_c > 1$ was analyzed through correlation functions. Climatic variables were represented by total precipitation and mean temperature of spring-summer (March-August), spring (March-May) and summer (June-August) periods. These periods were selected in order to analyze the possible interaction among spring and summer climatic conditions upon the species resistance and recovery. Tree biometric parameters were growth (mean BAI) during drought year, and age. Regarding the latter, as precise

Tab. 1 - Geographical location, number of analyzed trees and time span of the tree-ring chronologies.

Site	Lat (°N)	Long (°E)	Trees (n)	Time span
San Rossore	43.72	10.31	10	1890-2003
Cecina	43.31	10.52	8	1923-2003
Marina di Bibbona	43.30	10.48	22	1926-1996
Punta Tesorino	43.30	10.48	23	1929-1996
Duna Feniglia	42.44	11.22	12	1925-2003
Castelporziano	41.74	12.40	20	1897-2003
Lago di Fogliano	41.31	13.03	6	1878-2004
Parco del Circeo	41.31	13.03	15	1945-2004

age estimation of each analyzed tree was not possible, mean age was considered as the mean site chronology length when drought episodes occurred. Local precipitation and temperature data were obtained from the "Annali Idrologici" of Regione Toscana and Regione Lazio (available respectively at http://www.sir.toscana.it/annali-idrologici and http://www.idrografico.regione.lazio.it/std_page.aspx-Page=annali_idrologici.htm). Statistical analyses were run through the INFOSTAT software with its interface to R (Di Rienzo et al. 2018).

Results

A total of 116 stone pine trees distributed along 8 sites were analyzed in this research. ANOVA showed that only R_t significantly changes along the three consecutive drought events, being values statistically lower in 1987 than in 1973 (F = 5.61, p = 0.0040 – Fig. 3). Results emerged considering proportion of trees showed a decreasing trend for the $R_t > 1$ index (Fig. 4). Indeed, while $R_c > 1$ values are constant, being respectively 43% 40% and 41% in the 1973, 1987, and 1993 dry spells, $R_t > 1$ showed a tendency towards lower values along the three drought events, corresponding to 50% (1973), 37% (1987) and 35% (1993) of the analyzed trees (Fig. 4).

Correlation functions performed at the site level indicated that the species resilience to drought is climatically-driven. In this sense, R_c and $R_c > 1$ are significantly and positively related to the precipitation amount of spring-summer and spring periods on one hand and of spring-summer months on the other (Tab. 2). Concerning R_t and $R_t > 1$, these indexes were significantly and negatively correlated to spring-summer and spring temperatures respectively. No significant correlation emerged for summer period (Tab. 2). Finally, mean age and mean BAI did not represent influencing factors upon any of the examined indexes.

Discussion

This work assessed for the first time *P. pinea* resilience to drought *sensu* Lloret et al. (2011). Despite 21th century extreme dry spells were not considered in this study, analyzing the possible cumulative effect of consecutive dry spells upon stone pine resistance and recovery provided novel information useful to understand the species stem growth dynamics in the current climate unstable scenario (IPCC 2014).

Stone pine resilience to drought were clearly determined by climatic conditions. The significant relations among resistance and recovery indexes on one side and temperature and precipitation on the other suggested that local cooler and wetter conditions promoted resilience. On the other hand, extreme climatic events during spring, rather than summer, affected the species resistance and recovery, in agreement with reports showing that stone pine secundary growth is mainly related to envi-

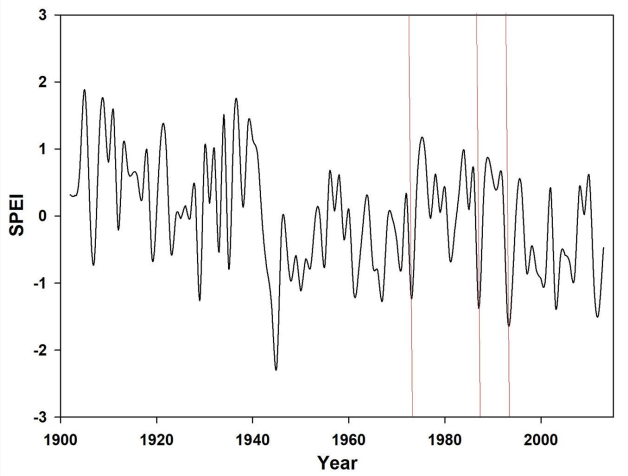

Fig. 2 - March-August SPEI of the 1902-2013 period for the examined area. Red lines represent the dry spells considered in this study.

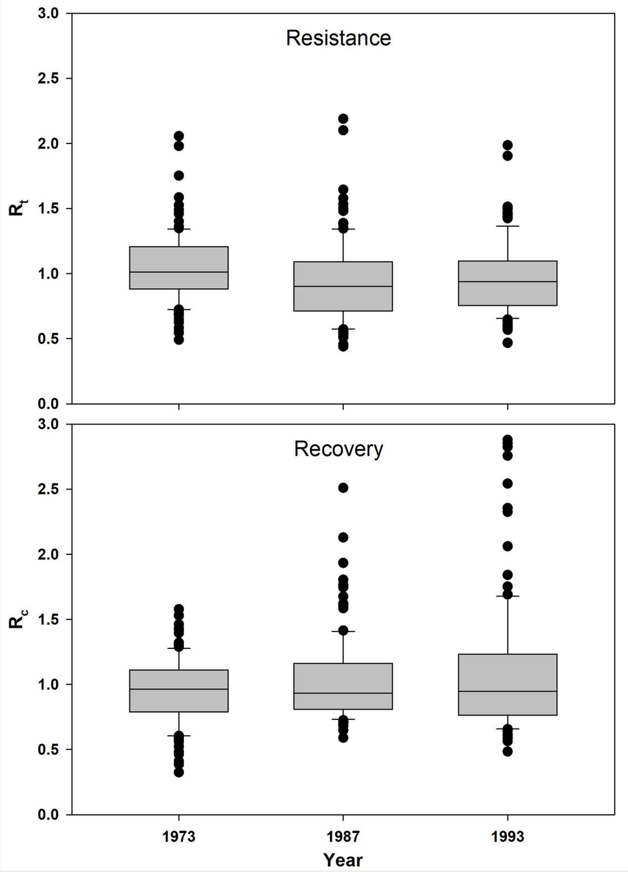

Fig. 3 - Box plots for resistance (R_t) and recovery (R_c) index between the different considered drought years. Each box shows the values within one interquartile distance (ID 25 % above and below the median). The median is shown as a black bar. Whiskers represent values of 1.5 times the IDs and are shown as black lines. Circles represent outliers. Statistical differences are reported in the main text.

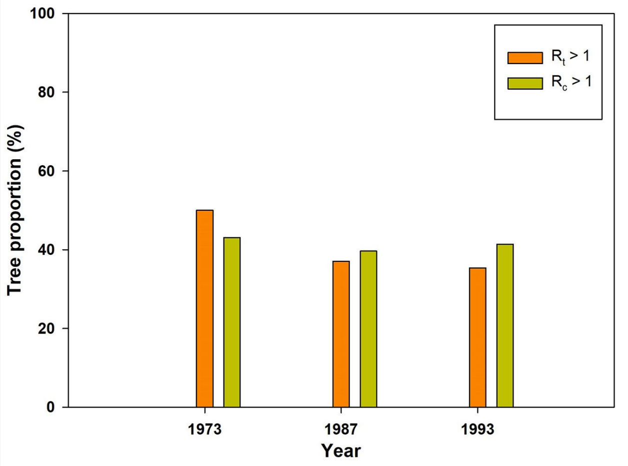

Fig. 4 - Bar plots for $R_t > 1$, and $R_c > 1$ between the different considered drought years.

Tab. 2 - Results of the Pearson's correlation function computed between resistance (R_t) and recovery (R_c) indexes and abiotic and tree biometric variables. (T): temperature; (P): precipitation; (BAI): basal area index; *ss, sp* and *su* (subscript) refers to spring-summer, spring and summer period, respectively; (*): p<0.05.

-	P_{ss}	T_{ss}	P_{sp}	P_{su}	T_{sp}	T_{su}	BAI	Age
R_t	0.23	-0.42 *	-0.05	0.37	-0.40	-0.40	- 0.30	- 0.24
R_c	0.44 *	0.09	0.46 *	0.14	0.18	0.01	0.05	- 0.00
R_t > 1	0.11	-0.40	-0.14	0.35	-0.40 *	-0.37	- 0.35	- 0.18
R_c > 1	0.50 *	0.06	0.40	0.36	0.15	-0.01	0.12	0.11

ronmental conditions at the beginning of the growing season (Castagneri et al. 2018).

P. pinea is an isohidric species able to tolerate drought through different physiological mechanisms, such as root mortality, stomata control and biomass allocation (Oliveras et al. 2003). Nevertheless, marked drought conditions affect the species growth diminishing needle length, reducing sap flow, and causing significantly decrease in stem increment (Teobaldelli et al. 2004, Mazza & Manetti 2013). The positive rainfall effect upon the species recovery could be linked to increasing soil moisture and consequently higher carbohydrates production (Novak et al. 2011). Similarly, the negative relation between temperatures and resistance can reflect the detrimental effect of increasing evapotranspiration and soil water evaporation upon the species growth (Campelo et al. 2006). These physiological interpretations are sound with studies showing that under severe environmental constraints, production of wood in *P. pinea* may be partially or even totally absent (Novak et al. 2011). Finally, it cannot be discarded that other variables not considered in this study, such as stand density, could modulate the species resilience to drought as in other Mediterranean pines species (Serra-Maluquer et al. 2018). Unfortunately, no data were available to retrospectively examine the influence of stand characteristics upon stone pine resilience.

Apparently, no cumulative stress emerged for the species recovery, while resistance slightly decreased along the considered dry spells as showed by $R_t > 1$ values. In this sense, $R_t > 1$ in 2003 drought calculated from data belonging to Piraino & Roig-Juñent (2014) represented 32% of examined individuals (n = 71 – data not shown), thus confirming the tendency towards lower values for this index. On the other hand, it is worth noting that approximately 60% of the analyzed stone pines were not able to reach pre-disturbance growth following drought episodes, which suggests a moderate ability of *P. pinea* to recover from particularly adverse climatic conditions. As stated in Fang & Zhang (2019), using proportion of trees can provide additional information which can be hidden by analysis performed considering only mean values of the resilience indexes, minimizing the effect that few outperforming trees can have upon a regional response to drought. Finally, these results encourage future researches focusing on possible higher performance of some of the genotypes examined in this study when facing extreme drought events, an information that would surely contribute to improve the conservation of this natural resource.

Concluding, the results emerged in this study suggested that *P. pinea* resilience will likely be threatened by more arid conditions expected for the Mediterreanean area, with a consequent decline in the species resistance rather than recovery. This novel information should be considered in management plans, particularly in the scenario of increasing frequency of extreme drought events anticipated for the Mediterranean basin (Giorgi & Lionello 2008, Boberg & Christensen 2012, IPCC 2014).

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