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RESEARCH PAPER

Short-term stem diameter variations in irrigated and non-irrigated stone pine (*Pinus pinea* L.) trees in a xeric non-native environment

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Abstract

• ***Key Message*** **Irrigation of adult stone pine trees growing in a xeric non-native habitat had positive effects not only in stem diameter growth but also in tree response to climatic variability.**

• ***Context*** Stone pine is a key species from Mediterranean Europe increasingly planted in South America. The knowledge about irrigation impact on short-term stem diameter dynamics is still limited in non-native arid areas.

• ***Aims*** To improve our understanding of the effect of irrigation on (1) stem diameter changes of stone pine trees in a drought-prone environment in Chile and (2) the sensitivity of the species to weather conditions.

• ***Methods*** We studied daily stem diameter changes in irrigated and non-irrigated 31-year-old stone pine trees during a growing season with below average precipitation in Chile. Short-term diameter changes were recorded using high-resolution dendrometers. The detrended daily stem diameter changes, expressing tree water status, were correlated with weather variability in both irrigated and non-irrigated trees.

• ***Results*** The growth period lasted longer and the cumulative sum of daily changes increased by 130% in irrigated trees. Moreover, a similar correlation of tree water status with climatic variables was found in non-irrigated, with the exception of precipitation.

• ***Conclusion*** Irrigation increased stone pine productivity in this xeric environment and reduced the correlations between daily stem diameter variations and local climatic variability.

Keywords Tree water status · Growth phenology · Daily stem variability · Digital dendrometer data · Species climate sensitivity

1 Introduction

Management of stone pine plantations under high climatic variability outside the species native habitat calls for a better understanding of the effects of irrigation on the stem diameter dynamics. For several mid-latitude regions, IPCC (2021) forecasted climate changes for the future decades, including significant warming, variation in seasonal rainfall patterns, and increased frequency and intensity of spring and summer drought, underlining the convenience of enhancing the knowledge of forest species growth and its response to water deficit. Drought induces reductions in soil water availability (Slette et al. 2019), affecting tree water status and impairing stem diameter growth.

Stone pine (*Pinus pinea* L.) is a tree species of ecological and economic relevance native to Europe; it is a well-known colonizer and soil stabilizer mostly planted in Mediterranean areas due to its resistance to water deficit,

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Contribution of the co-authors All authors contributed to the study conception and design. Material preparation and data collection were performed by Rodrigo del Rio, and Mónica Balzarini directed statistical analysis. Verónica Loewe-Muñoz wrote the first draft of the manuscript and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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being adapted to drought periods and low summer rainfall. Despite the low genetic variability to drought tolerance, a high phenotypic variability has been reported (Sánchez-Gómez et al. 2009). Under water stress, the species, like most tree species, reacts by closing stomata to decrease transpiration (Sánchez-Gómez et al. 2011). Despite the species ability to survive under arid conditions, a reduction in diameter growth has been detected under drought conditions in native areas (Natalini et al. 2015), confirming the species sensitivity to climatic conditions at the beginning of the growing season (Piraino 2020), and it is predicted that the species geographical distribution will move northward and towards higher altitudes in the next decades (Akyol et al. 2020).

The species has been cultivated for pine nut or *pinoli* production for over 6000 years in Europe and has been harvested from wild trees far before that (Lim 2012), with a well-known socio-economic contribution to local community development in countries such as Turkey (Küçüker and Baskent 2017), Lebanon (Sattout and Faour 2017), and Tunisia (Schröder et al. 2014). Stone pine cropping for pine nut production is also increasing in other Mediterranean areas outside its native habitat.

The species was introduced to Chile by European immigrants at the beginning of the nineteenth century and was used for forestry purposes in coastal sand dune stabilization programs for some years since 1912 (Loewe-Muñoz et al. 2019). Some of those trees are still alive despite the dryness of the area (over 8 dry months per year) (Santibáñez 2017). In the last decade, studies explored the growth and fruiting potential of this species as an alternative crop, confirming its ecological adaptation, vigorous growth, good health condition, and high cone production under average climatic conditions (Loewe et al. 2016). However, the species' stem diameter growth, which has been related to cone yield (Piqué, 2004; Freire et al. 2019), has been scarcely explored in relation to climatic variability in the southern hemisphere; this information is necessary to improve stone pine cropping in Chile.

Irrigation has been found to positively affect several pines, such as *P. pinaster* (Zas and Fernández-López 2005), *P. edulis*, and *P. monophylla* (McLain and Frazier 2008). However, in the arid coast of central Chile, where rainfall is concentrated in winter, most crops are cultivated under rainfed conditions. Among the few works addressing this management practice in stone pine are those of Deligoz and Gur (2015) and Correia et al. (2016), which reported an increase in the canopy water use efficiency in Europe driven by irrigation, and that of Castagneri et al. (2018), which mentioned the effect of water availability on xylem morphogenesis. However, the knowledge about stone pine xylem phenology and daily growth dynamics as well as tree water deficit in response to environmental factors is still limited.

An observational study of stone pine plantations in Chile reported significant effects of irrigation on diameter growth (Loewe et al. 2015) and fruiting (cone number tree^{-1}) (Loewe et al. 2016). The understanding of the annual dynamics of stem diameter growth is useful to define management strategies oriented to enhance growth and consequently cone yield.

Stem diameter changes are highly variable throughout a year, with growth rates changing between periods due to the biological growth curve (long-term trend) and day-to-day fluctuations caused by weather conditions (short-term variability) which affect the tree water status. Variations in daily stem diameter are caused by both irreversible growth due to cell growth and enlargement, and by reversible shrinking and swelling, influenced by the tree water status (De Swaeft et al. 2015; Sweifel et al. 2016; van der Maaten et al. 2018).

Since climate is the major environmental factor influencing tree growth, the pattern of stem variations is often similar among trees (Boninsegna et al. 2009). Thus, the effect of climate variability can be observed in the synchronous stem diameter changes of trees located at the same site. One way of detecting stem diameter growth is by measuring daily stem diameter changes with high-resolution dendrometers. Diameter growth can be studied continuously over the growing season to explain the intra-annual species growth pattern and the effects of seasonal weather on growth at a fine time scale (McMahon and Parker 2015; Cocozza et al. 2018; Zalloni et al. 2018).

This work aimed at characterizing daily stem diameter changes in irrigated and non-irrigated stone pine trees in Chile over a 1-year period, to answer the question of how the dynamics of seasonal growth and tree water status change in response to environmental factors in a xeric non-native environment. The study was conducted in an adult stone pine plantation located in a drought-prone environment in Chile to establish a better understanding of the effect of irrigation on (1) short-term stem diameter changes and (2) the sensitivity of the species to weather conditions.

2 Materials and methods

2.1 Site description and experimental design

The study was conducted in a 31-year-old stone pine plantation located in Cáhuil (34° 30′ S, 71° 59′ W), central Chile, on smooth hills at 125 m a.s.l. To ensure the identity of the species, one sample was deposited in the INFOR's herbarium; Dr. Loewe-Muñoz identified the voucher specimen in 2012. The climate is typically Mediterranean, with long dry summers and short intense winter rainfall, with maritime influence of the Pacific Ocean. Average annual climate data indicate annual rainfall of 641 mm, annual potential evapotranspiration of 1177 mm, 6 dry months year^{-1}, and annual average temperature of 13.2 °C (Santibáñez 2017). Soil is silty clay loam, granitic, slightly acid (pH = 5.9), with medium organic matter content (3.6%), and not salty (E.C. 0.11 mmho cm^{-1}).

The plantation was originally established to control erosion on a 30-ha area in winter 1983. A first thinning was applied 20 years after establishment, when 50% of trees were extracted; the first pruning and a second thinning (extraction of 65% of trees, resulting in 285 trees ha^{-1}) were conducted 1 year before establishing the experimental trial.

The trial was established in 2014 considering two treatments, irrigation and control (non-irrigation). Treatments were arranged in a randomized complete block design with three blocks ($n = 3$). Each plot within blocks had 25 trees. One central tree per plot was selected to install at breast height (DBH, *c.* 1.3 m) stem digital band dendrometers (EMS DLR26A with resolution < 1 μm, Environmental Measuring Systems, Czech Republic). Thus, three replicate trees were used for records of stem diameter variations by treatment.

Daily irrigation was provided from spring (September) to autumn (April) using a drip irrigation system. The amount of irrigation was calculated in terms of monthly air temperature, precipitation, and potential evapotranspiration (PET) of the previous 1-year period (Table 1). Daily irrigation increased from 1.9 L tree^{-1} in September to a maximum of 5.0 L tree^{-1} in January, and then decreased to 2.7 L tree^{-1} in April, totaling in a per tree base 71 mm year^{-1}, which is 5% of the annual PET (1476 mm).

2.2 Measurements of short-term stem diameter changes

Stem perimeter variations were recorded daily at 1-h intervals (00:00 to 24:00 h) from June 2014 to May 2015 using the software EMS Mini32 (Loewe-Muñoz et al. 2022). Stem perimeters were converted to hourly diameter increments assuming a circular stem cross-section (Vospernik and Northdurf 2018). Hourly increments of a day were added and accumulated in time. Daily stem diameter variation (SDV) is the accumulated diameter at the end of the day (at 24:00 h) minus the accumulated diameter at the end of the previous day, i.e., variation of stem diameters between day t and $t - 1$.

Automatically collected microclimate records of daily evapotranspiration and precipitation for the study year (DGA Pichilemu, Chile) were used, and the water supplied as irrigation was controlled by a Hydro-Rain HRC 990 in-ground timer. The temperature recorded by the dendrometer sensor was obtained at 1-h intervals from each replicate tree. The ombrothermic diagram shows air and rainfall distribution (Fig. 1a).

2.3 Data analyses

The DBH, height, and crown diameter of stone pine trees selected for dendrometer measurements were compared via ANOVA to check for the lack of initial differences (homogeneity) among trees assigned to the irrigated and non-irrigated treatments. Average initial DBH was 17.8 cm, without statistical differences between irrigated and non-irrigated

Table 1 Spring to autumn mean daily air temperature, potential evapotranspiration, and precipitation recorded in the study area during the growing season, and supplied irrigation

Month	Mean air temperature[1] (°C)	Accumulated Precipitation[2] (mm)	Potential evapotranspiration[3] (PET, mm)	Irrigation (L day^{-1} tree^{-1})
June 2014	10.4 ± 0.16	232.5	46	0.0
July 2014	10.6 ± 0.17	31	53	0.0
August 2014	11.9 ± 0.12	79.5	75	0.0
September 2014	13.0 ± 0.12	34.5	102	1.9
October 2014	14.6 ± 0.13	3	154	1.4
November 2014	14.9 ± 0.09	8	173	4.6
December 2014	16.0 ± 0.10	6.4	182	4.7
January 2015	17.4 ± 0.08	1.4	188	5.0
February 2015	16.9 ± 0.11	0	154	4.3
March 2015	18.3 ± 0.14	0	162	2.2
April 2015	16.0 ± 0.15	19	112	2.7
May 2015	12.9 ± 0.17	25.4	77	0.0
Overall	14.4 ± 0.07	440.7	1,476	

[1]Data obtained from dendrometers

[2]Data obtained from DGA Pichilemu, Chile

[3]Values estimated from automatically collected average, minimum and maximum temperatures from dendrometers, with extraterrestrial radiation values taken from FAO, following Hargreaves and Samani (1985)

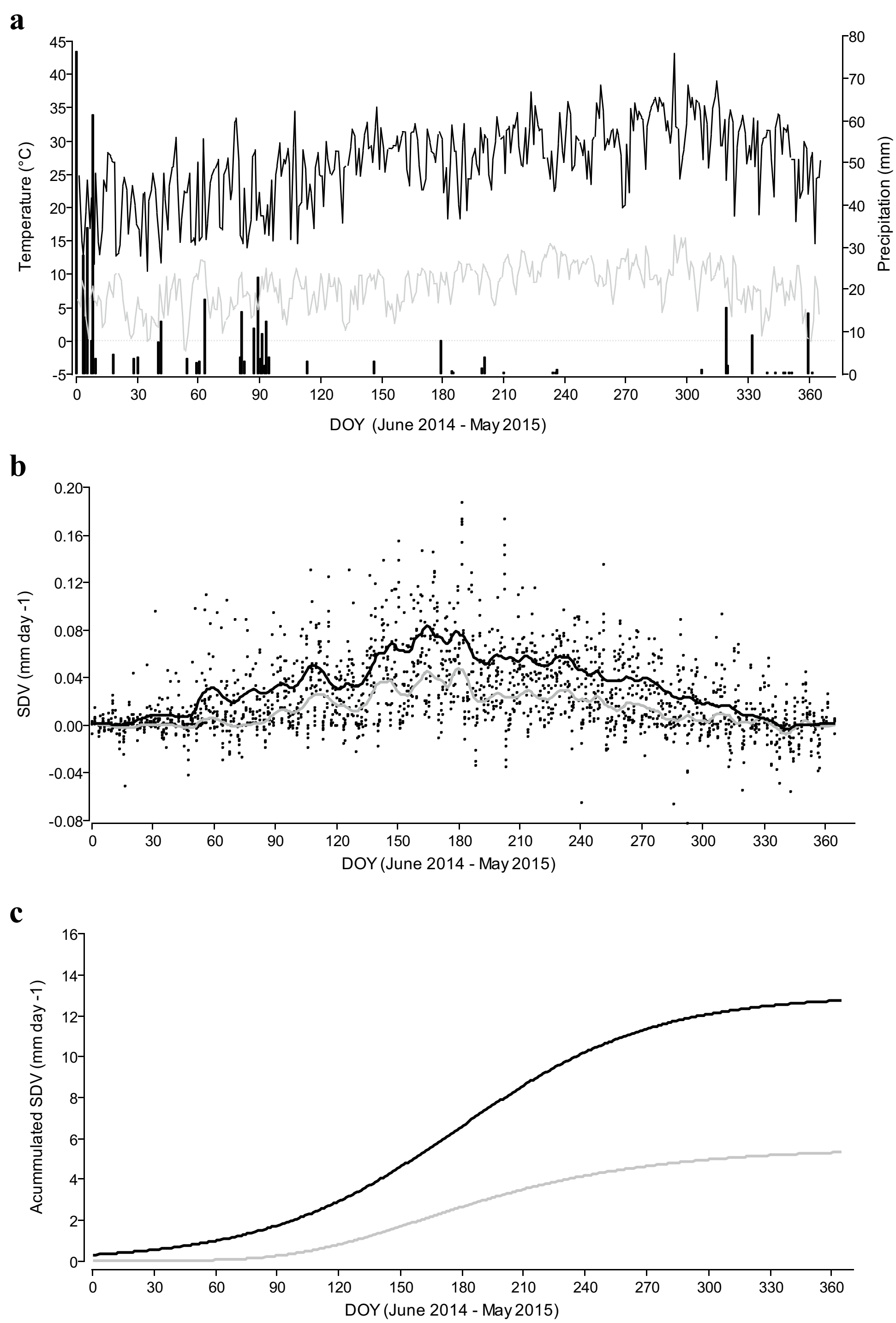

Fig. 1 **a** Maximum (*black*) and minimum (*grey*) air temperature and precipitation distribution (*bars*). **b** Daily stem diameter variation (SDV) in six trees (dots) and average SDV by treatment (*black* irrigated trees; *grey* non-irrigated trees). **c** Fitted models for the cumulative SDVs by treatment (*black* irrigated trees; *grey* non-irrigated trees)

trees ($p > 0.05$). Neither average stem height (5.9 m) nor average crown diameter (3.6 m) differed significantly between treatments ($p > 0.05$).

The SDVs for all trees and average SDV by treatment are shown in Fig. 1b. The trend of cumulative SDVs in irrigated and non-irrigated trees (Fig. 1c) were modeled using non-linear growth models. The Logistic and Gompertz statistical models were fitted to describe the growth trend in daily diameter changes over the whole year. Since SDVs from the same tree are non-independent, the non-linear models were estimated as mixed models, by adding a tree random effect to the model intercept (Fitzmaurice et al. 2008). The AIC and BIC fitting criteria (Wolfinger 1993) were used to select the best model for each treatment.

The onset was calculated as the 0.05 quantile and the cessation as the 0.95 quantile of the cumulative trend of

SDVs by treatment; the duration of the growing period for each treatment was defined as the interval between both the onset and cessation.

Additionally, a period of fast growth of stem diameter for all trees was identified. Fast diameter growth was assumed to start at DOY 80 when the distributions of the dendrometer values were positive and significantly different from zero in control trees (tested by t-test as suggested by Zar (1999)), and to end at DOY 180 when diameter growth started to be less intensive (identified according to the daily diameter growth rates) (Fig. 1b). Therefore, the period DOY 80 (August 20 2014) to 180 (November 27, 2014) was identified as a window with fast growth of stem diameter for the control trees.

The daily amplitudes in stem diameter measurements were obtained as the difference between the maximum and minimum dendrometer measurements from 0 to 24 h (King et al. 2013), and compared between irrigated and non-irrigated trees by mixed model ANOVA including fixed treatment, random tree and day effects.

The detrended daily stem diameter variations were calculated by removing the fitted long-term trend from the SDVs. These standardized stem diameter variations (SSDVs) were assumed to express tree water status. The SSDVs were calculated from average SDVs per treatment and average growth trend to describe treatment differences rather than tree differences. Finally, the SSDVs of the DOY 80–180 window were correlated with weather (mean, minimum and maximum temperatures, precipitation, and potential evapotranspiration) using the Spearman rank correlation coefficient (rho) (Greene and Johnson 2004) ($\alpha = 0.05$) for irrigated and non-irrigated treatments. Statistical analyses were performed using the software InfoStat (Di Rienzo et al. 2021) and its interface with the software R (www.r-project.org).

3 Results

The best model to fit the long-term trend in cumulative SDVs was selected according with AIC and BIC criteria (smaller value indicates better model). The AIC of irrigated trees was 1672 and 1676 for the random intercept Logistic and Gompertz models, respectively. However, for non-irrigated trees, the AIC was 392 and 378 for the Logistic and Gompertz models. Same trend was observed for BIC. Thus, the Logistic model was selected for irrigated trees and the Gompertz model for non-irrigated trees (Fig. 1c).

Our data showed a synchronous onset of stem diameter growth for irrigated and non-irrigated trees at the end of June. The end of the growing period differed between treatments, with irrigated trees ending 20 days later than non-irrigated ones, with a growth period that lasted 315 days for irrigated trees and 265 days for non-irrigated ones.

In the DOY 80–180 window, temperatures increased gradually, whereas precipitations were rare and low (Fig. 1a), and remained in that condition up to DOY 315. From October 1 (DOY 120) to April 15 (DOY 315), PET was high, reaching 188 mm in January, whereas the accumulated precipitation for this month was 1.4 mm (Table 1).

A high synchronicity was observed among daily SDV series of both treatments. SDVs varied between −0.05 and 0.18 mm. Despite the high variability in daily SDVs, the long-term trends for irrigated and non-irrigated trees were different (Fig. 1c), with daily diameter variations being lower in non-irrigated than in irrigated trees. The accumulated SDVs reached on average of annual SDV of 5.3 mm and 12.2 mm for non-irrigated and irrigated trees, respectively. Thus, irrigation increased accumulated stem diameter by 130%.

In the DOY 80–180 window, average daily SDVs were 0.02 and 0.05 mm day^{-1} for non-irrigated and irrigated trees, respectively (Fig. 2a). After DOY 180, average differences of daily SDVs between treatments continued being significant but smaller (0.01 and 0.02 mm day^{-1} for non-irrigated and irrigated trees, respectively) (Fig. 2b).

For the DOY 80–180, there was a difference in the timing of maximum daily diameter variations of almost 3 weeks (20 days) between irrigated (maximum DOY 150) and non-irrigated trees (DOY 170). Maximum values were 0.09 and 0.04 mm day^{-1} for irrigated and non-irrigated trees, respectively. Stem diameter daily amplitudes between treatments were non-statistically different in both analyzed DOY windows ($p > 0.05$) (Fig. 2c, d).

The daily SSDVs of both treatments were highly correlated, with SSDVs of irrigated trees being higher than those of non-irrigated ones for the DOY 80–180 (rho = 0.85, $p < 0.0001$). During this fast growth period, in non-irrigated trees, daily SSDV correlations to mean and maximum temperatures, precipitation, and PET were stronger than in irrigated trees. In non-irrigated trees, a significant correlation between SSDVs and precipitation variability was found (Fig. 3).

4 Discussion

4.1 Short-term diameter changes

Variation in daily stem diameter has been reported to be caused by cell growth—irreversible growth, but also depends on stem water storage (De Swaeft et al. 2015), associated with reversible shrinking and swelling, all processes being influenced by the tree water status (Deslauriers et al. 2007; Zweifel et al. 2016). It is theoretically expected in terms of tree physiology no growth does occur during periods of stem shrinkage (named as zero-growth) (Zweifel

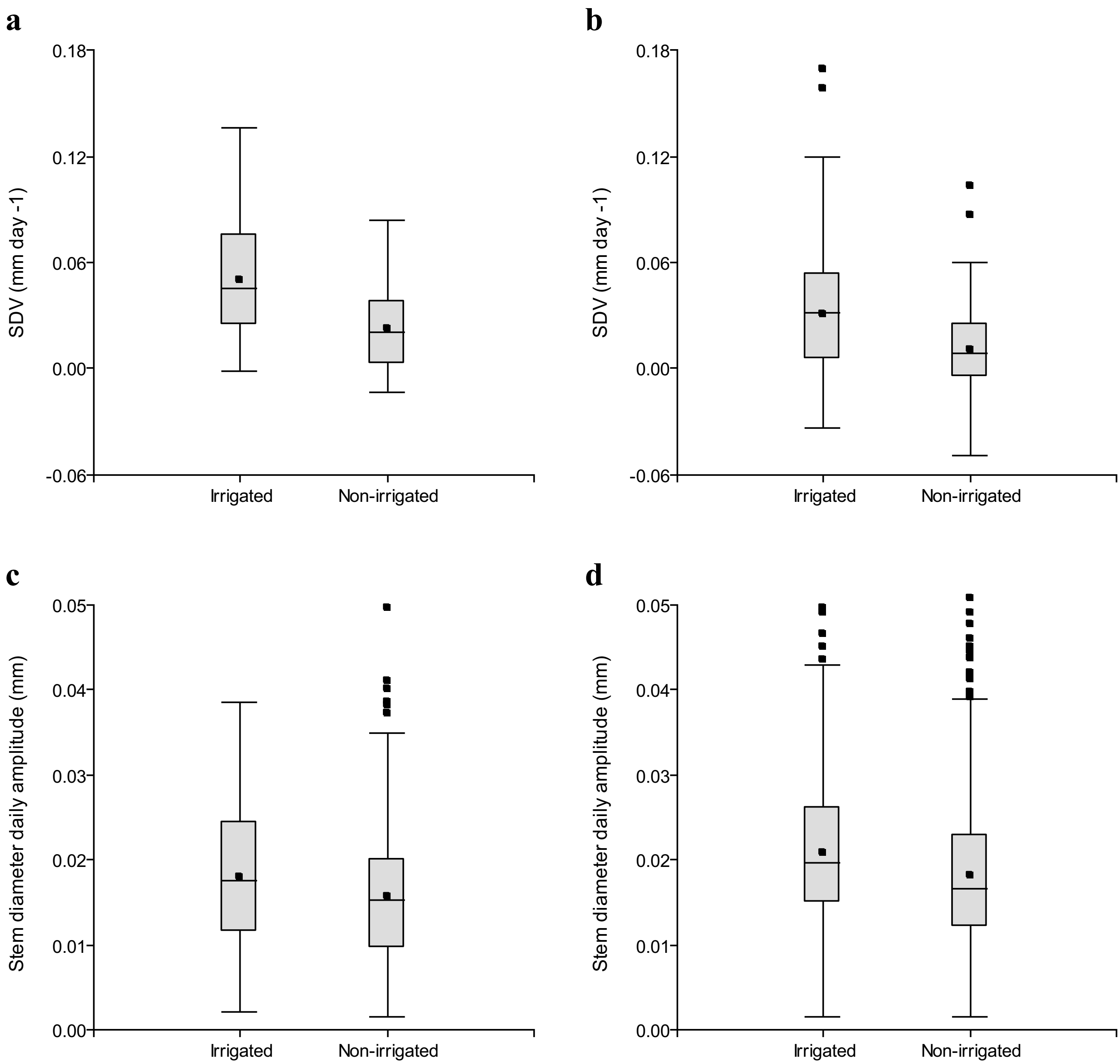

Fig. 2 Standardized SDVs for DOY 80–180 (**a**) and DOY 180–365 (**b**) for irrigated and non-irrigated trees. Stem diameter daily amplitude for DOY 80–180 (**c**) and DOY 180–365 (**d**) for irrigated and non-irrigated trees

et al. 2016). Consequently, correcting dendrometer series for reversible stem water changes is of great importance to better quantify tree growth (van der Maaten et al. 2018).

Variability in stem diameter changes due to tissue water content dynamics is expected to be higher within a day than between days (Oberhuber 2017). It is important though to consider that tree rings depend on the number of cells produced by cambial division and their ability to enlarge (Cuny et al. 2014), processes critically influenced by turgor (Peters et al. 2021). Wood formation may be studied with precision using microcore sampling (Rossi et al. 2006; Andrianantenaina et al. 2019), useful to characterize the dynamics of tree-ring development and carbon sequestration, and pinning, being these two techniques the most reliable for detailed monitoring. Considering the pros and cons of dendrometers and histological analyses, the accuracy of these methods could be improved if used in combination (Mäkinen et al. 2007).

The results of our study showed that *P. pinea* stem diameter growth was concentrated in spring and summer, when water demand is greatest, and rainfall is rare (Fig. 1a, b), indicating that the environmental conditions were not

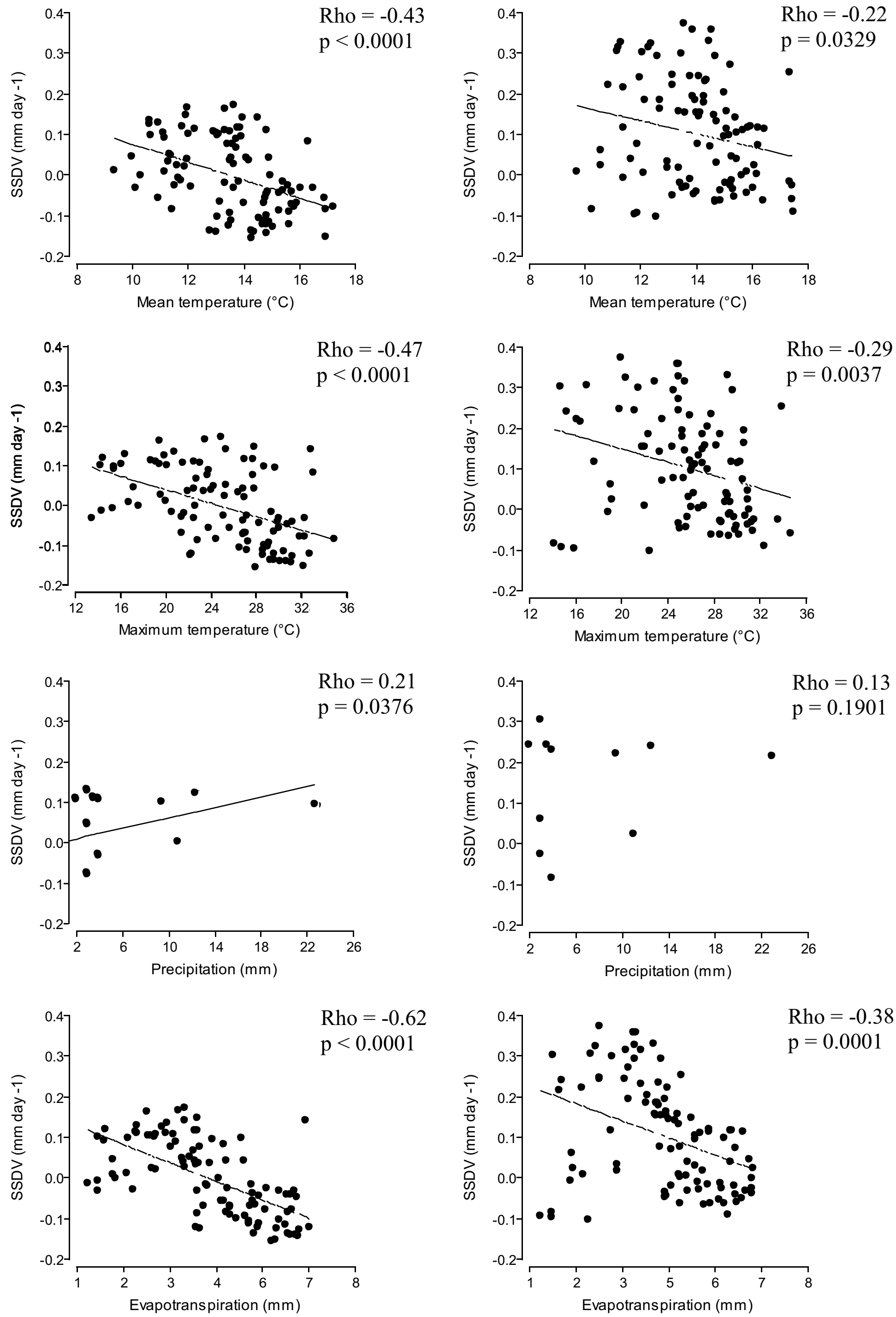

Fig. 3 Spearman correlation coefficients (rho) between standardized daily stem diameter variations (SSDV) and climatic variables in the DOY 80–180 window for irrigated (*right*) and non-irrigated trees (*left*)

limiting turgor (Peters et al. 2021). The temperature played an important role in SDV dynamics and in the overall tree growth, as stated by King et al. (2013). In fact, stone pine is regarded as a drought-resistant key species that may be used to replace others less adapted to challenging conditions (Ruiz-Navarro 2011). The species resistance to water deficit was noticed in stem growth during most of the year. At the beginning of the study, tree size was homogeneous in irrigated and non-irrigated trees; such homogeneity is important considering that tree size might alter growth patterns (De Luis et al. 2009). At the end of the study though, irrigation showed a positive effect on stem diameter growth. Although irrigation provided in our study was lower than PET, it influenced stem diameter growth in terms of both the length of the growth period and daily growth rates. For the fast growth period (DOY 80–180) and after, water supply allowed higher growth rates but with smaller differences after DOY 180. However, daily stem diameter amplitudes were similar among irrigated and non-irrigated trees along the growth year, which could be explained by the occurrence of growth cycles that lasted over 24 h under irrigation; further studies on the impact of water availability on stone pine circadian cycles are then recommended.

The growth period lasted 315 days for irrigated trees and 265 days for non-irrigated ones, longer than the 191 days reported by Bachtobji-Bouachir et al. (2017) in the arid coast of Tunisia, probably due to differences in air temperature. Daily stem diameter growth was recorded all throughout the year, except for May; accordingly, Balzano et al. (2018) reported cambial activity throughout the calendar year in southern Italy. Stem diameter growth peaked 1 month before the summer solstice (December 21, 2014), probably as an adaptation to the summer drought conditions, as reported for other coniferous species (Oberhuber et al. 2014). Maximum daily diameter growth peaked nearly 3 weeks earlier in irrigated trees than in non-irrigated ones. The end of the growing period differed between treatments, with irrigated trees ending 20 days later than non-irrigated ones, which is in agreement with results of Thabeet et al. (2009) for *Pinus sylvestris* L. in dry sites. Similarly, Deslauriers et al. (2016)

reported that water stress caused in conifers earlier deceleration of the partly turgor driven growth rates, thus shifting the timing of the maximum growth rate to a point of time earlier in the season. Accordingly, in our study, accumulated stem diameter growth was 130% higher in irrigated trees than in control trees (Fig. 1c). Feichtinger et al. (2014) quantified in *P. sylvestris* DBH increases ranging from 22 to 144% in a century-long irrigation experiment in comparison to control trees.

During the study year, control trees grew on average 5.3 mm, a lower value than that reported by Lamas and Rozas (2007) in northern Spain (7.0 mm) and in southern Portugal (6.7 mm) (Campelo et al. 2006), but higher than the 4.0 mm reported for regular stone pine stands of similar age in central Spain (Ruiz-Peinado et al. 2017).

Annual average temperature above 14.3 °C in Chile was found to reduce DBH growth (Loewe et al. 2015). Coincidently, in drought-prone sites, *P. sylvestris* onset and end of stem growth were found to be controlled not only by water availability but also by air temperature (Thabeet et al. 2009). It is known that in temperate trees, growth onset after winter dormancy is highly responsive to temperature (Hänninen and Tanino 2011), with warm spring temperatures resulting in earlier onset (Swidrak et al. 2011). Our data showed a synchronous onset of stem diameter growth at the end of June for irrigated and non-irrigated trees. These results confirm the strong environmental control reported by Oberhuber et al. (2014), and a good adaptation of the species to drought periods and low summer rainfall.

The effect of irrigation on daily stem diameter growth observed in our study agrees with findings of Mazza et al. (2014), who reported that water deficit limits the species growth, with a clear separation between stands from wetter and drier sites. Butler et al. (1997) showed that weekly drip irrigation also had a positive effect of up to 85% increase in DBH in 4-year-old stone pine trees. Campelo et al. (2006) reported a strong correlation of stone pine radial growth with precipitation in southern Portugal, with intra-annual fluctuations in a single tree ring caused by precipitation events early in summer following a water deficit in the growing season. Moreover, Calama et al. (2019) described the species annual growth in pure stands in a challenging environment and reported that water stress has a greater effect on tree growth than temperature.

4.2 Daily stem diameter changes and weather variability

The standardization of SDVs was a valuable tool for understanding the variability in tree water status in irrigated and non-irrigated adult stone pine trees in Chile over 1-year period under drought, and its correlation with climatic variables. This novel finding contributes to the understanding of the species response to weather in a challenging non-native environment.

The fastest growth period for non-irrigated trees was concentrated in a 100-day period in spring (August 20 to November 30), at the beginning of vegetative growth, as reported by Silva (2015). This fast growth period (DOY 80–180) was used to analyze tree water status; based in the positive correlation between SSDVs of both treatments, it becomes interesting studying the climate impact on that window. The correlation between SSDVs and climatic variables was performed in the fast growth period to avoid variability in SDVs due to the different annual tree growth phases. However, the positive effect of irrigation continued after this window up to DOY 330, with irrigated trees showing a higher growth than non-irrigated ones.

Tree water status was more impacted by climatic variables in non-irrigated trees than in irrigated ones, in agreement with Pardos et al. (2017), who reported a high sensitivity of stone pine to water availability, indicating that the species has an avoiding drought strategy. Specifically, irrigated trees were less sensitive than non-irrigated ones to temperature, evapotranspiration, and precipitation. Thus, irrigation might help trees to survive the impact of longer and more intense drought events in xeric environments.

The synchronicity of daily SSDVs for both irrigated and non-irrigated trees suggests a weather influence on tree water status, in agreement with Cocozza et al. (2018) and King et al. (2013) who reported a strong climatic control on reversible stem size fluctuations. In our study, the correlations with climatic variables showed that irrigated trees were less dependent on temperature and precipitation than non-irrigated ones. Similarly, Feichtinger et al. (2014) reported that a century-long irrigation was not sufficient to eliminate the growth responses of *P. sylvestris* to climate. Oberhuber (2017) highlighted the importance of late spring precipitation for diameter growth of *P. sylvestris* at xeric sites; this fact was not confirmed in non-irrigated trees, probably because of the low rainfall level recorded in our study during the monitored dry year. The superior SSDVs of irrigated trees compared to the non-irrigated ones evidence the higher variability in the tree water status under irrigation. The negative correlation between SSDVs and maximum air temperature agrees with findings of Bachtobji-Bouachir et al. (2017), since warmer temperatures cause water deficit.

In the light of global environmental change, tree monitoring over long-time scales should be implemented (Feichtinger et al. 2014; Pretzsch et al. 2018) to capture adjustment processes and feedback mechanisms of forests, which are also important to optimize recommendations for tree irrigation. An increased water supply to trees should enhance the stability of the species in a time of climate warming (Schäfer et al. 2019). Our results suggest that even a low dose of water supply, as complementary irrigation (Lodolini et al. 2014), has the potential to increase the species growth, and that it might reduce its sensitivity to climate. Our work confirms the species sensitivity to climatic conditions, predicting that the species cropping could extend either under irrigation or through rainfed plantations southward where climatic variability is reduced. Thus, as in other Mediterranean areas outside its native habitat, stone pine cropping for pine nut production would continue increasing in Chile. This novel information contributes to the understanding of stone pine growth dynamics in the climate change context of increasing aridity, providing useful information for a climate-smart forestry.

5 Conclusions

Irrigation in an adult stone pine plantation located in a xeric non-native habitat increased cumulative annual stem diameter and thus productivity and decreased tree sensitivity to temperatures, evapotranspiration and rainfall variability. This novel knowledge facilitates decisions for the species management and may contribute to predict its responses to environmental changes.

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Data availability The datasets generated and analyzed during the current study are not publicly available due to institutional guidelines, but are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Ethics approval authors declare integrity of the research and compliance to the rules of goodscientific practice.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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