Radial Growth Dynamics and Drought Resilience in *Pinus pinea* L. Plantations from Central-Western Argentina: Implications for Forestry Development

Dinámica del Crecimiento radial y resiliencia a la sequía de *Pinus pinea* L. en plantaciones del centro-oeste argentino: implicancias forestales

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Abstract

Forests play a crucial role in ecological stability, carbon sequestration, habitat provision and economy. As climate change intensifies, increasing drought frequency and severity challenge our understanding of forest resilience. Based on this premise, we examined radial growth dynamics and drought response of *Pinus pinea* L. in Mendoza Province in both mesic and xeric conditions. Using dendrochronological techniques, we assessed the long and short-term effects of soil and atmospheric drought on radial growth trends at two irrigated plantations with contrasting environments. Growth dynamics reflected differences in soil, climate, and irrigation. Growth rates were significantly higher at the mesic stand, which received nearly twice the precipitation and irrigation compared to xeric one. In contrast, growth at the xeric site was strongly limited by early-summer atmospheric drought, while late-growing season soil moisture and climatic conditions affected tree-ring development at the mesic site. Growth resilience to extreme events experienced site dependence, with edaphic drought exerting a stronger negative effect than atmospheric dry spells at the mesic stand. Our results underscore the importance of integrating short- and long-term drought assessment into *P. pinea* management strategies and support the potential of stone pine plantations in extra-Mediterranean South America for sustainable forestry under changing climatic conditions.

Keywords
climate change • forest management • mendoza • tree-rings

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Resumen

Los bosques son esenciales en la estabilidad ecológica, la captura de carbono, la provisión de hábitats y de recursos económicos. Ante el aumento de la frecuencia y severidad de las sequías asociado al cambio climático, comprender la resiliencia forestal resulta crucial. Este estudio analizó mediante métodos dendrocronológicos los efectos a corto y largo plazo de las sequías edáficas y atmosféricas sobre el crecimiento radial de *Pinus pinea* L. en dos plantaciones irrigadas bajo condiciones ambientales contrastantes en el centro-oeste argentino. Los patrones de crecimiento reflejaron diferencias ambientales y de manejo. Las tasas de crecimiento fueron significativamente mayores en el rodal mésico, que recibió casi el doble de precipitación e irrigación que el xérico. En este último, el crecimiento se vio limitado por sequías atmosféricas de comienzo del verano, mientras que en el mésico influyeron las sequías edáficas y climáticas al final de la temporada de crecimiento. La resiliencia ante eventos extremos mostró dependencia del sitio, con un efecto negativo más marcado de la sequía edáfica en el rodal mésico. Los resultados destacan la necesidad de integrar evaluaciones multitemporales de sequía en el manejo de *P. pinea* y su potencial para un desarrollo forestal sostenible en regiones extra-Mediterráneas de Sudamérica.

Palabras clave
cambio climático • manejo forestal • Mendoza • anillos de crecimiento de árboles

Introduction

Forests maintain ecological balance by storing carbon, regulating water cycles, and providing habitat for numerous species (Barnes *et al.*, 1997). Recent climatic shifts have increased the focus on the resilience of natural and planted forests under abiotic disturbances (Johnstone *et al.*, 2016). Drought threatens forest health and productivity, as dry spells become more frequent and intense (IPCC, 2023). Extreme drought events have severely impacted forests, reducing growth rates and increasing tree mortality (Allen *et al.*, 2010).

Due to their genetic uniformity, plantation forests may respond differently to dry spells than natural woodlands (Camarero *et al.*, 2021; Navarro-Cerrillo *et al.*, 2023). Their capacity to withstand and recover from a drought event dictates their long-term sustainability and broader environmental and economic values. Even considering that forest plantations only cover about 7% of the global forest area, they significantly contribute to mitigating deforestation impacts on natural woodlands (FAO, 2020). This provides particular importance to the in-depth understanding of their drought resilience.

Drought stress manifests in two primary forms: atmospheric drought, driven by low humidity and high evaporative demand, and edaphic drought, characterized by depleted soil water (Mishra & Singh, 2010). These conditions can occur separately or together, each uniquely impacting plant growth (Knutzen *et al.*, 2017). Disentangling these responses is key to predicting how trees will perform in a changing climate.

Forest responses to extreme drought can be assessed by analyzing long- and short-term growth trends. Long-term trends reveal climate-growth relationships, while short-term responses measure resilience, that is, the capacity to withstand and recover from dry spells (Lloret *et al.*, 2011). Dendrochronology provides a powerful method for investigating tree growth responses to ecological variables, allowing us to reconstruct growth trends and identify periods of stress, thereby illuminating species' resilience and adaptability (Piraino, 2020; Piraino *et al.*, 2022, 2024).

Pinus pinea L. (stone pine), a conifer prized for its edible seeds, holds significant ecological and economic value (Mutke *et al.*, 2012). In its native Mediterranean range, the species now suffers drought-related decline in cone yield (Calama *et al.*, 2020). Climate models project a contraction of its suitable habitat and a negative trend in radial growth (Mechergui *et al.*, 2021; Natalini *et al.*, 2024). Establishing extra-Mediterranean plantations could help offset the impending global shortfall in nut production.

Growers have successfully introduced stone pine to southern South America (Chile and Argentina) (Muñoz *et al.*, 2012), where it adapts well to diverse conditions and promises economic benefits from non-timber products (Loewe-Muñoz *et al.*, 2012). Recent studies have analyzed tree-ring variability and its relationship with climate trends and extremes in Chilean plantations under typical Mediterranean conditions (Loewe Muñoz *et al.*, 2024ab). However, no research has yet reconstructed radial growth dynamics in Argentina, where the species thrives in semi-arid environments (Calderón *et al.*, 2008; Diaz Dentoni, 2024).

This study aims to investigate how *P. pinea* radial growth interacts with drought conditions in two irrigated plantations located in Argentina's Mendoza Province. We hypothesize that drought events significantly suppress growth, with the stronger effects during extreme dry years. Our findings will clarify the potential of this species for forestry in extra-Mediterranean regions, especially as climate change threatens its native range.

Material and Methods

Study Site Characteristics

We selected two sites for this study: Dique Yaucha (hereafter YAU; 34°00'03" S, 69°07'03" W) and Malargüe (hereafter MAL: 35°35'55" S, 69°31'37" W), both located in southern Mendoza Province (figure 1, page XXX). These plantations represent the only undisturbed adult artificial forests in the region (Piraino *et al.*, 2021).

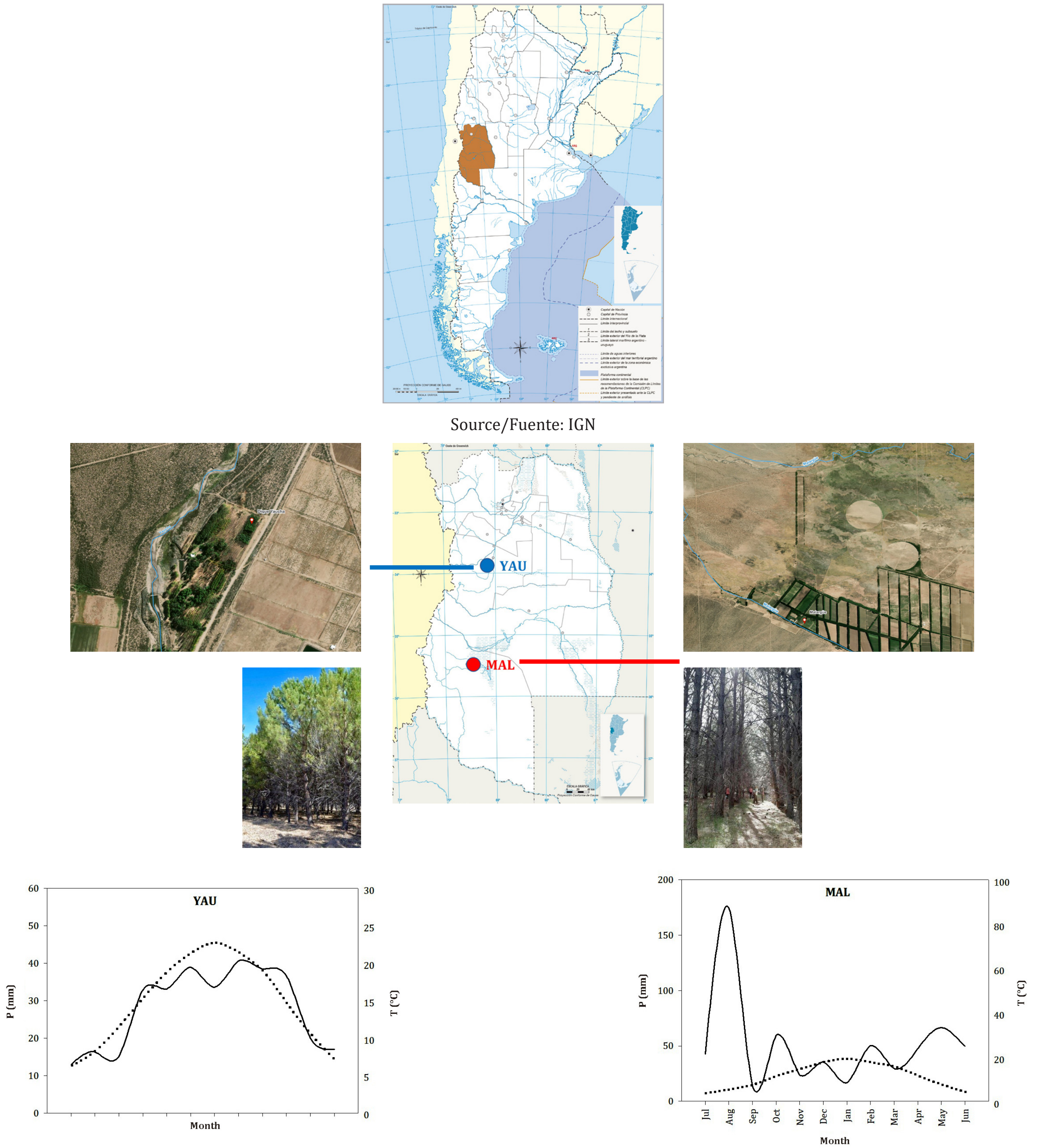
At both sites, stone pine seedlings were planted between the late 1980s and early 1990s, forming a monospecific plantation with a spacing of 3x3 m between rows and trees. The plantations are situated at similar elevations (1213 m a. s. l. for YAU vs 1470 m a. s. l. for MAL). The YAU site is characterized by semi-arid conditions, with mean annual temperature of 15°C, and total annual precipitation of 335 mm (figure 1, page XXX). In contrast, MAL grows under Mediterranean-type climate, with mean annual temperature and total annual precipitation values of 12.6°C and 610 mm, respectively (figure 1, page XXX). Soils are gravelly to sandy with good permeability at YAU, and loam to clay loam of alluvial origin at MAL. Both plantations receive supplementary irrigation: approximately 300-350 mm annually at YAU and 500-600 mm at MAL, evenly distributed across the irrigation season (September-July; current and projected upper river water balance 2020-2021; G. Aguado, *personal communication*). According to this characterization, we considered YAU and MAL sites xeric and mesic, respectively.

Dendrochronological Sampling and Tree-Ring Chronology Development

During the austral spring of 2021 and 2022, we extracted one core per tree at breast height (approximately 1.30 m above soil level) from 16 individuals at YAU and 10 at MAL, respectively, by using a 5.15 mm increment borer. We selected sampled trees based on their health status. Cores were glued onto wooden mounts, and the transverse section was polished with progressively finer sandpaper to highlight ring boundaries. Samples were scanned at 1200 dpi, and tree-ring width (TRW) was measured to 0.001 mm precision with CooRecorder software (Maxwell & Larsson, 2021). Calendar years were assigned following Schulman's convention for the Southern Hemisphere (Schulman, 1956).

TRW series were statistically validated with COFECHA software (Holmes, 1983). Two indices were calculated: 1) the mean correlation among individual series (MC); and 2) mean sensitivity (MS), the relative year-to-year variability in TRW, reflecting the species' sensitivity to environmental factors (Speer, 2010).

After statistical validation, individual chronologies were standardized to remove the low-frequency, age-related trends and highlight the high-frequency climate signal (Speer, 2010). Raw TRW series were detrended using a 20-years spline with a 50% frequency cutoff applied in ARSTAN40c software (Cook & Krusic, 2008). We used the standardized residual chronology version for all drought-growth analyses to minimize bias from non-climatic trends (Villalba & Veblen, 1997).



Precipitation and temperature data belong to the INTA San Carlos (Dique Yaucha: 33.73°S, 69.1°W; http://siga.inta.gob.ar/#/), and Malargüe Aero (Malargüe: 35.48°S; 69.58°W; http://www.meteomanz.com/) gauge stations, covering the 2000-2020 period. T: monthly mean air temperature; P: monthly total rainfall. Gray dot line refers to monthly mean air temperature, and black solid line to monthly total rainfall.

Los datos de precipitación y temperatura pertenecen a las estaciones climáticas INTA San Carlos (Dique Yaucha: 33.73°S, 69.1°O; http://siga.inta.gob.ar/#/) y Malargüe Aero (Malargüe: 35.48°S; 69.58°O; http://www.meteomanz.com/), y cubren el período 2000-2020. T: temperatura media mensual del aire; P: precipitación total mensual. La línea de puntos grises indica la temperatura media mensual del aire, y la línea negra continua, la precipitación total mensual.

Figure 1. Geographical location of the sampled sites and Ombrothermic diagram drawn according to the methods of Bagnouls & Gaussen (1953).

Figura 1. Ubicación geográfica de los sitios muestreados y diagrama ombrotérmico elaborado según los métodos de Bagnouls & Gaussen (1953).

Statistical Analyses

To assess differences in TRW trends among sites under varying environmental conditions, we compared the raw ring-width site chronologies for the common period 1992-2020 with a Kruskal-Wallis test hosted in the InfoStat software (Di Rienzo *et al.*, 2021). Then, we used site and individual- standardized chronologies to evaluate the effect of drought on growth at long and short-term timescales. For the long-term analysis, correlation functions were calculated between the standardized site-chronologies and two datasets: SPEI (Standardized Precipitation Evaporation Index; Vicente-Serrano *et al.*, 2010), and soil moisture at 100 cm depth (SM100). Monthly values of both datasets were obtained from the KNMI Climate Explorer for 1901-2018 (SPEI) and 1979-2016 (SM100) (Trouet & Van Oldenborgh, 2013; http://climexp.knmi.nl/). Correlation functions were computed with DENDROCLIM2002 for the common period 1992-2016 (n = 25) (Biondi & Waikul, 2004). We selected this interval because the YAU chronology began in 1992 and SM100 data ended in 2016. Based on prior research, stone pine plantations in South America (Loewe-Muñoz *et al.*, 2022), a 13-month time-window was selected, spanning June of the year preceding growth through June of the growth year. No monthly irrigation data were available, which prevented direct comparison between supplementary water inputs and ring development.

We assessed short-term growth responses to extreme drought using the line of full resilience (LFR; Schwarz *et al.*, 2020). The LFR approach evaluates the relationship between resistance and recovery *sensu* Lloret *et al.*, 2011; see below for mathematical definitions. and compares it with the theoretical scenario of full resilience (Schwarz *et al.*, 2020). This method provides an integrated assessment of tree capacity to withstand drought stress (Schwarz *et al.*, 2020).

We defined drought years based on the significant monthly windows identified by the correlation function analysis, which we used to calculate annual series for SPEI and SM100. We classified years with SPEI or SM100 values in the lowest 5th percentile as extreme drought events. For these events, we calculated tree-level resistance (R_t) and recovery (R_c) indices as $R_t = TRI_d/TRI\_pre_d$ and $R_c = TRI\_post_d/TRI_d$. TRI is the standardized tree-ring index, *d* refers to the drought year, and *pre* and *post* denote the year before and after extreme dry spell, respectively (Lloret *et al.*, 2011). Short p*re* and *post* time windows were chosen to minimize overlap among consecutive drought events (see Results). Finally, Finally, we calculated the LFR as $R_c = 1/R_t$.

Results

We developed two tree-ring chronologies from 10 (MAL) and 16 (YAU) wood samples (table 1 and figure 2, page XXX). The chronologies covered 1991-2020 at MAL and 1992-2021 at YAU (table 1, page XXX). Mean annual raw TRW (mTRW) was significantly higher at MAL than at YAU stand (H = 8.35; $p = 0.0039$; data not shown). Tree-ring statistics showed higher MC and MS values for YAU (table 1, page XXX).

Correlation function analyses revealed that radial growth at both sites was significantly influenced by long-term drought conditions, although responses differed between stands (figure 3, page XXX). At MAL, standardized growth was positively related to late spring (June; JUN) SPEI and SM100. At YAU, SPEI positively influenced ring width during December (DEC) of the year of growth, while no significant relationship emerged with SM100 (figure 3, page XXX).

Based on these results, we selected JUN-SM100 and JUN-SPEI to identify extreme drought events at MAL, and DEC-SPEI at YAU stand. Statistical analyses identified three extreme drought events at MAL (MAL-SM100 2010: MAL-SPEI 2012; MAL-SPEI 2014) and two at YAU (YAU-SPEI 2003 and YAU -SPEI 2011) (figure 4, page XXX). We excluded the YAU -SPEI 2003 event, as trees were likely in their seedling phase.

LFR analysis revealed contrasting responses among stands (figure 5, page XXX). At YAU, only 6% of trees displayed full resilience to the 2011 extreme drought. At MAL, no tree exhibited full resilience to the 2010 SM100 event. In contrast, LFR values were comparable between the MAL-SPEI 2012 (LFR = 40%) and the MAL-SPEI 2014 (LFR = 50%) events (figure 5, page XXX).

N: Number of sampled trees per site. Period: time range of the sampled cores. mTRW: mean annual tree-ring width value. MC: mean correlation between series at each stand. MS: mean sensitivity.

N: Número de árboles muestreados por sitio. Period: rango temporal de las muestras. mTRW: valor medio anual del ancho de anillo. MC: correlación media entre series en cada rodal. MS: sensibilidad media.

Table 1. Characteristics of the tree-ring chronologies.

Tabla 1. Características de las cronologías de anillos de crecimiento.

Site	N	Period	mTRW (mm/year)	MC	MS
YAU	16	1992-2021	0.41	0.57	0.37
MAL	10	1991-2020	0.72	0.55	0.18

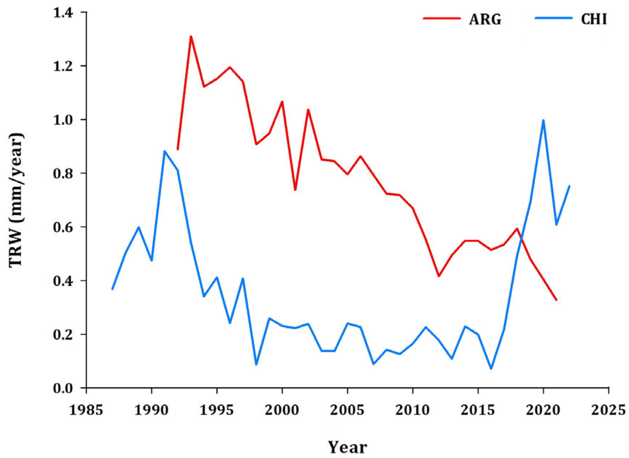


Figure 2. Raw tree-ring width (TRW) site chronologies of the sampled stone pine plantations.

Figura 2. Cronologías de datos brutos de ancho de anillo (TRW) de las plantaciones de pino piñonero muestreadas.

Black bars refer to significant Pearson *r* values at $p < 0.05$ level.

Las barras negras indican valores de correlación de Pearson significativos por $p < 0,05$.

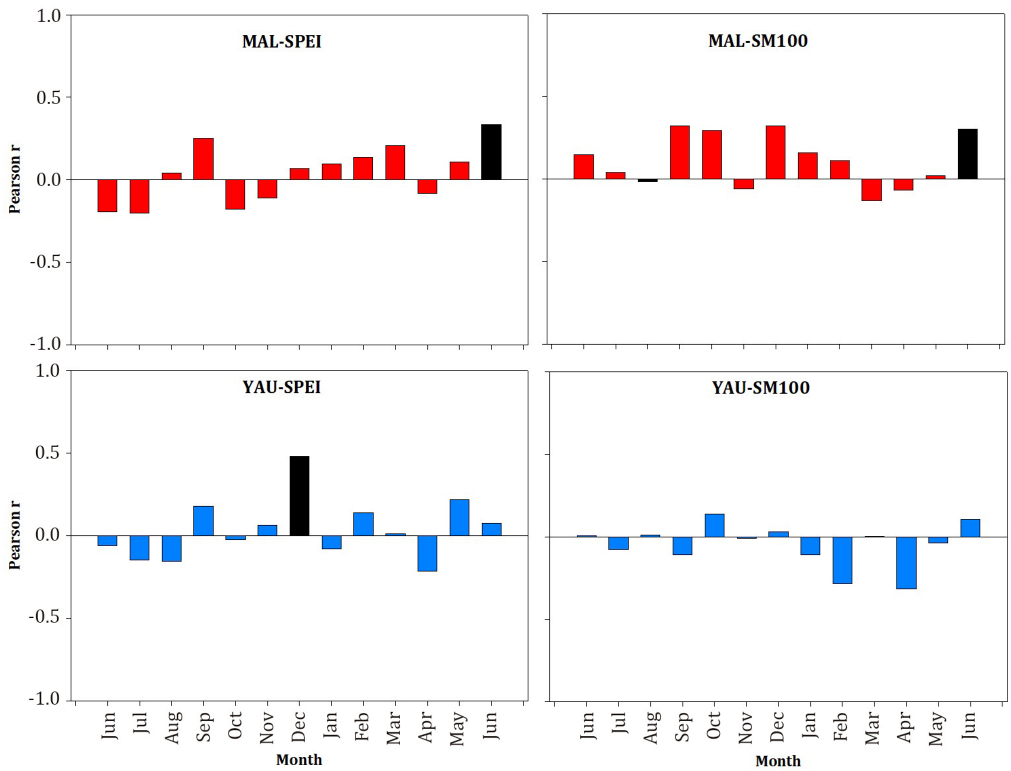
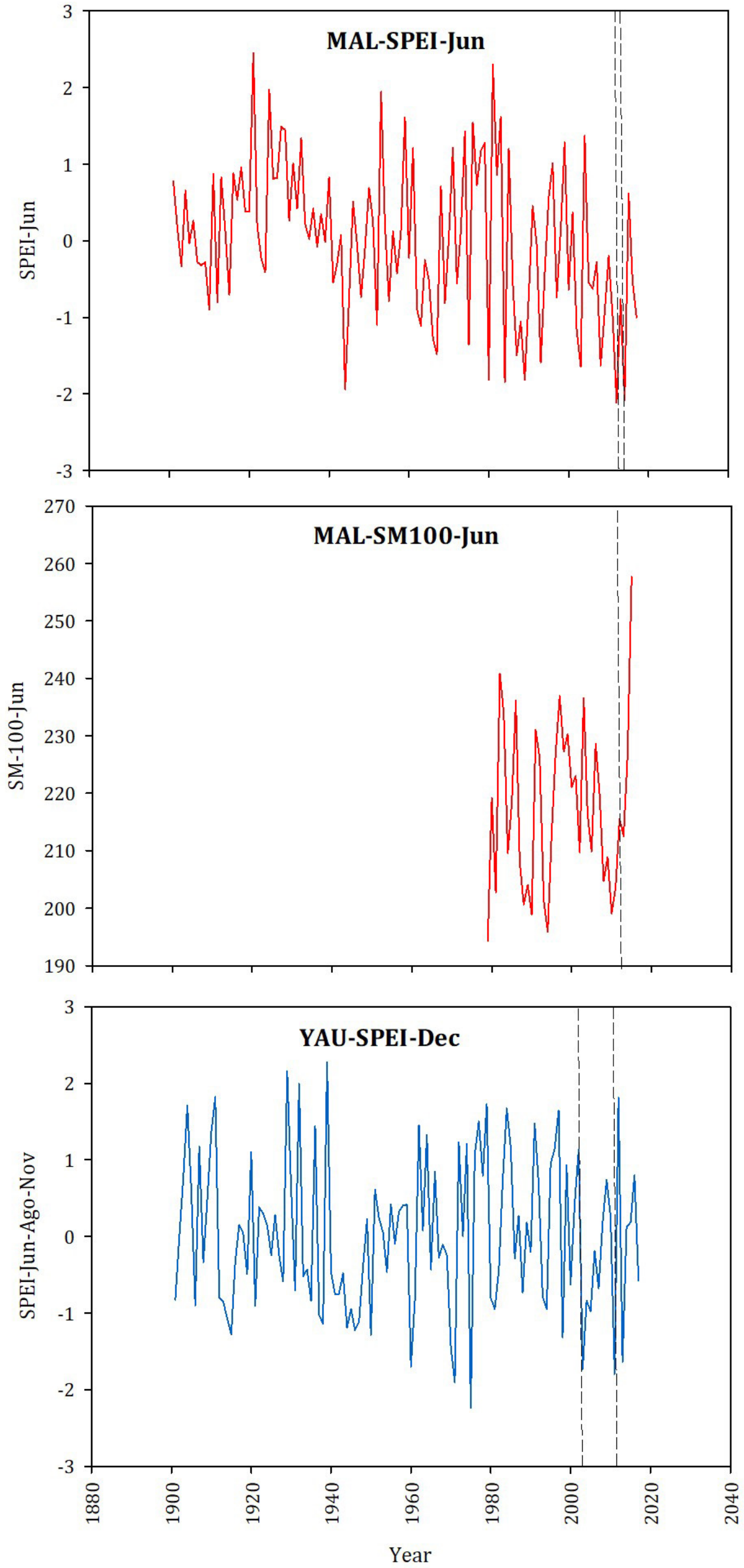


Figure 3. Correlation functions results between each residual chronology and monthly SPEI and SM100 values for the common period 1992-2016.

Figura 3. Resultados de las funciones de correlación entre cada cronología residual y los valores mensuales de SPEI y SM100 para el período común 1992-2016.

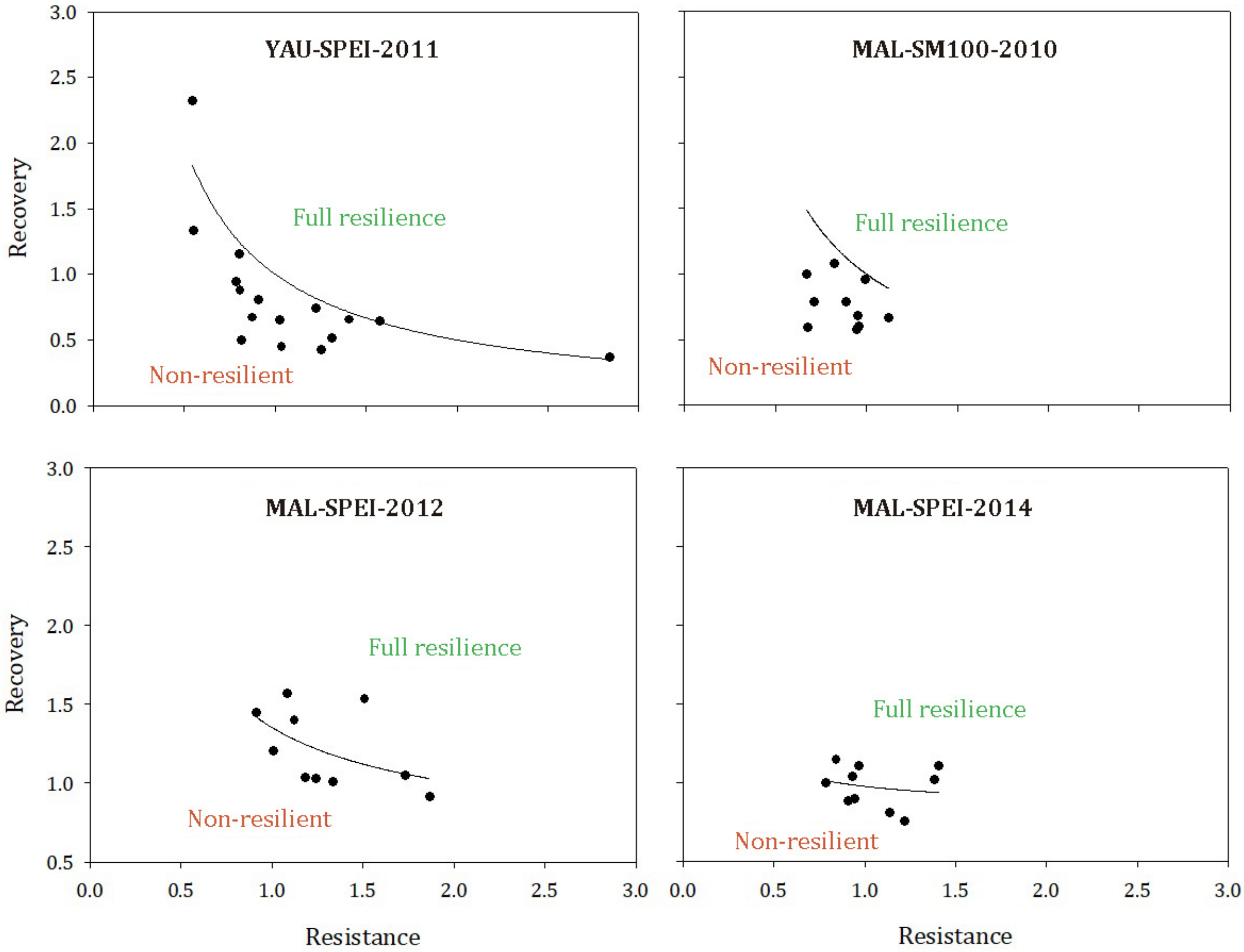


Vertical lines refer to local extreme drought events.

Las líneas verticales indican los eventos locales de sequía extrema.

Figure 4. Historical series of SPEI and SM100 at each site based on correlation function results.

Figura 4. Series históricas de SPEI y SM100 por cada sitio, basadas en los resultados de las funciones de correlación.



Dots located above the LFR correspond to trees exhibiting full resilience (Resilience = 1.0).
Los puntos situados por encima de la LFR corresponden a los árboles que exhiben resiliencia plena (Resiliencia = 1.0).

Figure 5. Comparison of the relationship between observed tree-level mean values of R_t and R_c and the hypothetical function (black curve) representing the LFR across all R_t values, for the analyzed extreme atmospheric and edaphic drought events.

Figura 5. Comparación de la relación entre los valores medios observados a nivel de árbol de R_t y R_c y la función hipotética (curva negra) que representa la LFR a lo largo de todos los valores de R_t, para los eventos analizados de sequía atmosférica y edáfica extrema.

Discussion

This study provided novel information of how stone pine growing in an extra-Mediterranean region responds to atmospheric and edaphic drought across multiple timescales. Previous research addressed the species' dendroclimatological signal and resilience to extreme climatic events in Chile (Loewe-Muñoz *et al.*, 2024ab), but no studies had explored these dynamics under the environmental conditions of central-western Argentina. Our findings offer new insights of *P. pinea* growth and drought resilience beyond its native Mediterranean habitat, confirming the species' adaptability to new climatic contexts.

Although our sample size was relatively small, it well represented growth dynamics of both populations. At MAL, sampled trees accounted for 85% of the original plantation (n = 12). At YAU, the tree-ring chronology reliably captured stand-level growth, with an Expressed Population Signal (EPS; Wigley *et al.*, 1984) exceeding the 0.85 threshold, indicating strong agreement between sampled trees and the overall population (data not shown).

The mean correlation coefficient among individual series fell within the range reported in literature, confirming the robustness of our ring-width measurements (Natalini *et al.*, 2016; Piraino *et al.*, 2013). At YAU, MS was twice as high as at MAL. Theoretically, MS should reflect MC variability, since both indices are strongly related (Fritts *et al.*, 1965). Nevertheless, MC differed only slightly between stands. The higher irrigation regime at MAL likely explained the differences in MS values by reducing growth sensitivity to environmental variability. This interpretation agrees with previous studies in Central European conifer comparing irrigated and non-irrigated woodlands (Feichtinger *et al.*, 2014; Rigling *et al.*, 2003).

Mean TRW at both sites exceeded values previously reported (Mechergui *et al.*, 2021). This pattern likely reflects both the relatively young age of the plantations, with trees probably still at their juvenile growth phase, and the benefit of irrigation, which can extend the growing season, enhance nutrient mobility, and increase primary production (Feichtinger *et al.*, 2014; Loewe-Muñoz *et al.*, 2024a). The higher mTRW at MAL compared with YAU further reflects the more favorable water balance at that site (precipitation + irrigation: see Materials and Methods).

Our analyses of drought-radial growth relationships across timescales indicated that irrigation did not fully decouple growth from climate, suggesting that the supplementary water was likely insufficient (Perulli *et al.*, 2019). This limitation was particularly evident at YAU, where radial growth benefited only during the early phases of ring development. These results have practical implications for managing future plantations in semi-arid central-west Argentina. However, the lack of systematic irrigation records prevented statistical evaluation of watering effect. For future *P. pinea* plantations in Mendoza, we recommend monitoring irrigation at least monthly to enable direct comparison between radial growth dynamics and water supply.

Correlation function analyses provided quantitative evidence of the species' distinct responses to atmospheric and edaphic drought. At MAL, radial growth correlated with high soil moisture and wet atmospheric conditions at the end of the growing season. In contrast, at YAU, ring width responded positively to early summer (December) SPEI. Previous studies in the Mediterranean range reported similar patterns, showing that radial growth benefits from low evapotranspiration during the growing season and from abundant precipitation before cambium reactivation (Mechergui *et al.*, 2021). Physiologically, *P. pinea* is a drought-tolerant species, capable of reducing photosynthetic activity during water stress through root mortality, stomata control, and biomass allocation (Mechergui *et al.*, 2021). Nevertheless, drought constrains tree growth by reducing sap flow and significantly decreasing stem increment (Mechergui *et al.*, 2021; Piraino, 2020). Our findings confirm that, regardless of irrigation, the species' radial growth remains constrained by unfavorable environmental conditions during the growing period (Loewe-Muñoz *et al.*, 2024b; Piraino, 2020).

Analysis of annual SPEI and SM100 series identified several extreme drought events that impacted growth dynamics at both sites. At MAL, edaphic dry spells exerted stronger short-term effects on growth than atmospheric droughts. This difference may reflect the direct impact of soil water deficit on roots uptake, whereas atmospheric drought primarily affects transpiration and leaf water potential, which may not immediately restrict stem growth if surface soil moisture remains sufficient (Berauer *et al.*, 2024). Future studies should integrate physiological data from both root and stem levels, along with site-specific infiltration rates, to better characterize the species responses to different drought types.

Conclusion

Our study provides critical baseline data on the radial growth and drought resilience of *P. pinea*, establishing a foundation for evaluating its potential for forestry development beyond Mediterranean environments. These findings are especially relevant for Mendoza Province, where current forestry focuses almost exclusively on medium-quality wood production from more water-demanding species like as *Populus* spp. Expanding *P. pinea* cultivation would diversify local forestry and could yield substantial economic benefits under the semi-arid conditions of central-western Argentina.

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