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Research article

Project in Mexico Climate sensitivity and resilience of *Pseudotsuga menziesii* (Mirb.) Franco to drought events

Sensibilidad climática y resiliencia de *Pseudotsuga menziesii* (Mirb.) Franco ante eventos de sequía

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Abstract

Climate change poses a threat to the dynamics and resilience of temperate forests, with profound implications for species sensitive to drought and water stress. The objective was to evaluate the sensitivity of the radial growth of *Pseudotsuga menziesii* to climate variability, as well as the resilience of the Basal Area Increment (*BAI*) to drought events as dendroecological proxies. A residual chronology (1948–2021) was developed with 40 series of 20 trees in a high conservation value forest (HCVF) in *Durango*, Mexico, using standard dendrochronological techniques.ك Climate data for maximum and minimum temperature, precipitation, and vapor pressure deficit (*Tmax*, *Tmin*, *PP*, and *VPD*) were obtained from TerraClimate for the period from 1958 to 2024, and the six-month Standardized Precipitation Evapotranspiration Index (*SPEI*) from the SPEI Drought Monitor. Radial growth was positively associated with *PP* and *Tmin* in winter and early spring. In contrast, December *Tmax* and spring *VPD* negatively affected growth, as did *SPEI*, on 3- to 11-month scales. The *BAI* had an upward trend interrupted by severe droughts in 1974, 1999, 2006, and 2011. Resilience indices showed a reduction in resistance and resilience to droughts; 1965 registered the event with the significantly shortest recovery time. These results confirm that *P. menziesii* is sensitive to winter and spring water availability, and droughts compromise its resistance and resilience to recent extreme weather events.

Keywords: Dendroecological, Basal Area Increment, resilience indices, climate variability, extreme droughts, *Sierra Madre Occidental*.

Resumen

El cambio climático representa una amenaza para la dinámica y la resiliencia de los bosques templados, con profundas implicaciones para las especies con sensibilidad a la sequía y estrés hídrico. El objetivo fue evaluar la sensibilidad del crecimiento radial de *Pseudotsuga menziesii* a la variabilidad climática, así como la resiliencia del Incremento en Área Basal (*IAB*) a eventos de sequía como *proxies* dendroecológicos. Se desarrolló una cronología versión residual (1948-2021) con 40 series de 20 árboles en un bosque de alto valor de conservación (BAVC) en Durango, México con técnicas dendrocronológicas estándar. Los datos climáticos temperatura máxima y mínima, precipitación y déficit de presión de vapor (*Tmax*, *Tmin*, *PP* y *DPV*) se obtuvieron de *TerraClimate* para el periodo 1958 a 2024, y el Índice Estandarizado de Evapotranspiración Precipitación (*SPEI*) a seis meses de *SPEI Drought Monitor*. El crecimiento radial se asoció positivamente con *PP* y la *Tmin* en invierno y principios de primavera. En contraste, *Tmax* de diciembre y *DPV* en primavera disminuyeron el crecimiento, al igual que el *SPEI* en escalas de 3 a 11 meses. El *IAB* tuvo una tendencia ascendente interrumpida por sequías severas en 1974, 1999, 2006 y 2011. Los índices de resiliencia evidenciaron una reducción en la resistencia y resiliencia frente a sequías, 1965 registró el evento con un tiempo de recuperación significativamente menor. Estos resultados confirman que *P. menziesii* es sensible a la disponibilidad hídrica invernal y primaveral, y las sequías comprometen su capacidad de resistencia y resiliencia ante eventos climáticos extremos recientes.

Palabras clave: Dendroecológico, Incremento en Área Basal, índices de resiliencia, variabilidad climática, sequías extremas, Sierra Madre Occidental.

Introduction

Droughts represent one of the main threats to the stability of forest ecosystems, as they affect their structural and functional integrity (Bhandari et al., 2019; Cook et al., 2016); they reduce water availability and alter physiological processes such as wood and foliage formation (Castruita-Esparza et al., 2019), which reduces radial growth in species sensitive to water stress (Piraino et al., 2022). Given this scenario, there has been a growing interest in understanding how tree species respond to climate variability and drought. In this context, the concept of forest resilience has become established as a key approach for assessing the ability of taxa to resist, recover, and mantein growth in the face of climate change (Correa-Díaz et al., 2023; Thurm et al., 2016).

Dendroecological studies based on radial growth analysis allow for the quantification of indicators of resistance, recovery, and resilience following extreme disturbances (Fang & Zhang, 2019; Lloret et al., 2011; Song et al., 2022). Combined with the Standardized Precipitation Evapotranspiration Index (*SPEI*), this approach facilitates the assessment of water stress (Vicente-Serrano et al., 2010) and its effect on the Basal Area Increment (*BAI*), a more accurate indicator than ring width for comparing forest productivity over time (Rojas-García et al., 2020; Serra-Maluquer et al., 2018).

Radial growth and forest productivity contribute to climate change mitigation by promoting carbon capture and storage (Rais et al., 2014). Therefore, understanding the dynamics of radial growth in response to climatic variations is essential to understand the adaptive capacity of species and establish management and conservation strategies (Song et al., 2022).

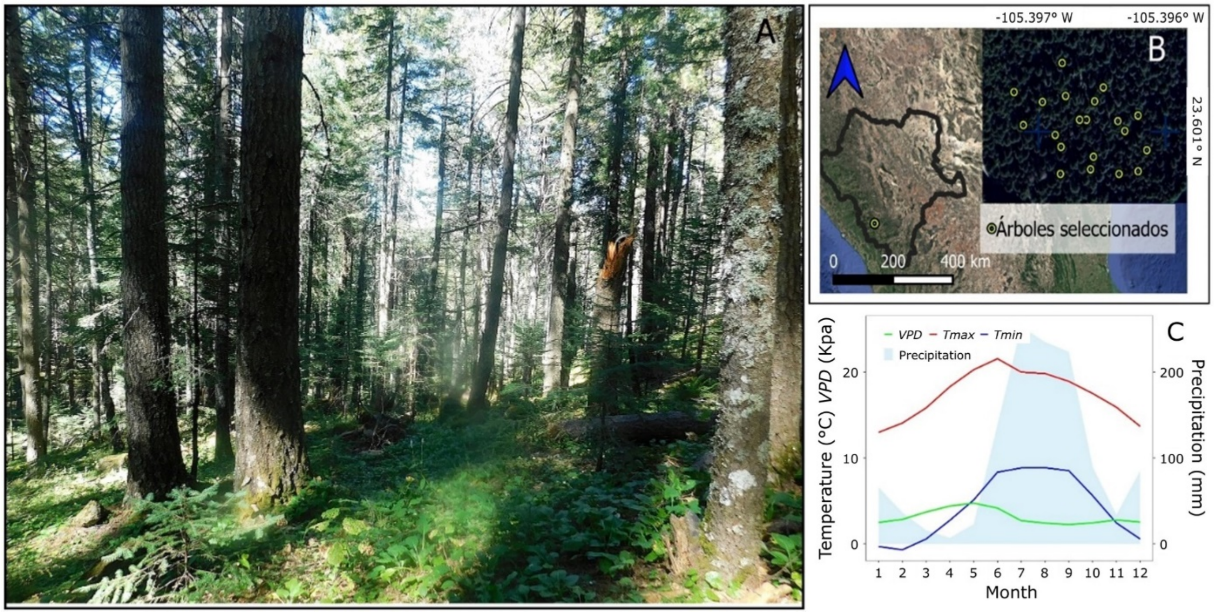
In Mexico, *Pseudotsuga menziesii* (Mirb.) Franco has a fragmented distribution (Instituto Nacional de Estadística, Geografía e Informática [INEGI], 2017) and is under special protection by NOM-059-SEMARNAT-2010 (Secretaría de Medio Ambiente y Recursos Naturales [Semarnat], 2019). Its longevity, climate sensitivity, and well-defined rings render it a reliable proxy for reconstructing extreme climate events (Martínez-Sifuentes et al., 2020; Villanueva-Díaz et al., 2009, 2020) and for making historical rainfall inferences (Chávez-Gándara et al., 2017).

Due to its ecological vulnerability and dendroclimatic potential, this species is suitable for determining the impact of climate variations on the resilience of the *BAI*. In this regard, we set out to evaluate the sensitivity of ring-width growth to climate and drought variations, as well as the resilience of the *BAI* of *Pseudotsuga menziesii*, using dendroecological proxies in a high conservation value forest (HCVF) in the Southwest of the *Sierra Madre Occidental* (SMO) in Mexico, specifically, to answer the research questions: (1) What are the climate elements that modulate the radial growth of *P. menziesii*?, and (2) Are there significant differences in the species' resilience, recovery, and resistance to drought events inferred by the *BAI*? The following hypothesis was formulated: the radial growth of *P. menziesii* is influenced by climatic variables, and the *BAI*'s resistance, recovery, and resilience indices differ significantly in response to recent drought events.

Materials and Methods

Study area and dendroecological methodology

The HCVF is located in *Pueblo Nuevo*, *Durango* (23.601° N, -105.396° W, at 2 726 masl), in the Southwestern SMO, Mexico (Figure 1). The site corresponds to a cool-temperate forest dominated by *P. menziesii* and *Abies durangensis* Martínez, with trees exceeding 25.96 (±3.21) m in height and 47.57 (±14.01) cm in diameter. The predominant soil type is dystric Cambisol, with a surface horizon rich in organic matter, moderate fertility, and medium texture (Instituto Nacional de Estadística y Geografía [Inegi], 2024). The climate is temperate subhumid with rainfall in summer (Cw), maximum precipitation (*PP*) in July and August (253 and 235 mm, respectively), and minimum rainfall in April (6.95 mm). Temperatures range from 21.6 °C in June to -0.7 °C in winter. The Vapor pressure deficit (*VPD*) is higher from March to May (~0.743-0.950 kPa) and lower in summer and winter (~0.484-0.541 kPa).



Árboles seleccionados = Selected trees. A = HCVF overview; B = Macro-location and distribution of sampled trees; C = HCVF climate chart from TerraClimate. *VPD* = Vapor pressure deficit; *Tmax* = Maximum temperature; *Tmin* = Minimum temperature.

Figure 1. Characterization of the site in the high conservation value forest.

The 20 trees closest to a randomly selected central tree were sampled (González-Elizondo et al., 2005), extracting two cores per tree at 1.3 m (normal diameter) with a Pressler auger (*Ө*=5 mm, Forestry Suppliers®) (Table 1).

Table 1. Descriptive statistics of the dasometric and dendrochronological variables of *Pseudotsuga menziesii* (Mirb.) Franco.

Variable	***n***	***Min***	***Max***	***q1***	***q3***	***Mean***	***SD***	***SE***
Nd	40	23	81.5	32	56.8	45	17.8	2.81
H	40	16	31.3	22.2	28.3	25	4.48	0.708
Age	40	44	86	57.5	73.5	65.6	10.9	1.72
Mean RWI	40	0.963	4.86	1.75	3.5	2.56	1.08	0.171
Stdev RWI	40	0.516	3.77	0.76	1.33	1.14	0.609	0.096

Nd = Normal diameter (cm); *H* = Total height of the tree (m); Age = Cambial age (years); *Mean RWI* = Mean value of the Ring width index; *Stdev RWI* = Standard deviation of the Ring with index; *n* = Number of observations; *Min* and *Max* = Minimum and maximum value of each variable, respectively; *q1* = First quartile (25 %); *q3* = Third quartile (75 %); *Mean* = Arithmetic mean; *SD* = Standard deviation; *SE* = Standard error.

This approach maximized the representativeness of the natural stand and ensured that the selected trees reflected the site's variability, not just individuals in preferential conditions (Pollard, 1971).

The cores were mounted and processed using standard dendrochronological techniques (Fritts & Swetnam, 1989). Visual dating was performed using marker rings (Stokes & Smiley, 1996) and ring width measurements were obtained using a high-precision VELMEX® system (0.001 mm; Bloomfield, NY, USA), with the last year of measurement corresponding to 2021. The quality of the dating was validated using COFECHA (Holmes, 1983), and ontogenetic tendencies were eliminated by applying a negative exponential model to each series, preserving the climate and stress signal (*i. e.*, standardization).

Residual chronology was used to eliminate the influence of tree age and size, retaining only the climate-induced growth signal (Pompa-García et al., 2014). This chronology was generated using the dplR package of R studio software version 4.5.0 (R Core Team, 2025), and its quality was evaluated using first-order autocorrelation (*AC*), mean sensitivity (*MS*), mean correlation between series (*Rbar*), and tree-to-tree correlation (*Rbt*). Statistical validity for climate purposes was determined using the expressed population signal (*EPS*>0.85).

Relationship between climate data and radial growth

Monthly climate data for *VPD*, *Tmax*, *Tmin*, and *PP* were obtained from the TerraClimate database (Abatzoglou et al., 2018), which provides high spatial resolution (~4 km) and global coverage from 1958 to 2024. To assess the influence of droughts, the residual chronology was correlated with the six-month *SPEI*, downloaded with a resolution of 0.5° and a time scale of 1-48 months from the *SPEI* Drought Monitor (Vicente-Serrano et al., 2010). To analyze the relationship between radial growth (1958-2021) and climate variables, Pearson correlations were applied using the treeclim package in R studio version 4.5.0 (R Core Team, 2025).

BAI estimates and drought resilience indices

The *BAI* allows the annual wood production to be estimated by eliminating the geometric effect of radial growth (Equation 1) (Biondi & Qeadan, 2008).

$$BAI = \pi(R_t^2 - R_{t-1}^2) \qquad (1)$$

Where:

BAI = Basal area increase

R_t^2 = Cumulative radius of the trunk up to year t

R_{t-1}^2 = Cumulative radius of the trunk up to the previous year t_{-1}

The *BAI* series were analyzed using the pointRes 2.0 software package (van der Maaten-Theunissen et al., 2021) in R Studio version 4.5.0 (R Core Team, 2025). The pointer years were identified with the method of Neuwirth et al. (2007), which uses a 13-year moving-window normalization to compare the annual *BAI* to the average of previous years. The pointer years were classified into three levels of intensity: weak, strong, and extreme (0.9, 1.15, and 1.5, respectively), reflecting degrees of variation in radial growth. Based on the *BAI* series, the resilience indices proposed by Lloret et al. (2011) were estimated: recovery, resilience, and resistance (Equation R_c,2; R_s,3; R_t,4, respectively). To do this, the *BAI* was considered before, during, and after the drought events. The recovery period was also calculated to determine legacy effects, which assesses the time required for the forest to return to pre-disturbance growth conditions.

$$R_c = \frac{BAI\_Dr_{Post}}{BAI\_Dr} \qquad (2)$$

$$R_s = \frac{BAI\_Dr_{Post}}{BAI\_Dr_{Pre}} \qquad (3)$$

$$R_t = \frac{BAI\_Dr}{BAI\_Dr_{Pre}} \qquad (4)$$

Where:

BAI_Dr_{Pre}, BAI_Dr and BAI_Dr_{Post} = They indicate the *BAI* for the 5 years before, during, and 5 years after the drought, respectively

To evaluate significant differences in *BAI* resilience indices across drought events, Student's t-tests for independent samples were applied using the rstatix package, version 0.7.3 (Kassambara, 2025). Multiple comparisons were adjusted using the Bonferroni method (Bland & Altman, 1995), with a significance level of α<0.05.

Results

Response to climate variations

The mean total ring width was 2.56±1.08 mm. The residual chronology was generated from 40 growth series with a total of 2 622 measurements for the 1936 to 2021 period. The *Rbar* was 0.369, the *MS* equaled 0.282, the *Rbt* amounted to 0.409, and the *AC* was -0.112. Since *EPS* exceeded the recommended threshold of 0.85 starting in 1948, the analyses were performed for the 1948-2021 period (Figure 2).

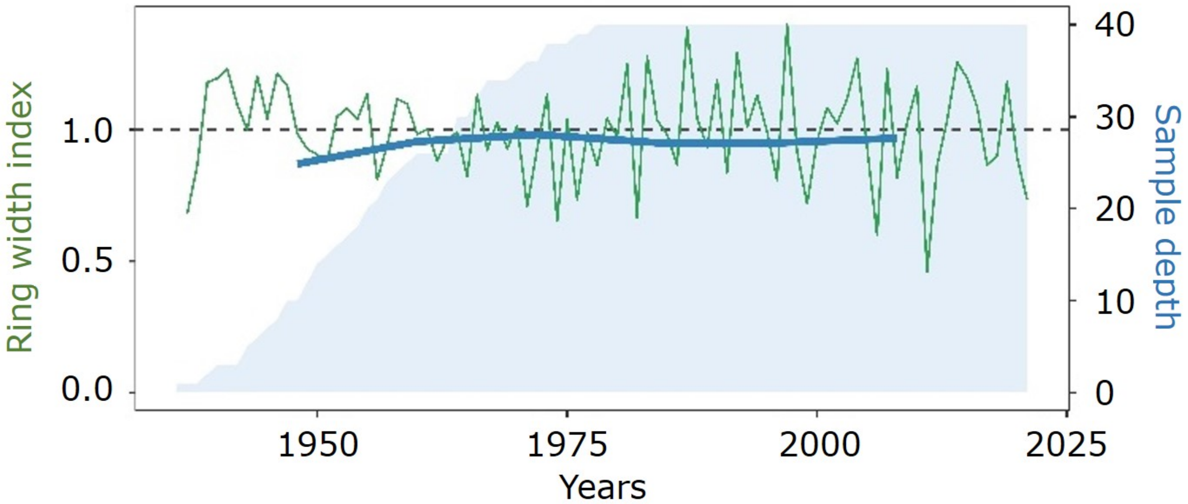
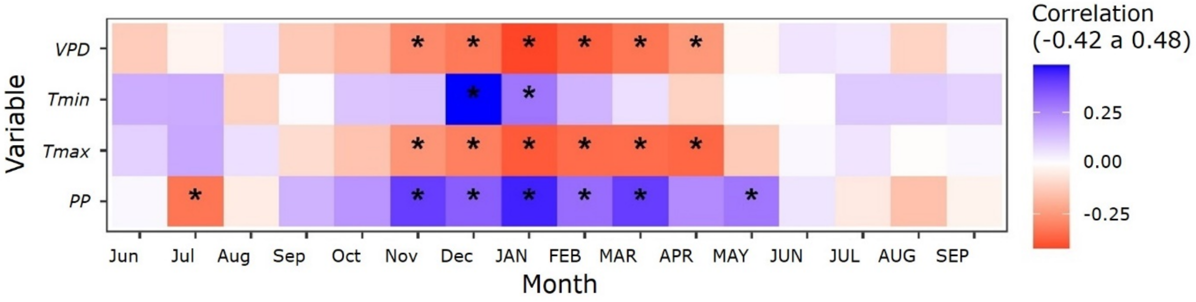


Figure 2. Residual chronology of the Ring width index (green line), dynamic *EPS* (blue line), and sample depth (blue area) of *Pseudotsuga menziesii* (Mirb.) Franco for 1947-2021.

Variability in the radial growth of *P. menziesii* was evident in 1971, 1974, 1976, 1982, 1999, 2006, 2011, and 2021, which showed reductions, whereas the years 1981, 1983, 1987, 1992, 1997, 2004, 2007, and 2014 showed increases.

The radial growth of *P. menziesii* exhibited significant correlations ($p<0.05$) with climatic variables (Figure 3). The *Tmin* was positively associated in December of the year prior to growth (autumn-winter) and in January of the current year (spring-summer) ($r=0.48$ and 0.29, respectively). In contrast, the *Tmax* in November and December of the year prior and January-April of the current year limited growth ($r=-0.39$, -0.35, -0.35, and -0.36, respectively; Figure 3). With regard to the *PP*, it showed positive associations from November of the year prior to April of the current year, with January being the month with the greatest influence ($r=0.45$), whereas July of the year prior registered a negative correlation ($r=-0.33$). The *VPD* was negatively correlated in November and December of the year prior ($r=-0.28$ and $r=-0.31$) and in January-April of the current year ($r=-0.42$, -0.37, -0.33, and -0.26, respectively; Figure 3), indicating that high vapor pressure in spring limits growth.



Months in lowercase = Previous year; Capital letter= Current year. *VPD* = Vapor pressure deficit; *Tmax* and *Tmin* = Maximum and minimum temperature; *PP* = Precipitation. The asterisks correspond to significant correlations with an $\alpha=0.05$.

Figure 3. Monthly climate correlations with radial growth of *Pseudotsuga menziesii* (Mirb.) Franco.

Radial growth of *P. menziesii* showed positive correlations with cumulative *SPEI* at scales of 3 to 11 months, particularly between March and July (Figure 4). High correlation values (>0.35) were concentrated in April and May.

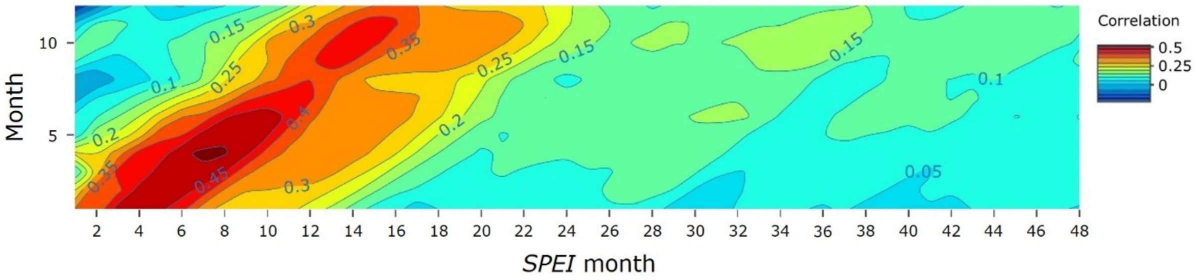
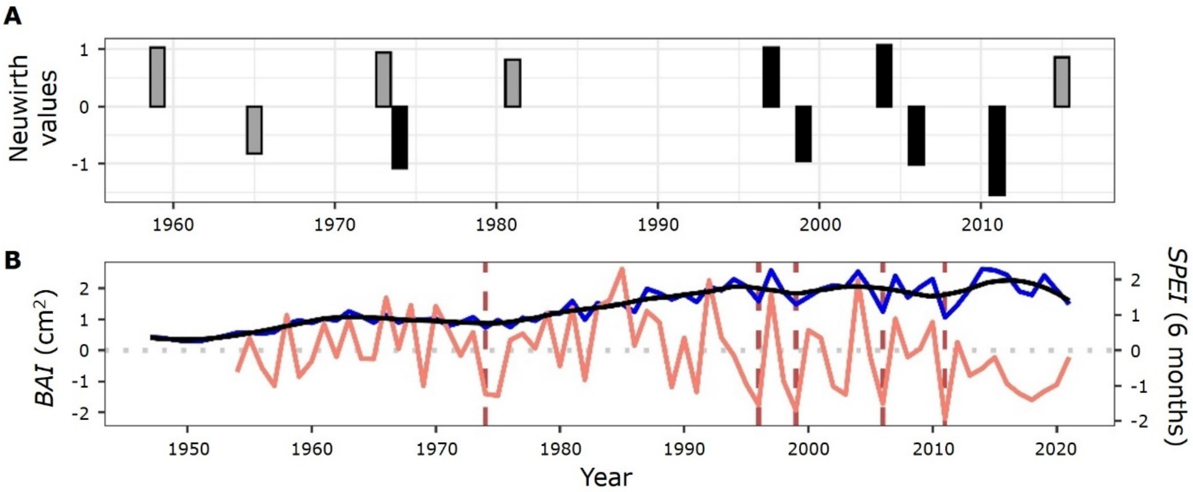


Figure 4. Pearson correlation coefficients between the *SPEI* Index and the residual chronology of *Pseudotsuga menziesii* (Mirb.) Franco.

Growth dynamics and their response to resilience indices in the face of droughts

The pointer years estimated from the *BAI* of *P. menziesii* showed alternating positive and negative events (Figure 5). The extreme negative events occurred in 1974, 1999, 2006, and 2011, while 1965 was considered strong. A cyclical pattern of negative events was observed approximately every nine years, with high frequency and severity noted in 2011, 2006, and 1999.

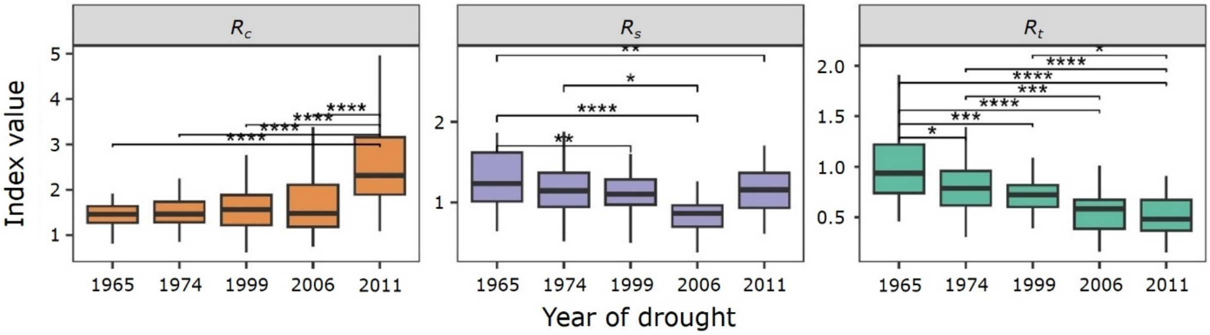


A = Pointer years: strong pointer year (gray) and extreme pointer year (black); B = Temporal variation of the *BAI* (blue line, black line trend) and the six-month *SPEI* Index (orange line) for the 1947-2021 period. The dashed vertical lines indicate the years associated with severe drought events.

Figure 5. Identification of pointer years and temporal variation of the *BAI* in *Pseudotsuga menziesii* (Mirb.) Franco and *SPEI*.

The *BAI* exhibited an upward trend from 1947 to 1997, with initial values (1947-1950) averaging ~0.40 cm^2 and increasing in 1960-1970 to ~1.2 cm^2. Between 1980 and 2000, greater variability was recorded, with peaks in 1987 (1.98 cm^2), 1994 (2.29 cm^2), and 1997 (2.57 cm^2), interspersed with declines associated with droughts. The *BAI* has remained high (~2.0 cm^2) since 1995, stabilizing after 2000, and reaching its maximum (2.62 cm^2) in 2014. These results suggest a sustained increase in radial growth, occasionally interrupted by drought events (Figure 5).

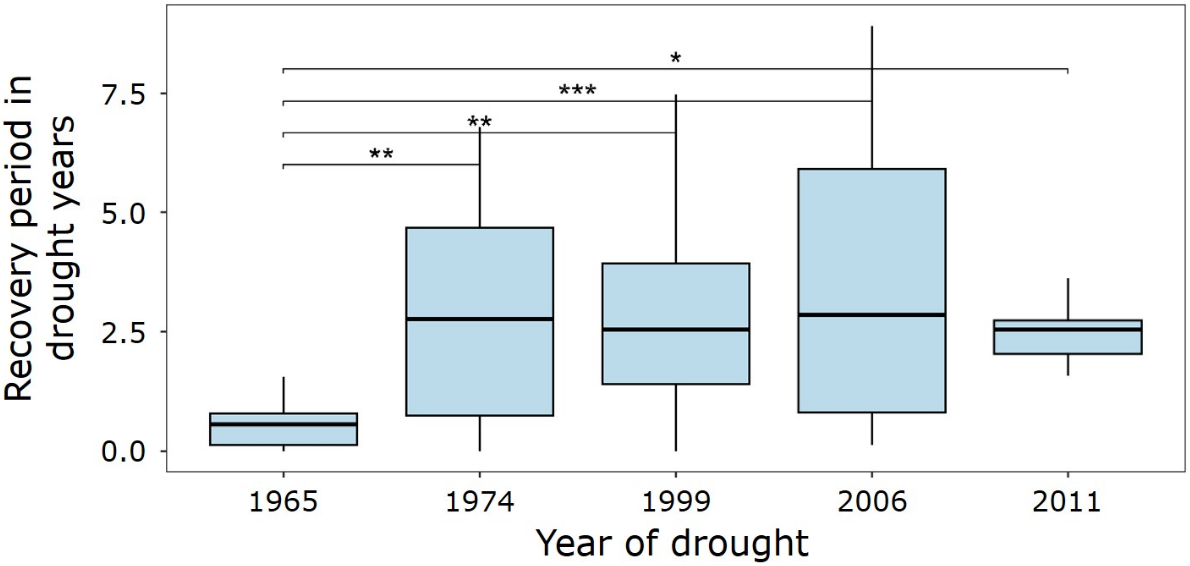
Figure 6 shows the recovery, resistance, and resilience of the *BAI* of *P. menziesii* during droughts. The R_c index in 2011 showed significant differences compared to other critical years (1965, 1974, 1999, and 2006). The R_t index showed the greatest number of significant comparisons, indicating a decrease in resistance in recent events. The year 1965 differed statistically from 1974, 1999, 2006, and 2011; 1974 differed from 2006 and 2011; and 1999 differed from 2011. This pattern indicated that resistance in maintaining growth declined in 2006 and 2011.



The lines on the boxplots indicate significant comparisons between drought years, and the asterisks indicate the level of significance according to the paired *t*-test with Bonferroni correction: $p \leq 0.05$ (*), 0.01 (**), 0.001 (***), 0.0001 (****).

Figure 6. Recovery (R_c), Resilience (R_s), and Resistance (R_t) indices of the *BAI* of *Pseudotsuga menziesii* (Mirb.) Franco.

The R_s index showed that resilience was also compromised in 2006 and 2011, reflecting accumulated stress or reduced water availability. These results reveal a downward trend in resilience following drought events, indicating the vulnerability of *P. menziesii* (Figures 4 and 5), although with a high capacity for growth recovery in subsequent years (Figure 6). The recovery period showed significant differences between droughts (Figure 7). The 1965 drought showed rapid recovery, while the event of 2011 exhibited a more homogeneous recovery period. Recent events showed significantly longer recovery times and greater variability.



The asterisks above the lines indicate comparisons with significant differences according to paired *t*-tests with Bonferroni correction: *$p<0.05$, **$p< 0.01$, ***$p<0.001$.

Figure 7. Comparison of recovery period in years of drought.

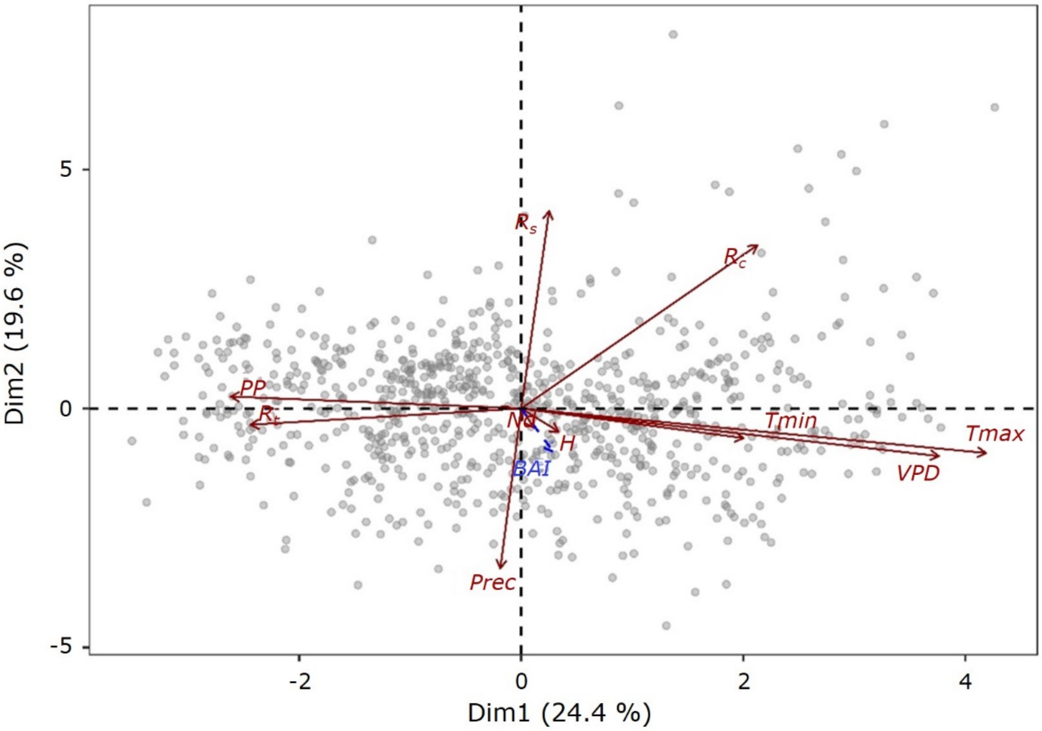
Discussion

The growth dynamics of *P. menziesii* offer an exceptional window into understanding the relationship between climate and forest resilience. The species demonstrated its dendrochronological potential, with a high-quality chronology (Figure 2) comparable to those of *Pinus lumholtzii* B. L. Rob. & Fernald, *Pinus arizonica* Engelm., *Abies durangensis*, *Pinus leiophylla* Schiede *ex* Schltdl. & Cham., and *P. menziesii* from Northern Mexico (Villanueva-Díaz et al., 2020). This also allowed us to analyze the *BAI*'s response to droughts and its resilience (Figures 5 and 6). The results confirm that *P. menziesii* is susceptible to climatic variations (Figure 3). High *Tmax* and *VPD* values in winter and spring increase evapotranspiration and reduce soil moisture, while previous winter *PP* helps to recharge it. Thus, warm, dry conditions limit radial productivity (Figure 3), a pattern consistent with *P. menziesii* and *Pinus arizonica* in Northern Mexico.

The positive correlation between *PP* and *Tmin* in the previous winter and the first months of the current year favors radial growth (Figure 3), a pattern observed in historical records of *P. menziesii* in the *Sierra Madre Occidental* (González-Elizondo et al., 2005). However, late frosts and severe droughts can damage developing tissues and affect growth (Greenwood et al., 2017). The *Tmin* and winter *PP* from the previous year and early in the current year help retain soil moisture, promoting radial Growth (Chávez-Gándara et al., 2017). In *P. menziesii*, the *VPD* had significant negative correlations in the previous winter and spring, indicating that low water availability in the environment limits growth at the beginning of the growing season. This pattern coincides with dendroclimatic reconstructions of *P. menziesii* in the Mayo River basin, which show a positive and significant correlation with the *SPEI* (Martínez-Sifuentes et al., 2020) and with studies on *Tsuga dumosa* (D. Don) Eichler in Nepal (Bhandari et al., 2019); these results demonstrate the importance of seasonal humidity.

In this study, the correlation with the *SPEI* highlights the influence of drought on growth (Figure 4). Recent droughts that affected the growth of *P. menziesii* also impacted *P. durangensis* in the *Sierra Madre Occidental* (Cabral-Alemán et al., 2023), with similar patterns of growth reduction, although there were differences in magnitude and timing (Villanueva-Díaz et al., 2020), probably due to recent increased climate variability and the sampling strategy, resulting in reduced interannual variability and climate sensitivity of the chronologies.

During extreme droughts, the *BAI* of *P. menziesii* decreased, a pattern similar to that observed in Western Mexico (*P. menziesii*) (Castruita-Esparza et al., 2019), exhibiting greater intensity in a natural forest according to resilience parameters (Figure 8).



Dim1 = First principal component, which explains the largest proportion of the total variance; Dim2 = Second principal component, orthogonal to Dim1; *PP* = Precipitation; R_s = Resilience Index; R_c = Recovery index; R_t = Resistance index; *Tmin* = Minimum temperature; *Tmax* = Maximum temperature; *VPD* = Vapor pressure deficit; *BAI* = Basal area increase; *Prec* = Recovery period; *Nd* = Normal diameter (cm); *H* = Total height of the tree (m). Active variables in brown vectors and *BAI* as supplementary variable in blue. The gray dots represent individuals, and the vectors indicate the direction and magnitude of each variable's influence on the first two principal components.

Figure 8. Biplot of Principal Component Analysis (PCA) with *BAI* as a supplementary variable.

The years of decline coincide with droughts registered in Northern Mexico (Cook et al., 2016; Villanueva-Díaz et al., 2020). However, the resilience of *P. menziesii* was lower in 2006 and 2011, with greater recovery in more recent negative events. This downward trend in growth due to extreme droughts has been documented in Tibet, where trees exposed to recurring events show a progressive decline in resistance (Fang & Zhang, 2019), unlike European populations of *P. menziesii*, which showed greater resilience and even increased resistance under extreme drought conditions (Mondek et al., 2021; Vejpustková & Čihák, 2019). These differences could be due to the fact that in Europe these trees are cultivated in plantations, while Mexican natural populations are more vulnerable, possibly because they grow under more variable environmental conditions and without silvicultural management.

The longest recovery periods occurred during the most recent droughts (Figure 7), indicating that *P. menziesii* takes longer to recover than during historical droughts. The years of decline coincided with severe droughts in Northern Mexico, as evidenced by other pine trees (González-Tagle et al., 2024; Villanueva-Díaz et al., 2020), underscoring the vulnerability of conifers and their limited resilience to extreme water conditions (Correa-Díaz et al., 2023). Recurrent droughts progressively reduce the resilience of *P. menziesii* by causing cumulative physiological exhaustion (*e. g.*, legacy effects). Recovery periods are longer in more recent droughts (Figure 7), indicating that trees require more time to restore their growth rates. This pattern agrees with the observations of Linares et al. (2013), according to whom the age and size of trees influence their capacity for recovery; thus, larger individuals are less resistant and resilient (Serra-Maluquer et al., 2018; Thurm et al., 2016). In contrast, López-Upton et al. (2015) note that age is not always a determining factor, implying a complex interaction between environmental stress, tree structure, and growth history.

The interaction between inherited recovery periods and recurring droughts suggests that trees reduce their resistance to subsequent stress episodes (Figure 7). This behavior explains the trend toward lower resilience and coincides with patterns described in other temperate forest species (Camarero et al., 2010; Lloret et al., 2011).

This type of study has important ecological and forest management implications. Understanding how the species responds to climate variation enables us to assess its vulnerability and guide adaptive management strategies in the face of climate change. It has been suggested that thinning and stand composition can reduce water competition and the climatic dependence of growth, thereby improving tree resistance and resilience to drought (Manrique-Alba et al., 2022; Pardos et al., 2021; Rais et al., 2014).

Finally, the limitations of this study lie in its monospecific approach and the lack of integration of structural and physiological variables. Therefore, it is suggested that research be expanded to include different species and regions, and incorporate complementary approaches, such as remote sensing and xylogenesis analyses, to better understand growth processes across temporal scales. (Camarero et al., 2010).

Conclusion

Using the dendroecological approach, it was possible to quantify resilience indices. The results confirm the hypothesis that *P. menziesii* is sensitive to climate variability and drought, as shown by its reduced growth and by the impact of water availability on its *BAI*. The recovery time indicates that *P. menziesii* has prolonged periods to compensate for growth losses, highlighting its vulnerability to more frequent droughts combined with heat waves in the study area. The results constitute reliable parameters that provide solid evidence of *P. menziesii*'s ecological response to climate change, positioning it as a key bioindicator of the dynamics of temperate forests under scenarios of increasing climate variability.

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Conflict of interest

The authors declare that they have no conflict of interest.

Contributions by author

José Alexis Martínez-Rivas: Conceptualization, Investigation, Data curation, Formal analysis, Supervision, Writing – original draft; Marín Pompa-García: Conceptualization, Supervision, Writing – review & editing; Andrea Cecilia Acosta-Hernández: Investigation, Data curation, Formal analysis; Pablito Marcelo López-Serrano: Methodology, Statistical analysis; Christian Wehenkel: Methodology, Statistical analysis; Carlos Arturo Aguirre-Salado: Validation, Interpretation of results, Technical review, Writing – review & editing. All authors have read and approved the final version of the manuscript.

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