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Dendroclimatic potential of *Pinus hartwegii* Lindl. and its relationship with precipitation and temperature in the Sierra Juárez, Oaxaca, Mexico

Vázquez-González, Ana M.[1]; Barrrios-Calderón, Romeo de J.[2*]; Marroquín-Morales, Pablo[2]; Bejar-Pulido, Silvia J.[3]; Luna Robles, Erik, O.[3]; Guzmán-Santiago Juan C.[4,5]

[1] Universidad Autónoma de Nuevo León, Facultad de Ciencias Forestales. Linares, Nuevo León, México. C.P. 67700.
[2] Universidad Autónoma de Chiapas, Facultad de Ciencias Agrícolas. Huehuetán, Chiapas. C.P. 30660.
[3] Instituto Tecnológico de El Salto, El Salto, Durango, México. C.P. 34942.
[4] Centro de Investigación, Divulgación y Asesoría Técnica Forestal y Agropecuaria, Isabel la Católica, Tlaxiaco, Oaxaca, México
[5] Colegio de Postgraduados, Campus Montecillo, Km 36.5 Carr. México-Texcoco, C.P. 56264. Montecillo, Estado de México, México.
* Correspondence: romeo.barrios@unach.mx

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ABSTRACT

Objective: To assess the dendroclimatic potential of *Pinus hartwegii* Lindl in the Sierra Juárez region of the state of Oaxaca and to describe the relationship between tree-ring width and regional precipitation and temperature patterns.
Methodology: A total of 66 samples were dated, in which chronologies of total ring (RWI), early wood (EWR) and late wood (LWR) were developed covering a period of 201 years (1818 to 2019).
Results: Significant associations were found between ring growth (RWI, EWR, and LWR) and precipitation during the December-April period ($p<0.01$), with correlation coefficients of $r=0.54$, $r=0.23$, and $r=0.25$, respectively. These findings indicate that precipitation is the climatic variable most strongly associated with the radial growth of *P. hartwegii*.
Conclusions: *P. hartwegii* demonstrates strong dendrochronological potential, supported by the results of the present study where it provides chronological information of 201 years (1818 to 2019) on the radial growth of the species, determined by climatic variables, precipitation and temperature.

Keywords: Growth rings; Dendroclimatology, *Pinus hartwegii.*

INTRODUCTION

Forests around the world are under increasing pressure due to climate-induced stress factors and the growing demand for forest products (FAO, 2024). These ecosystems are home to millions of species that, in turn, influence the climate through the exchange of

water, carbon dioxide, energy, and chemical compounds with the atmosphere (Parmesan *et al.*, 2022). However, climate change —defined as significant variations in climatic parameters such as precipitation and temperature, with global warming being its most evident manifestation— has become one of the most pressing environmental issues in recent decades. The increasing frequency and intensity of droughts are disrupting ecosystem dynamics and negatively impacting forest growth (INECC, 2018; Luna *et al.*, 2022; Brichta *et al.*, 2024).

Rojas-García *et al.* (2020) point out that in natural forests, climate is the main factor regulating species growth and is responsible for the formation of tree rings. The analysis of ring growth has made it possible to improve and expand meteorological records beyond those obtained from instrumental data (Aquino *et al.*, 2019). In this regard, dendrochronological methods for historical climate reconstruction have been widely evaluated and are considered a reliable and efficient source of information (Bradley, 1999; Villanueva *et al.*, 2018; Manzanilla-Quiñones *et al.*, 2023). Specifically, tree rings serve as permanent and continuous records of the environmental conditions in which trees develop (Reyes-Basilio *et al.*, 2021). According to Manzanilla-Quiñones *et al.* (2020), the formation and thickness of tree rings are directly related to environmental, edaphic, topographic, and ecological factors of the area being evaluated. Various authors identify precipitation as the main and most limiting factor for tree growth, particularly in conifer species (Villanueva-Díaz *et al.*, 2018; Manzanilla-Quiñones *et al.*, 2020; Brichta *et al.*, 2024). Moreover, ring growth is often more evident in deep soils and areas with high light availability. Therefore, the relationship between tree growth and environmental conditions enables inferences about environmental variables based on ring width fluctuations, and even allows for the reconstruction of specific climatic variables (Gutiérrez *et al.*, 2022).

Dendrochronological studies in Mexico have primarily been documented in the north-central regions of the country, whereas studies in the southern region are limited (Aquino, 2019). The Sierra Juárez in southern Oaxaca is considered one of the most diverse mountainous systems, featuring ecosystems with high biodiversity and various vegetation types, dominated by pine-oak forests and montane cloud forests (Ponce-Reyes *et al.*, 2012). Among the most abundant species in the region is *P. hartwegii*, which has great ecological value due to its adaptability to high-altitude areas with low temperatures. Its typical altitudinal range is between 2,200 and 3,300 meters above sea level, although it may be found at elevations exceeding 3,300 meters (Pérez-Suárez *et al.*, 2022).

Pinus hartwegii Lindl. has been scarcely studied in Mexico. Its importance in dendrochronology lies in the fact that it is considered a subalpine species that develops in pure forests above 3,000 meters above sea level, where its growth rings are well-defined (Astudillo-Sánchez *et al.*, 2017; Manzanilla-Quiñones *et al.*, 2021). This species exhibits great longevity, surpassing 400 years (Villanueva-Díaz *et al.*, 2015), and shows a high physiological responsiveness to climatic factors. Consequently, it serves as a valuable proxy for climatic variation, from which relevant climate information can be extracted using dendrochronological techniques (Astudillo-Sánchez *et al.*, 2017). Based on the above, the objective of this study was to determine the dendroclimatic potential of *Pinus hartwegii*

Lindl. in the Sierra Juárez of the state of Oaxaca, as well as to describe the relationship between ring width and regional precipitation and temperature patterns.

MATERIALS AND METHODS

Study Area

The study was conducted in Santa María Jaltianguis, located in the northern part of the Sierra Juárez in the state of Oaxaca (Figure 1). The vegetation of the sites consists of coniferous forests dominated by pine and pine-oak forests. The climate is temperate subhumid with summer rainfall and warm subhumid with summer rainfall, with temperatures ranging from 26 to 32 °C and an average annual precipitation of 1,448 mm. The soil in the study area belongs to the Acrisol group (Aquino *et al.*, 2025). Sampling sites were located in specific distribution areas where *Pinus hartwegii* Lindl. is the dominant species, at an altitude between 3,000 and 3,100 meters above sea level.

Sampling Design and Sample Collection

Using selective sampling, 66 mature *P. hartwegii* trees were selected, characterized by sparse, thin branches, free of pests and diseases, without mechanical damage, and with minimal disturbance in the stand. Two to three growth cores per tree were extracted using Pressler increment borers (Haglöf brand) with a 5 mm internal drill diameter and 48 cm length. Samples were taken at a height of 40 cm above the ground (Contreras-Mata *et al.*, 2024).

Sample Processing and Measurement

The cores (samples) were placed in grooved molds and secured with glue and adhesive tape. They were then subjected to a sanding process, which enhances the visibility of the growth rings. Samples were processed following standard dendrochronological techniques (Stokes & Smiley, 1968).

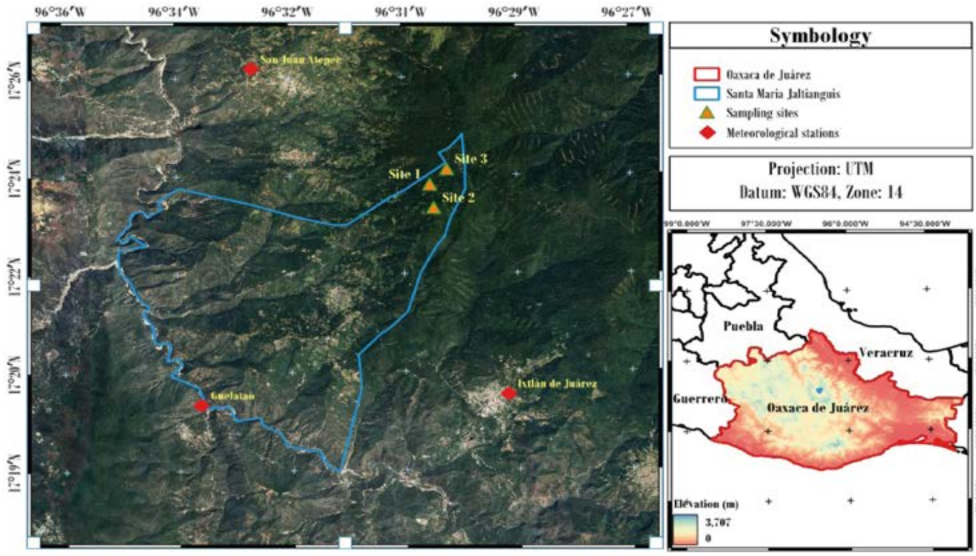

Figure 1. Geographic location of the study area.

Growth Ring Dating

Using a Velmex stereomicroscope with a resolution of 0.001 mm, the growth rings of each sample were counted, and the widths of earlywood and latewood in each growth ring were measured to obtain the total ring width. These measurements were conducted in the Dendrochronology Laboratory of the Faculty of Forestry Sciences at the Autonomous University of Nuevo León. Subsequently, the quality of the dating was verified using the COFECHA program, correlating growth cores in 50-year subperiods with 25-year overlaps (Pompa-García and Camarero-Martínez, 2015).

Chronology Development and Dendroclimatic Potential Determination

To remove growth trends and environmental factors unrelated to climate, a preliminary standardization of the growth ring width measurements was performed using the ARSTAN program to determine the dendroclimatic potential of *P. hartwegii*. A double standardization of the growth rings was applied to improve the fit, consisting of a cubic smoothing spline that preserved 50% of the variance contained in the series. The ring width was divided by the value of the fitted curve, transforming the increments into ring-width indices (RWI), which allowed comparison of growth series of different ages.

Using the RWI values, an annual chronology was generated based on the standard and residual chronologies provided by ARSTAN. According to Contreras-Mata *et al.* (2024), these statistics help eliminate endogenous effects caused by stand disturbance and maximize the common climatic signal contained in the growth rings.

Evaluation Criteria of the *P. hartwegii* Chronology

Several parameters of the chronology were determined to assess the species' response and sensitivity to climatic variables (Buras, 2017):

- Inter-series correlation: indicates the intensity of the climatic signal that is common at the tree population level.
- Mean sensitivity: relative change in ring width from one year to the next.
- Standard deviation: variation in ring width growth.
- First-order autocorrelation: influence of the previous year's ring growth on the width of the following year's ring; low values reflect greater year-to-year growth variability.
- Signal-to-noise ratio: proportion of the climatic signal relative to other non-climatic factors.
- Expressed Population Signal (EPS): indicates the intensity of the climatic signal expressed by the population as it approaches the oldest segment of the chronology.

Relationship between radial growth and regional climate

To analyze the influence of climate on the radial growth of *P. hartwegii*, the annual RWI was correlated with the series of mean annual precipitation and temperature values. This allowed for the determination of the climatic influence on ring width (Arroyo-Morales *et al.* 2023). Precipitation and temperature data were obtained from meteorological stations near the study sites with complete and reliable climate records (Table 1).

Table 1. Meteorological stations with complete data near the sampling sites.

Station	Latitude (N)	Longitude (W)	Altitude (m)	Period (years)
Guelatao	17° 19' 49"	96° 33' 51"	1496	1955-2002
Ixtlán de Juárez	17° 19' 59"	96° 28' 59"	2312	1955-2002
San Juan Atepec	17° 25' 59"	96° 32' 59"	1975	1955-2002

RESULTS AND DISCUSSION

Table 2 presents the results obtained from the COFECHA program, showing that 66 cores from 45 trees were successfully dated, corresponding to 86.8% of the total analyzed sample. The remaining cores were discarded due to growth anomalies, such as sections with ring compression and release pulses that prevented the identification of the beginning and end of the growth rings (Urquijo *et al.*, 2022). According to the parameters obtained from COFECHA and ARSTAN, *Pinus hartwegii* has high dendrochronological potential for the reconstruction of climatic events (Acosta-Hernández *et al.*, 2017).

According to Díaz-Ramírez *et al.* (2016), the above results exceed the parameters reported in various studies on conifer species. Specifically for *P. hartwegii*, the interseries correlation is notably higher compared to the results obtained by Astudio-Sánchez *et al.* (2016). The total ring-width dendrochronological series spans from 1810 to 2020 (210 years in length). The most suitable period for climate reconstruction (chronological reliability) extends from 1888 to 2020 and includes more than 10 radii, with an EPS of 0.86, surpassing the 0.85 threshold (Wigley *et al.*, 1984). Manzanilla-Quiñones *et al.* (2020) indicate that EPS is evaluated on a scale from 0 to 1; therefore, values above 0.80 are considered acceptable and recommended (Figure 2).

Response Function

Climatic data from the region and the analysis of the residual chronology from 1955 to 2002 were positively correlated with three meteorological stations: Ixtlán de Juárez,

Table 2. Statistical results generated by the COFECHA program for the ring width of *P. hartwegii*.

Statistics	Values obtained	Range (Astudillo-Sánchez *et al.*, 2016)	Range (Manzanilla-Quiñones *et al.*, 2020)
Number of dated series	66	104	78[1], 26[2] y 25[3]
Intercorrelation between series	0.57	0.50	0.58[1], 0.51[2] y 0.41[3]
Master series	201 años (1818- 2019)	307 años (1705-2012)	147 años (1869-2016)[1] 158 años (1858-2016)[2] 142 años (1874-2016)[3]
Average sensitivity	0.31	0.32	0.31[1], 0.24[2] y 0.23[3]
Average ring width	105 años	---	---
Standard deviation of ring width	0.21	---	---
First-order autocorrelation	0.39	---	0.24[1], 0.10[2] y -0.15[3]
Signal-to-noise ratio	12.15	---	9[1], 12[2] y 18[3]
Expressed population signal (ESP)	0.86	0.85	0.80

[1]=Nevado de Colima, [2]=Nevado de Toluca y [3]=Pico de Orizaba (Manzanilla-Quiñones *et al.*, 2020). --- Without data.

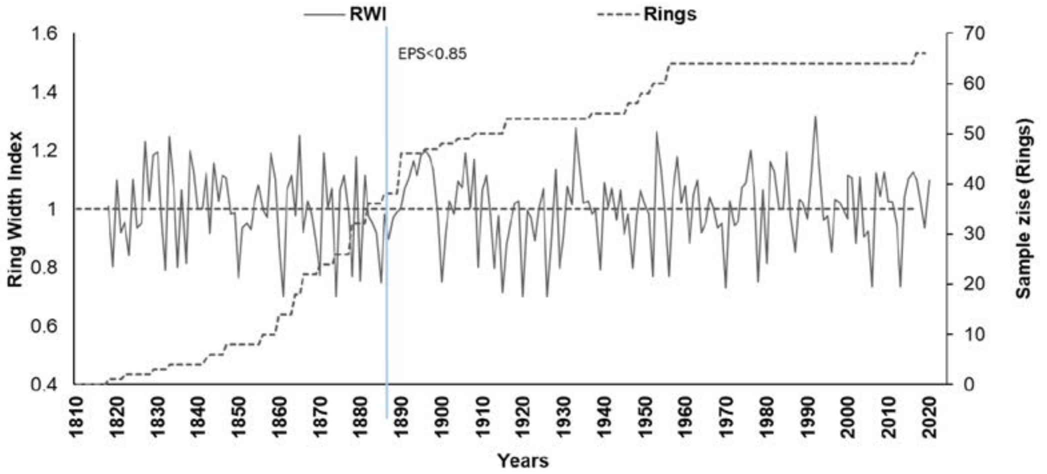

Figure 2. Residual chronology of total ring width (RWI) for *Pinus hartwegii* Lindl. (solid line) and sample size (dotted line). The blue line indicates the year from which the chronology exceeds the EPS value of 0.85. The dashed black line represents the threshold for a significant confidence level ($p<0.05$).

Atepec, and Guelatao. These stations are located within a radius of approximately 100 km. In general, the correlation between the residual chronology and precipitation with ring width was negative in the months of June, July, September, and December (−0.11, −0.03, −0.04, and −0.43); the rest of the months showed positive correlations, with December being the most significant. Temperature correlated negatively throughout all seasons, with January showing the highest significance (−0.27) (Figure 3).

In relation to earlywood, it showed a similar behavior with precipitation, except for September; temperature was correlated with the records for the month of April (−0.38) (Figure 4).

Finally, latewood showed a positive relationship with precipitation except for the months of May, November, and December (−0.02, −0.07, and −0.24). Regarding temperature, the correlation was negative throughout the year, with April showing the strongest effect (−0.38) (Figure 5).

In general, the accumulated seasonal precipitation between January and April showed a significant correlation with the residual chronology of the three variables analyzed.

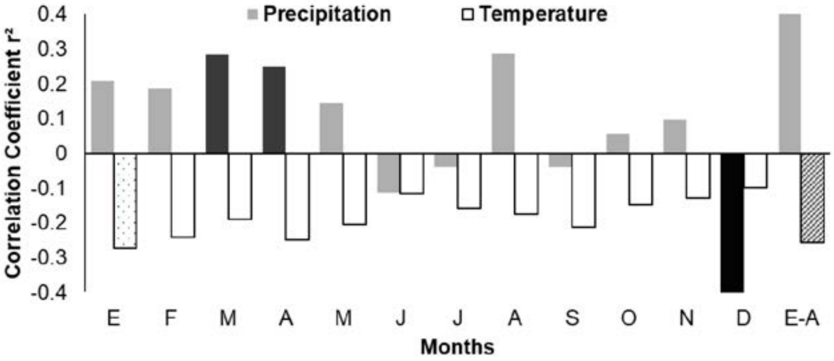

Figure 3. Response function of the residual chronology with precipitation and temperature correlated to ring width (RWI) for the period 1955-2002.

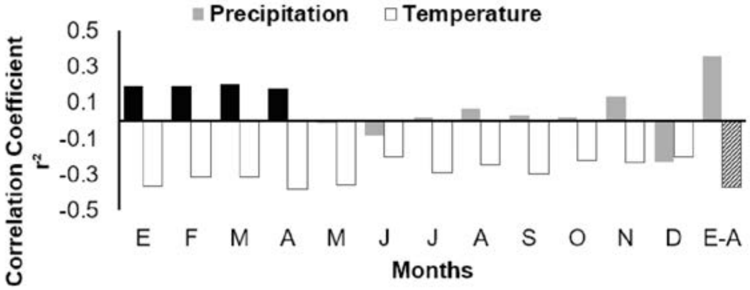

Figure 4. Response function of the residual chronology of precipitation and temperature with earlywood (EWR) for the period 1955-2002.

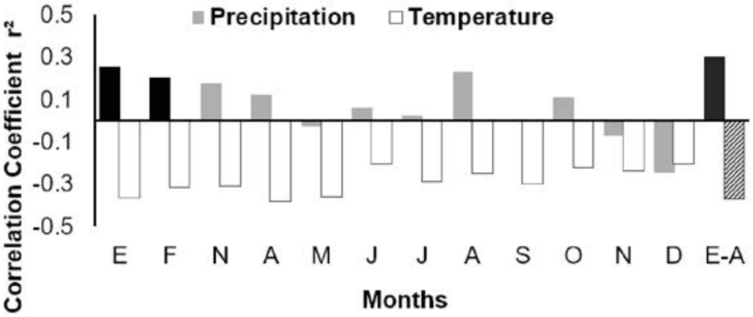

Figure 5. Response function of the residual chronology of precipitation and temperature with latewood (LWR) for the period 1955-2002.

Specifically, total ring width exhibited a significant negative correlation with precipitation ($r=-0.54$), while earlywood ($r=0.36$) and latewood ($r=0.31$) showed significantly positive correlations. These results are consistent with Astudillo-Sánchez *et al.* (2016) for *P. hartwegii* in Nevado de Toluca and Monte Tlaloc, where they found a pattern of relationships between climate and tree growth with positive associations to precipitation and negative associations to temperature, highlighting a stronger relationship between precipitation and species growth.

On the other hand, the residual correlations of maximum temperature from January to April with total ring width ($r=-0.26$), earlywood ($r=-0.37$), and latewood ($r=-0.37$) were significantly negative ($p<0.05$). These associations with total ring width, earlywood, and latewood growth have been reported by various authors who developed dendrochronological networks in conifers (Selem *et al.*, 2015; Villanueva *et al.*, 2015; Villanueva-Diaz *et al.*, 2018).

The standard chronology data of the total ring indicate that precipitation from December to April during the period 1955-2002 ($r=0.54$, $p<0.01$) explains up to 54% of the annual growth of *P. hartwegii* (Figure 6). These results are similar to those reported by Manzanilla-Quiñonez *et al.* (2020), who found a 53% variation in December for *P. hartwegii* at Pico de Orizaba in Veracruz. Additionally, it has been reported that the growth of *P. hartwegii* begins from March to April and ends in October-November (Biondi *et al.*, 2005). In this regard, Aquino *et al.* (2019) mention that the first months

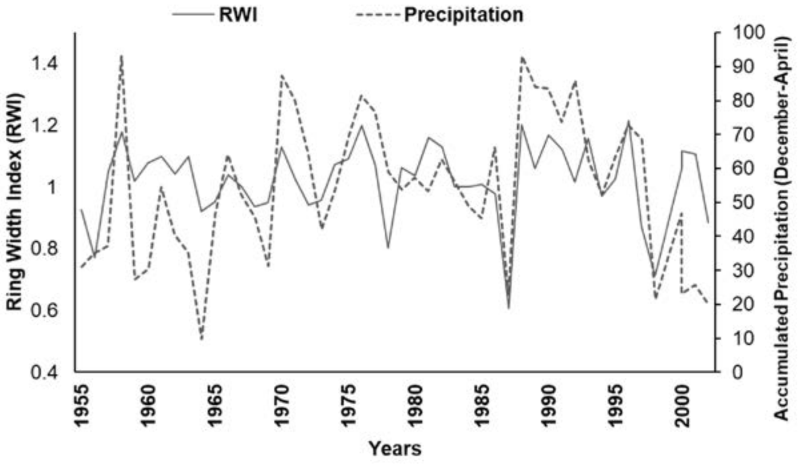

Figure 6. Association between the total ring index and accumulated precipitation from December to April using meteorological station records for the period 1955-2002.

of the year show the most significant correlations with radial growth in pines, which coincides with the results of the present dendrochronological analysis. However, the increase in temperature affects radial growth (Lo *et al.*, 2010). For instance, Astudillo-Sánchez *et al.* (2019) report that in Mexico the rise in temperature was beneficial for the growth of *P. hartwegii*. The relationship of radial growth indicates an association that is regulated and mainly limited by the availability of rainfall during the winter-spring season, as it occurs with sufficient intensity to retain soil moisture. Díaz-Ramírez *et al.* (2016) state that precipitation influences up to 52% of radial growth. This has been documented in various dendrochronological analyses in North America (Gutiérrez-García and Ricker, 2019; Cerano-Paredes *et al.*, 2014; Aquino *et al.*, 2019; Manzanilla-Quiñonez *et al.*, 2020).

CONCLUSIONS

Pinus hartwegii shows dendrochronological potential, supported by the results of the present study which provides a 201-year chronology (1818 to 2019) on the radial growth of the species, determined by climatic variables such as precipitation and temperature.

The total ring width, earlywood, and latewood have a high potential (54%) to explain the growth of *P. hartwegii* in relation to climatic variables.

The parameters obtained from the *P. hartwegii* series reveal a reliable dating with a strong annual growth signal. The variable with the greatest influence on this growth is winter-spring precipitation; additionally, maximum temperature was negatively associated, implying that as maximum temperature increases, radial growth decreases.

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