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TEMPORAL VARIATION OF THE RESILIENCE OF *Pinus durangensis* MARTÍNEZ TO EXTREME CLIMATE EVENTS IN NORTHERN MEXICO

VARIACIÓN TEMPORAL DE LA RESILIENCIA DE *Pinus durangensis* MARTÍNEZ ANTE EVENTOS CLIMÁTICOS EXTREMOS EN EL NORTE DE MÉXICO

THESIS

That as a partial requirement to obtain the degree of:

DOCTOR EN CIENCIAS EN RECURSOS NATURALES Y MEDIO AMBIENTE EN ZONAS ÁRIDAS

By:

CITLALLI CABRAL ALEMÁN

Under the supervision of:

JOSÉ VILLANUEVA DÍAZ, Ph.D.

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TEMPORAL VARIATION OF THE RESILIENCE OF *Pinus durangensis* MARTÍNEZ TO EXTREME CLIMATE EVENTS IN NORTHERN MEXICO

Thesis carried out by **Citlalli Cabral Alemán** under the direction of the indicated Advisory Committee, approved by it and accepted as a partial requirement to obtain the degree of:

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DEDICATORIA

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GENERAL SUMMARY

Temporal variation of the resilience of *Pinus durangensis* Martínez to extreme climate events in northern Mexico

Understanding, predicting, and quantifying the tree growth response o to extreme drought events is of great interest. The main objective of this study was to evaluate the temporal variation of the resilience of Pinus durangensis to extreme climatic events. 286 cross-sections of *P. durangensis* were analyzed using conventional dendrochronological techniques. In addition, total ring width, earlywood, and latewood chronologies were generated, spanning 296 years. The association between the tree-ring series and drought was analyzed through the Standardized Precipitation-Evapotranspiration Index (SPEI). The residual earlywood chronology showed the greatest association with the six-month cumulative SPEI for February-May (SPEI6FM). This allowed the reconstruction of 296 years of the SPEI6FM, where 18 % were classified as wet years, 16 % were dry, and 66 % presented average values. Subsequently, the radial growth of 200 cross-sections extracted at different heights from the stem of P. durangensis trees was analyzed and ring-width indices (RWI) were generated. Seven extreme drought events were identified and the annual radial growth before, during, and after each drought event was determined. Based on the RWI values, resistance, recovery, and resilience indices were calculated. The results indicated a significant correlation ($p \leq 0.05$) between the annual radial increase and drought along the stem (0.56—0.80). The climatic sensitivity was higher in the lower part of the stem. The values of the resistance index ranged between 0.44 and 0.76 and were better expressed in the highest sections of the stem. Resilience indices changed over time. Regardless of the height of the tree trunk, recent extreme drought events have caused a lower resilience of the trees, indicating a decrease in their capacity for recovery. These results represent an advance in the understanding of the tree growth behavior along the stem, laying the foundations for future studies on this and other tree species in Mexico.

Keywords: drought, recovery, resistance, tree-rings, SPEI, tree growth.

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RESUMEN GENERAL

Variación temporal de la resiliencia de *Pinus durangensis* Martínez ante eventos climáticos extremos en el norte de México

Comprender, predecir y cuantificar la respuesta del crecimiento de los árboles a eventos de sequía extrema es de gran interés. El objetivo principal de este estudio fue evaluar la variación temporal de la resiliencia de *Pinus durangensis* a eventos climáticos extremos. Se analizaron 286 cortes transversales de *P. durangensis* utilizando técnicas dendrocronológicas convencionales. Además, se generaron cronologías de ancho de anillo total, madera temprana y madera tardía, que abarcan 296 años. La asociación entre la serie de anillos de árboles y la sequía se analizó mediante el Índice Estandarizado de Precipitación-Evapotranspiración (SPEI). La cronología residual de la madera temprana mostró la mayor asociación con el SPEI acumulado de seis meses para febrero—mayo (SPEI6FM). Esto permitió la reconstrucción de 296 años del SPEI6FM, donde el 18 % se clasificó como años húmedos, el 16 % como años secos y el 66 % presentó valores medios. Posteriormente, se analizó el crecimiento radial de 200 secciones transversales extraídas a diferentes alturas del fuste de árboles de *P. durangensis* y se generaron índices de ancho de anillo (RWI). Se identificaron siete eventos de sequía extrema y se determinó el crecimiento radial anual antes, durante y después de cada evento de sequía. Con base en los valores RWI, se calcularon índices de resistencia, recuperación y resiliencia. Los resultados indicaron una correlación significativa ($p \leq 0.05$) entre el incremento radial anual y la sequía a lo largo del tallo (0.56—0.80). La sensibilidad climática fue mayor en la parte inferior del tallo. Los valores del índice de resistencia oscilaron entre 0.44 y 0.76 con los mayores valores en la parte superior del fuste. Los índices de resiliencia cambiaron con el tiempo. Independientemente de la altura del tronco del árbol, los recientes eventos de sequía extrema han provocado una menor resiliencia de los árboles, lo que indica una disminución en su capacidad de recuperación. Estos resultados representan un avance en la comprensión del comportamiento de crecimiento de los árboles a lo largo del fuste, sentando las bases para futuros estudios sobre esta y otras especies arbóreas en México.

Palabras clave: sequía, recuperación, resistencia, anillos de crecimiento, SPEI, crecimiento de los árboles.

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CHAPTER I: GENERAL INTRODUCTION

1.1. Introduction

Forest ecosystems cover approximately one third of the earth's surface (4,060 million of hectares), providing multiple environmental services such as the production of raw materials, soil conservation, carbon capture and storage, among other benefits (FAO, 2020). These services represent key factors to ensure the integrity and sustainability of the future of humanity, acting as natural climate regulators and cushioning the impacts caused by extreme natural phenomena (Mori et al., 2017; PROFEPA, 2020).

In the last decades it has been evidenced that natural disturbances (wildland fires, insect outbrakes, droughts) and human activities (greenhouse gas emissions, land-use change, deforestation) have produced negative effects on the ecological process characterizing the forest ecosystems (Malhi et al., 2008; Miles and Kapos, 2008; Thompson et al., 2016; Cai and Chang, 2020). In addition, such activities have contributed to accelerate global warming (Allen et al., 2010; IPCC, 2014; Roshani et al., 2022).

The effects of global warming have been reflected in climate variability, with an increase in temperature and a decrease in precipitation (Xu et al., 2020). As a result, extreme weather events, such as heat waves and droughts, are expected to occur with greater frequency and intensity, causing direct effects on forest dynamics (Allen et al., 2010; Clark et al., 2016; Piraino, 2020).

Extreme drought events are direct drivers in the reduction of productivity and affecting the carbon balance, causing forest decline, and an increase in mortality of different forest species (Camarero et al., 2015; Moreno -Fernández et al., 2021; Piraino et al., 2022). Therefore, understanding, predicting, and quantifying the response of different forest species to extreme drought events is one of the main areas of interest in scientific research (Allen et al., 2010; Khoury and Coomes, 2020; Schwarz et al., 2020).

In this sense, resilience and its components (resilience, resistance and recovery), have been widely used to analyze the response of tree growth before and after extreme drought episodes (Lloret et al., 2011; Camarero et al., 2018; Schwarz et al., 2020; de Andrés et al., 2022). Resilience is understood as the ability of ecosystems to recover their functionality before disturbance (Lloret et al., 2011; Allen et al., 2019) and is the result of the interaction of different biotic and abiotic factors, at different scales: spatial and temporal scales (Carnicer et al., 2021; Piraino et al., 2022).

The response of trees to extreme drought events has been evaluated at different time scales (decades to millennia) thanks to the analysis of tree-rings (Salzer and Kipfmueller, 2005; Ma et al., 2015; Stahle et al., 2016). Therefore, based on tree rings, it has been possible to analyze historical patterns of resilience and its components from the indices proposed by Lloret et al. (2011). These indices have been used to quantify the resilience of different forest species present in different parts of the world (Gomes-Márquez et al., 2018; Camarero et al; 2018; Fang and Zhang, 2019; Schwarz et al., 2020). However, this type of research in Mexico is still scarce.

Mexico has around 42% of the species of the genus *Pinus* in the world, of which 55% are endemic. For this reason, Mexican pines are considered important valuable natural resource in genetic, economic and environmental terms (Sánchez-González, 2008). Within these species, *Pinus durangensis* Martínez, is considered one of the most important species for its ecological and economic value in northern Mexico, due to its dominance and valuable characteristics of its wood (Monárrez-González et al., 2020; Graciano- Avila et al., 2020). In addition, it has been proven that its annual radial growth is sensitive to climatic variations (Villanueva-Díaz et al., 2014; Díaz-Ramírez et al., 2016).

1.2. General objective

To evaluate the temporal variation of the resilience of *Pinus durangensis* Martínez to extreme climatic events in northern Mexico.

1.2.1. Specific objectives

a) To reconstruct droughts based on SPEI from tree rings of Pinus durangensis collected at a site in northern Mexico.

b) To estimate the resilience indices at different stem heights of *Pinus durangensis* trees at a site in northern Mexico.

1.3. Hypothesis

a) *Pinus durangensis* is sufficiently sensitive to drought in such a way that the evolution of its radial growth is statistically correlated with the SPEI.

b) Resilience indices estimated for extreme drought events differ along the stem height.

c) The increase in the frequency and intensity of droughts recorded in recent decades has reduced the resilience of *Pinus durangensis* to drought.

1.4. Thesis structure

This thesis document is divided into several chapters. In Chapter I, a general introduction is presented; Chapter II deals with the theoretical framework related to the effects of climate on forest species. Chapter III shows the first scientific paper in which the first specific objective is addressed describing the reconstruction of the Standardized Precipitation-Evapotranspiration Index (SPEI), through the analysis of the tree-rings of *P. durangensis* for the western region of the state of Durango, Mexico. Chapter IV presents the second scientific paper addressing the second specific objective. In this article, seven extreme drought events were identified and used to evaluate the response of the *Pinus durangensis* annual radial growth at different heights of the stem, through the estimation of resilience indices. Finally, Chapter V includes the general conclusions of this thesis.

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CHAPTER II: THEORETICAL FRAMEWORK

2.1. Impact of climate change on ecosystems

The World Meteorological Organization (WMO) has reported the last decade (2011-2020) as the warmest since pre-industrial times (1850-1900), with an approximate increase of 1.2 °C in global temperature and it is expected that by 2024 the increase will exceed 1.5 °C (IPCC, 2014; WMO, 2021). These changes have altered climate variability, with more frequent extreme weather events such as heat waves and severe droughts (Anderegg et al., 2015).

The increase in the frequency and intensity of extreme weather events will cause ecosystems to exceed critical thresholds, causing changes in their dynamics, with consequences that will compromise the survival of living beings (Scheffer et al., 2001; IPCC, 2018; Piraino et al., 2022). Especially, forest ecosystems have been seriously affected by climatic extremes, with changes in their functioning and biodiversity, which compromises the provision of basic goods and services (Ding et al., 2016).

Forests cover approximately one-third of the earth's surface and are home to more than 80% of the planet's terrestrial biodiversity (FAO, 2020; FAO, 2022). In addition, their interaction with the atmosphere through the exchange of energy, water, and chemical components, represents a high potential to face the effects of climate change (Bonan, 2009).

Forests are recognized as natural carbon capture and storage systems, which identifies them as natural regulators of global temperature (CONAFOR, 2017). Currently, they store more than half of the world's carbon reserves (662,000 million tons) (FAO, 2022). Therefore, evaluating the response of forests to current climate extremes has positioned itself as one of the main areas of scientific interest (Nimmo et al., 2015; Camarero et al., 2015; Falk et al., 2022).

2.2. Droughts: major drivers of forest dynamics

The increase in the severity of meteorological disturbances has caused changes in the dynamics of ecosystems. However, extreme drought events are recognized as one of the main drivers of forest dynamics, mainly affecting tree growth (Allen et al., 2010; Camarero et al., 2015; Piraino et al., 2022).

Drought is a phenomenon caused by the intense and prolonged scarcity of rainfall, with negative implications in the different sectors, ecological, economic, and social (Vicente-Serrano et al., 2010; Zargar et al., 2011). The reduction in forest production, increase in fire severity, dieback and increased mortality (from individual tree level to stand level) are among the main responses of trees to extreme drought events (Camarero et al., 2018; Value et al., 2020).

During the last decades, extreme drought events have increased in frequency and intensity (Díaz-Ramírez et al., 2016; Tirivarombo et al., 2018; Martínez-Sifuentes et al., 2020), which is why it is of great importance to improve the understanding of natural climate variability over time. Droughts are difficult to characterize in terms of intensity, duration, and spatial extent (Vicente-Serrano et al., 2010). However, in recent years techniques have been developed to study and monitor these variables (Zargar et al., 2011).

2.2.1. Drought indices

Drought indices arise as a response to the need for an adequate definition of the phenomenon and have been in constant evolution in recent decades (Heim, 2002; Zargar et al., 2011). These indices have been used to characterize droughts, with the main objective to determine the beginning, end, and intensity of each event (Kchouk et al., 2022).

A drought index integrates different meteorological and hydrological parameters (precipitation, temperature, evapotranspiration, runoff, among others) into a single numerical value. The value obtained from the estimation of an index is easier to interpret than the raw data, which represents a basic tool in planning and decision-making regarding the prevention and mitigation of the effects of drought events (Eslamian et al., 2017).

There are a large number of indices for the representation of a drought. However, the subjectivity surrounding the concept of drought makes it difficult to establish a unique and universal drought index (Vicente-Serrano et al., 2010; Zargar et al., 2011).

The Palmer Drought Severity Index

The Palmer Drought Severity Index (PDSI) was developed by Palmer (1965) and is based on the supply and demand concepts of the water balance equation. The variables incorporated for its estimation are previous and current humidity (precipitation), humidity supply, runoff and potential evapotranspiration (Alley, 1985; Vicente-Serrano et al., 2011; Dai, 2011). However, the PDSI is based on a fixed time scale and an autoregressive characteristic, whereby the index values are affected by conditions up to four years in the past (Guttman et al., 1992).

The Standardized Precipitation Index

The Standardized Precipitation Index (SPI) was developed by McKee et al. (1993), with the main objective of establishing an indicator that would serve as a versatile tool for monitoring and analyzing droughts. Unlike the PDSI, the SPI incorporates cumulative precipitation deficits on various spatio-temporal scales, which identifies it as a multiscalar index (Hou et al., 2007). The SPI allows an adequate understanding of droughts, regarding their duration, magnitude and spatial extension, which makes it possible to identify the beginning and end of drought episodes (Karavitis et al., 2011). However, it is a simplified index that incorporates precipitation as the only input variable (Vicente-Serrano et al., 2010).

The Standardized Precipitation-Evapotranspiration Index

Although droughts are controlled to a greater extent by precipitation variability, temperature variation is of vital importance in determining the severity of drought events. For this reason, the use of drought indices that include temperature data in their formulation is more appropriate to identify the impacts of drought-related to warming in different ecological, hydrological, and agricultural systems. (Vicente-Serrano et al., 2012).

The Standardized Precipitation-Evapotranspiration Index (SPEI) was developed by Vicente-Serrano et al. (2010), and offers an advantage over the rest, because it integrates the multiscalar nature of the SPI and the sensitivity of the PDSI to changes in potential evapotranspiration based on the water balance equation (Vicente-Serrano et al., 2012).

2.3. Forest resilience to drought

The response of forests to drought events depends on various factors such as the characteristics of the trees (species, age), the site (topography, climate, structure, and competition), and the drought (intensity, duration, and frequency) (Gazol et al., 2017; Gomes-Marques et al., 2018; Zhang et al., 2022). This response is reflected in the resilience of tree growth (Piraino et al., 2022). For this reason, quantifying and understanding the effects of drought on the growth of different species and as many biomes as possible has been considered a primary topic of current research (Camarero et al., 2018; Schwarz et al., 2020; Falk et al., 2022).

The response of the forest, through tree growth, to extreme drought events can be evaluated in terms of resistance (*Rt*) and recovery (*Rc*), considered components of resilience (*Rs*). Lloret et al. (2011) proposed indices of aforementioned components based on observed growth, before, during, and after the disturbance. *Rs* is the ability of the tree to withstand drought with minimal growth reduction, *Rc* represents the extent to which trees return to their original condition after a disturbance, and *Rs* refers to the tree's ability to sustain growth. after the disturbance (Lloret et al., 2011; Castagneri et al., 2021; Manrique-Alba et al., 2022).

These indices have been widely reported to analyze the response of different forest species in different biomes (Sánchez-Salguero et al., 2018; Valor et al., 2020; Schwarz et al., 2020).

2.4. Tree-rings to assess the resilience of forests

Indices to quantify resilience in forest ecosystems have been determined from two main approaches: tree-ring analysis (Du et al., 2022; Belokopytova et al., 2022; Manrique-Alba et al. 2022) and satellite images (Gazol et al., 2017; Urrutia-Jalabert et al., 2021). However, ring-width chronologies provide information on the growth response to drought at the individual tree level (Camarero et al., 2015) and allow estimation of resilience indices on decadal to millennial time scales (Villanueva-Díaz et al. al., 2011). In addition, the analysis of the radial growth of individual trees and their response to climatic variables constitute a basis for evaluating the response of forests to future climate scenarios (Zhang et al., 2022).

Currently, dendrochronological methods have been widely used to reconstruct the resilience of trees to drought events in different parts of the world (Lloret et al., 2011; Gomes-Marques et al., 2018; Valor et al., 2020; Schwarz et al., 2020; Piraino et al., 2022). However, in Mexico, this type of analysis is still scarce.

2.5. *Pinus durangensis* Martínez

Pinus durangensis Martínez is an endemic species of Mexico and is considered one of the most important species in the north of the country due to its ecological and economic value (García & González, 2003; Hernández-Salas et al., 2013; Monarrez-Gonzalez et al. al., 2020). Due to its distribution and quality of wood, it is considered one of the most important timber species in the Sierra Madre Occidental (Perry, 1991; Pompa-García et al., 2009; Hernández-Velasco et al., 2016). However, extensive harvesting has placed it on International Union for Conservation of Nature's (IUCN) “Near Threatened” status (Farjon, 2013; Simental-Rodriguez et al. 2021). In addition, its proven sensitivity to climatic variations (Díaz-Ramírez et al., 2016), justifies its use in the present investigation.

2.5.1. Botanical characteristics

The *Pinus durangensis* trees can be 12—25 m tall and 20—80 cm in diameter. The bark is dark gray to black when young and with reddish plates 4-5 cm thick, forming deep grooves when mature. The leaves are grouped in fascicles of 3-5, characterized by a lemon green color, they are thin and flexible, 11—18 cm long, with finely serrated margins, with 2—4 resin canals and 2 vascular bundles. The cones are oval shaped, 6—8 cm long, and 3—6 cm wide (García & González 2003; De la Paz-Pérez and Olvera & Dávalos Sotelo, 2016).

2.5.2. Ecological distribution

P. durangensis has a wide distribution in the Sierra Madre Occidental, covering the states of Chihuahua, Durango, and Sonora, and is located at altitudes above 2000 m a.s.l. This species is characterized by forming pure and mixed stands on slopes with a slight slope and a relatively humid climate. It can be found in association with *Pinus cooperi*, *Pinus teocote*, *Pinus leiophylla* and *Quercus sideroxyla* (González-Elizondo et al., 2012).

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CHAPTER III: RECONSTRUCTION OF THE STANDARDIZED PRECIPITATION-EVAPOTRANSPIRATION INDEX FOR THE WESTERN REGION OF DURANGO STATE, MEXICO

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Article

Reconstruction of the Standardized Precipitation-Evapotranspiration Index for the Western Region of Durango State, Mexico

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Abstract: In recent decades, droughts associated with climate change have increased in frequency and intensity. Given this trend, the understanding of climate variability over time has raised great interest. The main objective of this study was to reconstruct the standardized precipitation-evapotranspiration index (SPEI) from tree rings of *Pinus durangensis* Martinez at a representative site in the western region of the Durango State, Mexico. To this end, we used radii of 286 cross-sections, which were processed through conventional dendrochronological techniques. In addition, chronologies of total ring and early and latewood were generated, covering 296 years. In parallel, we analyzed the association between the chronologies obtained and the cumulative SPEI for 3, 6, 9, and 12 months. The earlywood residual chronology (EWres) showed the closest association with the six-month cumulative SPEI for February–May ($SPEI6_{FM}$). Thus, the $SPEI6_{FM}$ for the past 296 years was reconstructed through a simple linear regression model. In this reconstruction, 18% of the years were wet, 16% dry, and 66% average. In addition, an increase in the frequency of droughts was observed from 1880 onwards, which might have been related to the rise in temperature due to climate warming. Therefore, the annual rings of *P. durangensis* are suitable for use as a proxy for the reconstruction of historical climatic events in this region of northern Mexico.

Keywords: climate change; dendroclimatology; *Pinus durangensis* Martinez; SPEI; climate variability

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1. Introduction

The rise in global temperature in response to climate change has led to a marked increase in the frequency and intensity of drought in recent decades [1–3]. Droughts caused by the prolonged absence of precipitation, combined with increased evaporation, have negatively impacted both society and the environment [4–6]. In particular, forests are among the ecosystems most affected by this phenomenon, which causes severe impacts such as reduced productivity [7] and increased intensity and frequency of fires [8,9].

Given this situation, improving our understanding of natural climate variability over time is of great interest. However, this is a complex task because our knowledge of past climate conditions is limited by the lack of historical climate records [10,11]. In Mexico, weather data come from meteorological stations with records covering less fewer

75 years [12]. Consequently, instrumental records can only provide limited information regarding climate variability, including droughts.

In recent decades, it has been demonstrated that tree rings are a suitable proxy for the historical reconstruction of climatic variability. In Mexico, tree rings of forest species have been used to reconstruct precipitation [13,14], temperature [15], surface runoff [16,17], and droughts [18,19], among other climatic variables.

Droughts are difficult to characterize in terms of intensity, duration, and spatial extent [5]. However, in recent years, techniques have been developed to study and monitor these variables [20]. These techniques include drought indices, which are an effective method for analyzing this phenomenon [9]. In addition, there is a large number of drought indices [6,20]. Among the most widely used indices is the Palmer Drought Severity Index (PDSI) [21] and the Standardized Precipitation Index (SPI) [22]. For its part, the PDSI is based on the water balance equation and on a fixed time scale. However, droughts are known to be a multiscale phenomenon. In this sense, the SPI is a multiscale and widely accepted index, but its main disadvantage is that it does not include temperature, which strongly affects the severity of droughts. In this way, the SPEI tries to overcome these limitations by combining the multiscale nature of the SPI and the water balance equation used in the PDSI [5].

Therefore, the main objective of this study was to reconstruct droughts based on the SPEI from tree rings of *P. durangensis* collected in the San Diego de Tezains site, in the municipality of Santiago Papasquiaro, Durango, Mexico. The working hypothesis was that *P. durangensis* is sufficiently sensitive to drought so that the evolution of its radial growth is closely correlated with the SPEI.

2. Materials and Methods

The San Diego de Tezains site is located in the northwestern region of the state of Durango, in the Sierra Madre Occidental, between coordinates 24°48′16.98″ N, 25°12′38.91″ N and 106°12′37.63″ W, 106°12′25.58″ W. It stretches across the municipalities of Tepehuanes, Topia, Canelas, Otaez, and Santiago Papasquiaro, the latter comprising the largest surface area (Figure 1a).

The predominant climate is temperate with rains in the summer. The mean annual precipitation ranges between 1000 and 1200 mm, with a mean annual temperature of 5 °C to 18 °C; the minimum temperature is –6 °C in January and the maximum is 28 °C in May [23,24] (Figure 1c). According to the World Reference Base for Soil Resources 2014, the predominant soil associations are Leptosol, Cambisol, Luvisol, Regosol, and Phaeozem [25]. The dominant vegetation type is pine–oak forest [26]. The minimum altitude is 1787 m a.s.l. and the maximum altitude is found at the “El Nevado” mountain, with 3028 m a.s.l. [27] (Figure 1a).

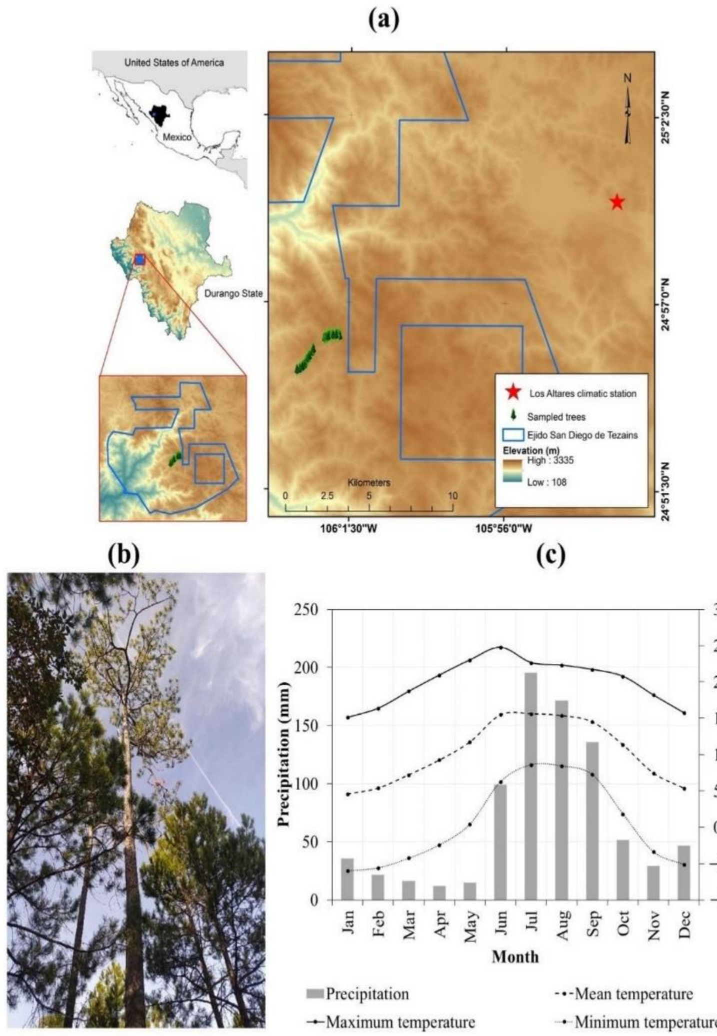

Figure 1. (**a**) Location of the study area; (**b**) photograph of a *Pinus durangensis* specimen; (**c**) mean monthly weather conditions from 1973 to 2019.

2.1. Development of Chronologies

From five to eight cross–sections were extracted from 50 *P. durangensis* trees, the first at ground level, and then every 30 cm until reaching the diameter at breast height (DBH). The remaining sections were extracted every 2.5 m until the tip. A total of 286 cross–sections was obtained. By measuring two radii of each cross–section, a total of 572 series was generated.

Samples were processed and dated according to standard dendrochronological techniques [28]. Total ring width, earlywood, and latewood were measured using a sliding-stage Velmex measuring system to the nearest 0.001 mm. The dating quality was checked with the COFECHA program, including only dendrochronological series with intercorrelation values greater than 0.328 ($p < 0.01$) [29]. Although cross-sections of the same tree were correlated, having between five and eight sections per tree ensured that the horizontal and vertical variation of tree rings was captured. This was a more complete assessment of growth of each tree, which could produce better correlations between dendrochronological series and detect a better response to environmental factors.

The chronologies were constructed by removing biological (competition, suppression, and release) and geometric (tree aging and stem growth) trends unrelated to climate.

This process consisted of the adjustment of negative exponential functions to the series of measurements of TRW, EW, and LW to obtain standardized and residual series. The standardization process allowed the transformation of the ring widths into dimensionless indices, preserving the highest frequency portion of the climate signal [30]. This procedure was performed using the dplR library package [31] in R studio software [32]. The quality of the chronology was assessed through the mean, standard deviation (SD), mean sensitivity (MS), and series intercorrelation (SI) [33]. Additionally, to assess the reliability of the chronology over time, a running expressed population signal (EPS) and the mean inter-series correlation (Rbar) [34], was calculated using a 50-year moving window with 25-year overlaps.

2.2. Climate Data Gathering and SPEI Calculation

Climatic data were gathered from the 10121-Los Altares meteorological station (24°53′38.4″ N, 106°7′15.59″ W, 2490 m a.s.l.), located 10 km from the study area (Figure 1). The precipitation (pp), maximum temperature (Tmax), minimum temperature (Tmin), and mean temperature (Tmean) records of the station covered a total of 47 years (1973–2019).

The SPEI was calculated using the SPEI package in R (Available online: http://sac.csic.es/spei, accessed on 1 May 2022) based on temperature and precipitation data for the period 1974–2019. This produced SPEI values for time scales of 3, 6, 9, and 12 months (cumulative drought) to identify the scale with the greatest correlation between the SPEI and the chronologies obtained. SPEI values regularly range between −3 and 3, where negative values indicate periods of drought and positive values indicate wet periods [5].

2.3. Correlation Analysis and Response Function

The monthly and seasonal relationships of climatic variables with total ring width, earlywood and latewood chronologies of *P. durangensis* were evaluated using the *seascorr* function, initially developed in MATLAB [35], and later included in the *treeclim* package in R studio software [32]. For this analysis, we conducted 1000 iterations based on a stationary bootstrap resampling process, whereby 95% confidence intervals were calculated considering a 5% significance level [36]. Correlations were tested seasonally from June of the previous growth year to September of the current growth year, based on the fact that the weather conditions in the year before the growing season significantly influence the development of annual tree rings [37].

2.4. Reconstruction Model Calibration and Verification

The stability of the reconstruction model was tested by splitting the total chronology into two subperiods: the first for calibration (1974–1995, 22 years) and the second for verification (1995–2017, 22 years). The process was developed through the VFY subroutine of the Dendrochronology Program Library (DPL) at the University of Arizona, using as references the significance of the Pearson correlation value (r), reduction of error (RE), coefficient of efficiency (CE) [38], t-value (tV) [39], sign test (ST), and first-negative difference [30].

2.5. Comparison with Other Drought Indices

The reconstructed SPEI was compared with other drought indices, such as the Standardized Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI). Instrumental and reconstructed SPI data were obtained from the North American Seasonal Precipitation Atlas (NASPA) page (Available online: http://drought.memphis.edu/NASPA/Default.aspx#, accessed on 1 May 2022) [40]; instrumental and reconstructed PDSI data were downloaded from the Mexican Drought Atlas (Available online: http://drought.memphis.edu/MXDA/Extract.aspx, accessed on 1 May 2022) [18].

2.6. Spatial Representativeness of the Reconstructed SPEI

To understand the regional representativeness of the $SPEI6_{FM}$ reconstruction, a field spatial correlation was performed between reconstructed $SPEI6_{FM}$ data and baseline

6-month cumulative SPEI data of the Global Drought Monitor in KNMI climate explorer (Available online: https://climexp.knmi.nl/start.cgi?id=someone@somewhere, accessed on 1 May 2022).

2.7. Ocean–Atmosphere Circulation Modes

The influence of ocean–atmosphere circulation patterns on reconstructed droughts was explored through a Pearson correlation analysis between the ring-width chronology, the Multivariate El Niño Southern Oscillation (ENSO) Index (MEI) [41,42], and the Pacific Decadal Oscillation (PDO) Index [43]. MEI data were obtained from the National Office of Oceanic and Atmospheric Administration (NOAA) website (Available online: https://psl.noaa.gov/data/climateindices/list/, accessed on 1 May 2022); PDO data were obtained from the Climate Data Guide website (Available online: http://research.jisao.washington.edu/pdo/PDO.latest, accessed on 1 May 2022). A Multi-taper power spectrum analysis [44] was carried out to understand reconstructed SPEI in the frequency domain. Additionally, the periods in which the reconstruction showed significant frequencies were identified with a wavelet spectral analysis using the dplR library [31] in R studio software [32].

3. Results

3.1. Total Ring Width, Earlywood, and Latewood Chronologies

Dendrochronological statistics corresponding to the total ring width (TRW), earlywood (EW), and latewood (LW) series were obtained for the standard (std) and residual (res) forms. TRW and EW showed the maximum value of EPS = 0.99, in both cases, with a minimum difference of r_{bt} = 0.62 (TRW) and 0.61 (EW). However, the MS of EW (0.39) was higher (Table 1).

Table 1. Dendrochronological statistics for total ring width, earlywood, and latewood chronologies.

Chronology	Dendrochronological Statistics					
	Mean	SD	EPS	SI	MS	AC1
TRWstd	0.95	0.27	0.99	0.62	0.35	0.51
EWstd	0.95	0.29	0.99	0.61	0.39	0.50
LWstd	0.95	0.22	0.98	0.44	0.37	0.49
TRWres	0.98	0.21	0.99	0.62	0.35	−0.08
EWres	0.98	0.22	0.99	0.61	0.39	−0.05
LWres	0.98	0.18	0.98	0.44	0.37	0.02

TRW, total ring width chronology; EW, earlywood chronology; LW, latewood chronology; std, standard chronologies; res, residual chronologies; SD, standard deviation; EPS, expressed population signal; SI, series intercorrelation; MS, mean sensitivity; and AC1, first-order autocorrelation.

The EWres was selected for the present study because it showed a greater association with calculated SPEI data (Table 2).

Table 2. Correlation between SPEI values calculated on a 6-month cumulative scale and standard and residual chronologies of *Pinus durangensis*.

Chronology	February	March	April	May
TRWstd	0.66	0.66	0.65	0.62
EWstd	0.67	0.66	0.67	0.64
LWstd	0.60	0.60	0.56	0.52
TRWres	0.68	0.71	0.73	0.69
EWres *	0.68	0.70	0.74	0.70
LWres	0.68	0.69	0.67	0.62

* Refers to the chronology with greater association with calculated SPEI data. All values were significant ($p < 0.01$).

The 572 analyzed growth series of *P. durangensis* were used to build a dendrochronological series for 296 years (1725 to 2020) (Figure 2a). The EPS value based on the number of trees and radii per tree indicated that the 1725–1795 period had an EPS lower than the critical value of 0.85, while the 1795–2020 period exceeded this critical value, indicating that this last period was more suitable for reconstruction purposes. The Rbar values exceed 0.3 in the periods of 1795–2020 (Figure 2b).

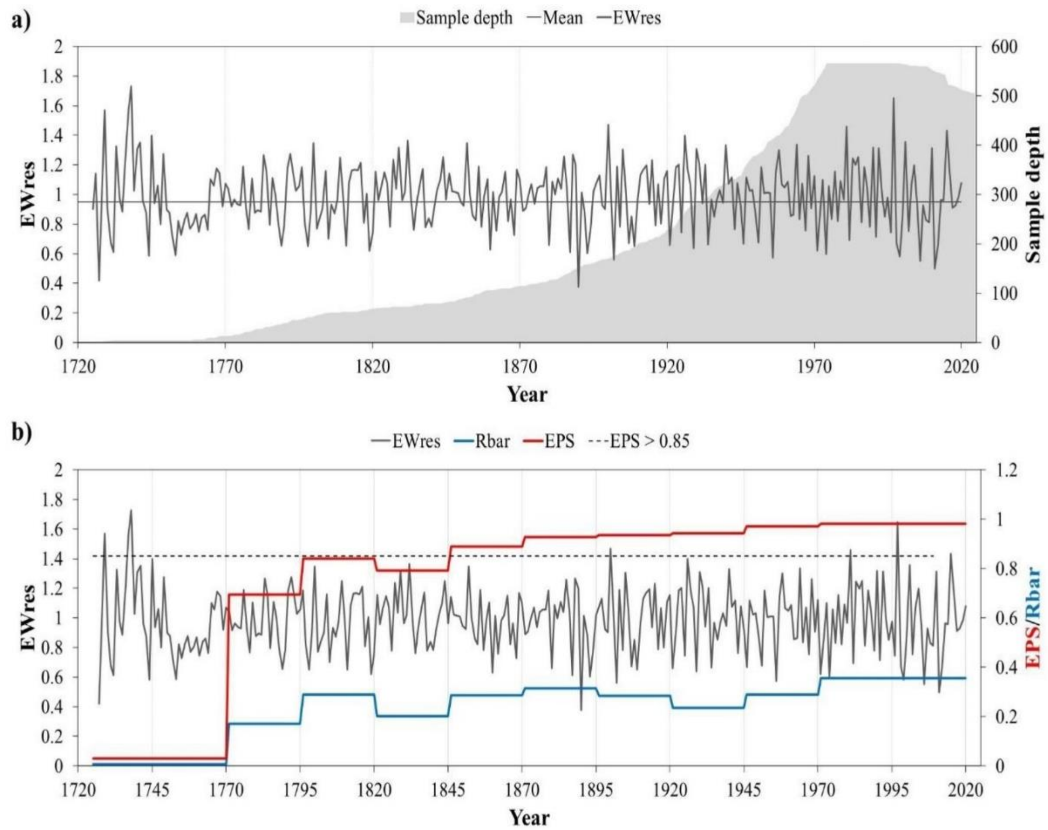

Figure 2. (**a**) Earlywood residual chronology (EWres) of *Pinus durangensis* (gray line). The black horizontal line represents the average index value that shows the interannual variability for the period 1725–2020; the gray shaded area represents the number of radii used to produce each annual index value (right *y*-axis). (**b**) Earlywood residual chronology (EWres) of *Pinus durangensis* (gray line). The running EPS was calculated based on the number of sampled trees and is represented by a red line and the minimum EPS of 0.85 is represented by the black horizontal dotted line. The running Rbar is represented in a blue line.

3.2. Relationship between Tree Growth and Climate

The correlation analysis between the records of climatic variables for 1974–2019 (46 years) and the EWres chronology showed a positive association with precipitation from November of the previous year to April of the current growth year (r = 0.42, $p < 0.05$). Tmax showed the greatest negative association for March and April of the current growth year (r = −0.455, $p < 0.05$). Tmin was positively associated with the period from January to March of the current growth year (r = 0.40, $p < 0.05$). Tmean showed a positive association in September (r = 0.31, $p < 0.05$) of the current growth year. The SPEI calculated for a six-month period (SPEI6) showed the greatest positive association from February to May (r = 0.70, $p < 0.01$) of the current growth year. This result confirms the working hypothesis that *P. durangensis* is sufficiently sensitive to drought events, so that the evolution of its radial growth is closely correlated with the SPEI (Figure 3).

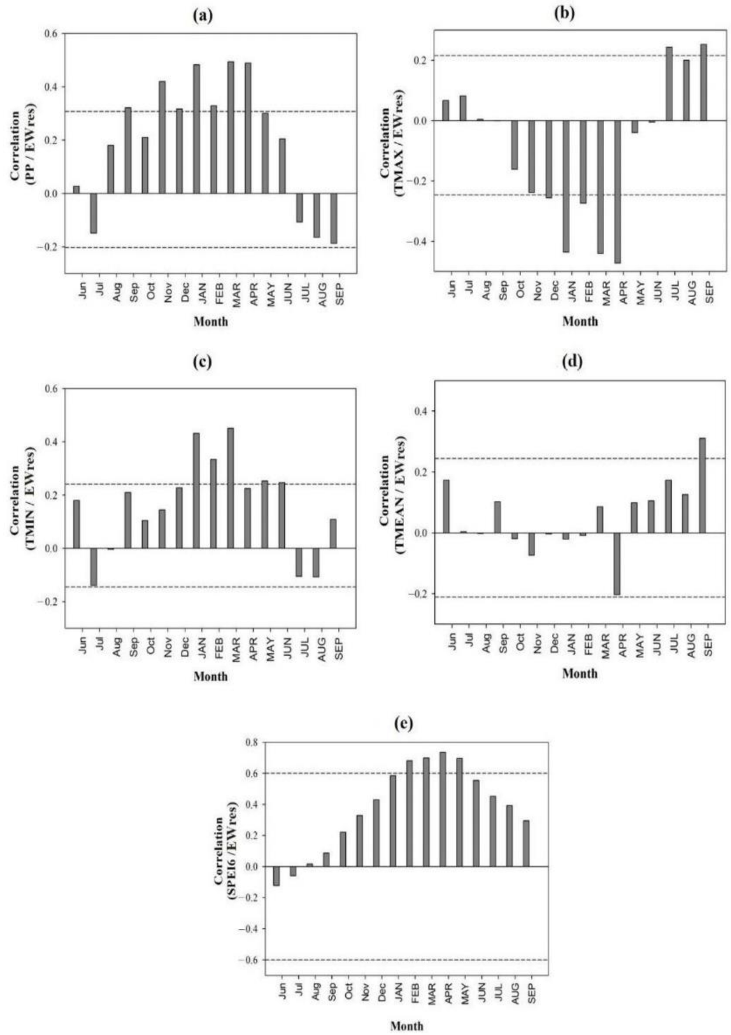

Figure 3. Correlations between the earlywood residual chronology (EWres) and the monthly climatic variables (**a**) precipitation, (**b**) maximum temperature, (**c**) minimum temperature, (**d**) mean temperature, and (**e**) SPEI calculated on a 6-month cumulative scale. Months in lowercase indicate the previous year, while months in uppercase correspond to the current growth year. Climate data were obtained for the period 1974–2019 (46 years). The dotted horizontal lines indicate the level of significance ($p < 0.05$). For the SPEI association with the EWres the level of significance was $p < 0.01$.

The EWres of *P. durangensis* showed positive responses to the SPEI, i.e., the earlywood indices increased when drought severity decreased, with the highest correlation values observed for a cumulative six-month period and from February to May (r = 0.68–0.73, $p < 0.01$) (Figure 4).

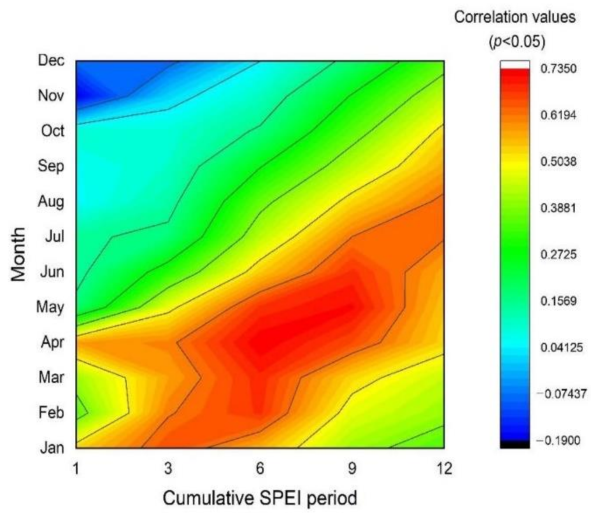

Figure 4. Drought–growth association calculated for *Pinus durangensis* by relating the SPEI drought index to the earlywood residual chronology. The value was assigned to the last month of the SPEI cumulative period.

3.3. SPEI Reconstruction

The cumulative SPEI on a six-month scale was calculated for the February–May period ($SPEI6_{FM}$) of the Los Altares meteorological station, which was strongly associated with tree growth. Therefore, a linear regression model was developed to reconstruct $SPEI6_{FM}$ for the period 1725–2020 (296 years).

Using a simple linear regression analysis, a transfer function was established between the earlywood index chronology of *P. durangensis* and $SPEI6_{FM}$, resulting in Equation (1) (Figure 5).

$$SPEI6_{FM} = -2.6062 + 2.6687 \times X_i \quad (1)$$

where: $SPEI6_{FM}$ is the six-month cumulative SPEI for February–May and X_i is the value of EWres for the year *i*.

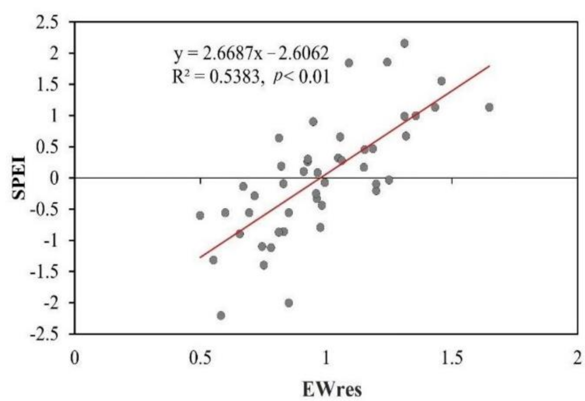

Figure 5. Scatterplot of the linear regression model showing the variability of the earlywood residual chronology (EWres) with the six-month cumulative SPEI from February to May 1974–2019 (46 years).

Regarding the calibration and verification process, it is worth mentioning that the correlations were positive for both periods. Since the verification analysis performed for the subperiod 1996–2019 showed that all parameters were statistically different from zero at the 5% significance level (Table 3), we proceeded to develop the reconstruction model.

Table 3. Statistics for the validation process of the seasonal SPEI from February to May of the current growth year.

Period	r	tV	ST	FND	RE	CE	DW
Calibration (1974–1996)	0.707	3.037	4	3	0.476	0.476	1.865
Verification (1997–2019)	0.763	3.979	5	5	0.626	0.626	

r, Pearson's correlation coefficient; tV, t-value; ST, sign test; FND, first negative difference; RE, reduction of error; CE, coefficient of efficiency; and DW, Durbin–Watson coefficient. The significance in both periods was maintained at 5% ($p < 0.05$). All values were significant ($p < 0.05$).

The reconstructed $SPEI6_{FM}$ values covered 296 years (1725–2020), in which high inter-annual and multi-annual variability was detected. The mean reconstructed $SPEI6_{FM}$ value was 0.023 with a standard deviation (SD) of $\pm$ 0.585. Triangles represent the years showing a value above the upper limit of the standard deviation, defined as wet years; circles mark years below the lower SD limit, considered periods of extreme drought (Figure 6a).

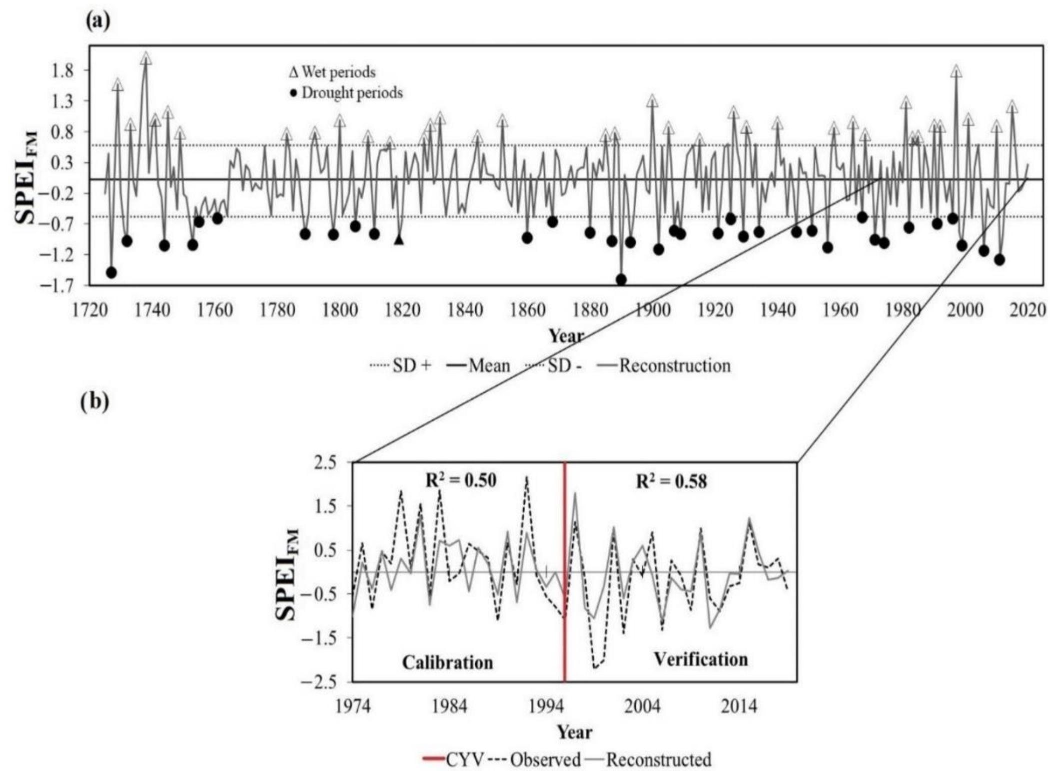

Figure 6. (**a**) Reconstructed SPEI for the western region of the State of Durango during 1725–2020; (**b**) comparison between observed SPEI (dashed line) and reconstructed SPEI (gray line). Triangles denote wet years and black dots represent extreme drought events. The vertical red line indicates the year in which the instrumental SPEI was split for calibration and verification purposes.

Of the 296 years analyzed, 54 years (18%) were classified as wet, 48 years (16%) as drought, and 194 years (66%) as normal. The last century of the period analyzed showed an increase in the number and frequency of droughts. The first century (1725–1824) had 15 years of extreme drought; the second century (1825–1924) had 12 years of extreme drought, and the last century (1925–2020) had 21 years of extreme drought. Of note, in the last century, we observed droughts lasting two to three years (1945–1946, 1950–1951, 1971–1972, 1998–2000, 2008–2009, and 2011–2012) (Figure 6a).

In the graphical relationship between the observed and reconstructed $SPEI6_{FM}$, as well as the division into the subperiods used for calibration (1974–1996) and verification (1997–2020), the similarity between both chronologies is highlighted, particularly in the verification period where the reconstructed SPEI accounts for 58% of the observed SPEI variability (Figure 6b).

3.4. Comparison of the Reconstructed SPEI with Other Drought Indices

The relationship between our drought reconstruction and other corresponding products using different drought indices was statistically significant ($p < 0.05$), and may suggest that severe droughts were more frequent in the past century than earlier in the records (blue shaded lines in Figure 7).

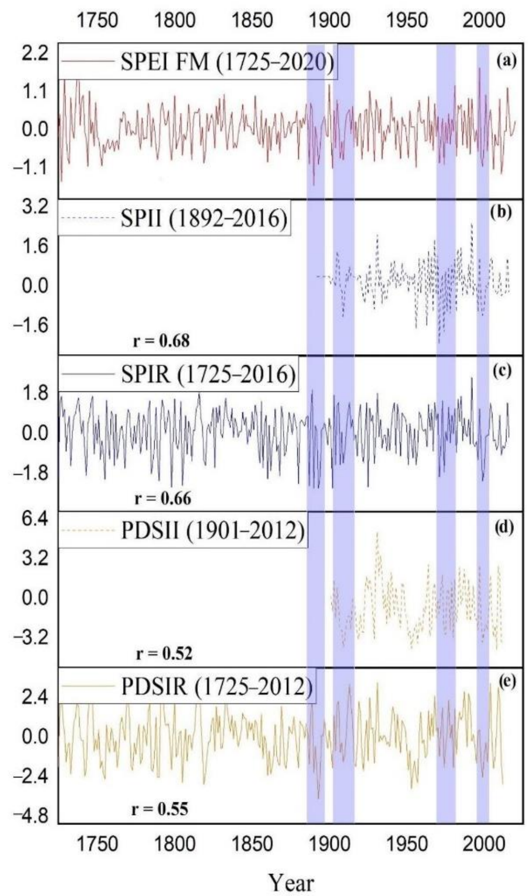

Figure 7. Temporal variation for different drought indices, reconstructed SPEI (**a**), instrumental SPI (**b**), reconstructed SPI [40] (**c**), instrumental PDSI (**d**), and reconstructed PDSI [18] (**e**). Pearson's correlation coefficients (r) between drought indices and $SPEI6_{FM}$ are indicated in every panel. The blue shaded lines represent periods of common severe droughts in the different analyzed indices and the reconstructed SPEI.

The field spatial correlation showed positive and higher than 0.5 in a large area of northern Mexico and even the southwestern United States, indicating high representativeness of the reconstructed $SPEI6_{FM}$ for a large part of that region. Figure 8 shows the results for February–May because these were used to reconstruct this variable to represent the study area for northern Mexico.

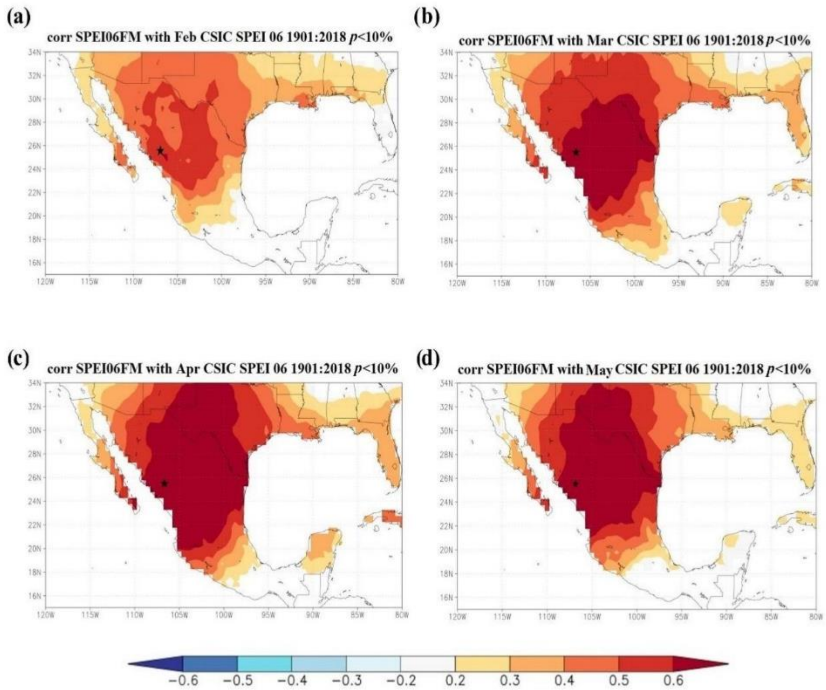

Figure 8. Spatial correlation between the reconstructed $SPEI6_{FM}$ and the six-month cumulative SPEI of the Global Drought Monitor for the months used in the reconstruction: (**a**) February, (**b**) March, (**c**) April, and (**d**) May.

Influence of Ocean-Atmosphere Phenomena

The associations between the reconstructed $SPEI6_{FM}$ and ENSO through the mean MEI from February to May (1979–2020) yielded an r-value of 0.386 ($p < 0.05$) and through the mean PDO from February to May, an r-value of 0.385 ($p < 0.05$). The power spectral analysis of the reconstructed SPEI chronology detected significant ($p < 0.01$) high-frequency peaks of 4.1, 3.2, 2.6, 2.4, and 2.2 years (Figure 9).

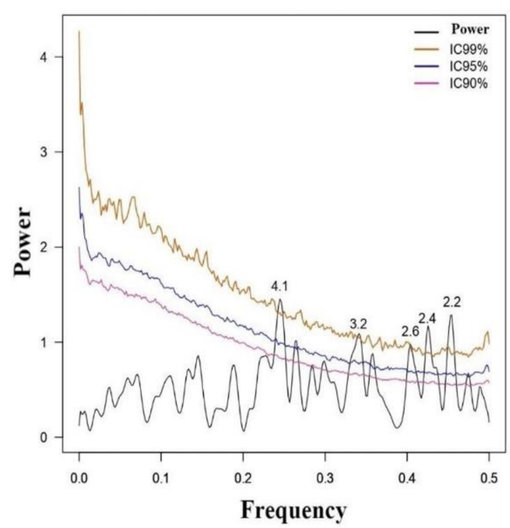

Figure 9. Power spectral analysis for the six-month reconstructed SPEI (February–May). Values above the confidence limits are significant.

The wavelet power spectral analysis showed significant 4.1-year frequencies in the periods 1725–1748, 1796–1801, 1921–1929, and 1994–2005. Frequencies of 2 to 3 years were observed in 1886–1891, 1899–1905, 1971–1974, 1986–1994, and 2011–2013 (Figure 10).

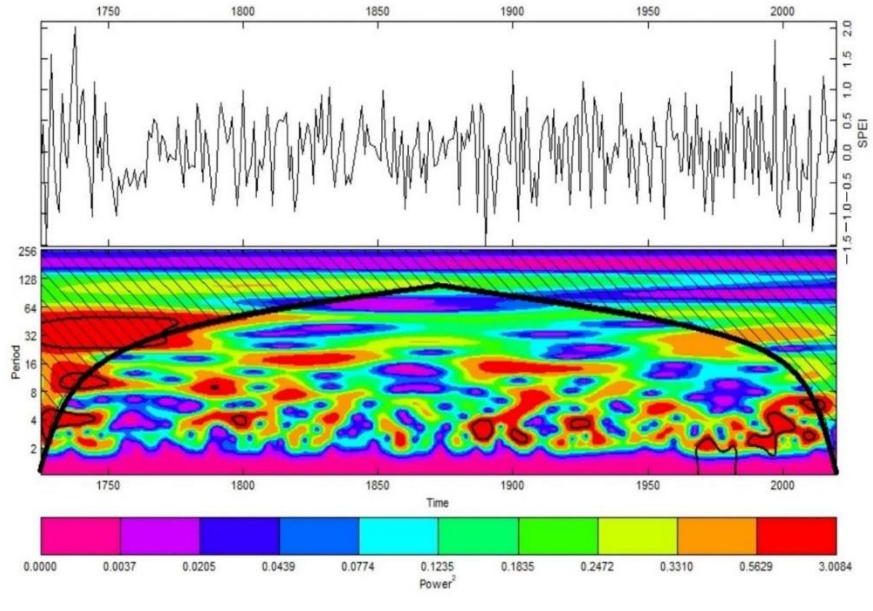

Figure 10. Wavelet coherence analysis for six-month reconstructed SPEI (February–May). Perimeters marked with a thick dark line within the cone of influence indicate significant areas ($p < 0.05$).

4. Discussion

P. durangensis is one of the most important timber species for forest harvesting in the Sierra Madre Occidental (SMO), mainly because of the high timber quality [45,46]. Consequently, this species has been harvested extensively, to the extent that it is currently listed as "Near Threatened" by the International Union for the Conservation of Nature (IUCN) [46,47]. In addition to its valuable timber characteristics, *P. durangensis* has been proven to have a remarkable dendroclimatic potential [48], with statistics similar to those reported by Irby et al. [49], i.e., an SI of 0.61, and higher than the SI of 0.28 reported by González-Cásares et al. [50]. The SI value of 0.61 calculated in the present study confirms an adequate common response between chronologies. In addition, the estimated EPS based on the number of trees and radii per tree was higher than those reported for species coexisting in nearby sites (0.85) [14,51]. We should recognize that the EPS index is highly dependent on the number of trees and sample size; therefore, the high EPS values are not constant over time, such that the period for reconstruction purposes was established from 1795 to 2020 when the EPS value reached over 0.85. Also, it must be considered that cross-sections from the same tree are correlated, partly explaining the relatively high values of the indicators obtained in the present study. For dendrochronological purposes, two to three wood cores from the same tree should be collected to capture the dominant climate variability. In this study, the number of cross-sections ranged from 5 to 8, equivalent to obtaining 5 to 8 replicates per tree, thus capturing the high- and low–frequency climate variability.

The positive relationship between the earlywood chronology of *P. durangensis* and precipitation in the cold season (from the previous November to the current April, Figure 4) is consistent with previous studies for other conifers in northern Mexico [17,52]. This is mainly because the growth of conifers in northern Mexico is significantly influenced by precipitation in winter–spring. This period is characterized by low-intensity precipitation that favors water infiltration and storage in the shallow soil, which the tree can efficiently use during the growing season [19,30,53].

The association of EWres with Tmax showed the greatest negative response to the warm conditions in March and April, probably caused by increased respiration and, therefore, evapotranspiration, leading to drought stress [54,55]. On the other hand, Tmin had a positive effect on the growth of *P. durangensis* under the cold conditions of the current January to March related to low evaporation and higher soil moisture [56]. Consequently, water availability for trees is sufficient to activate the cambium in spring, which is typical in temperate zones [57].

An additional aspect to consider is that trees may be subject to double stress, i.e., two interruptions of cambium activity: one caused by low temperatures in winter and another by drought in summer [57,58]. In this sense, the EWres of *P. durangensis* showed the greatest positive association with the six-month SPEI (current February to May), suggesting that the development of this growth band occurs in this period and is largely limited by water deficit and evapotranspiration–variables on which the SPEI is based [3].

The reconstruction of $SPEI_{FM}$ identified extreme drought periods (1727–1729, 1731–1734, 1752–1756, 1805–1819, 1860–1862, 1890–1893, 1902–1909, 1934, 1946–1956, 1971–1974, 1998–2000, 2006–2009, and 2011–2012). It is important to mention that some of the drought periods observed here do not match some of the extreme drought events reported for northern Mexico [18,59]. However, in the past century (1900–2000), we detected coincidences between the drought events reconstructed here and some droughts reported in previous studies, such as the droughts of 1890–1909, a period of extensive drought that caused significant damage to crops and livestock due to poor crop yields, affecting much of Mexico [60]. The decade 1946–1956 identified in this study has been reported elsewhere as one of the most extensive droughts having affected northern Mexico [18,61,62] and the southern United States, a country where this has been considered the most severe drought of the past millennium [63]. This scarcity scenario occurred again in 2006–2009, consistent with the results obtained here and in previous investigations [17,64].

The period 2011–2012, identified as a drought event in the present study, has been considered the worst drought in the past 70 years in Mexico, affecting to a large extent the livestock sector [65,66]. It was also an atypical year in terms of the area affected by forest fires [67]. In addition, the low crop yields caused food shortages and poverty, which may have been associated with increased insecurity levels and high migration rates [68].

The close association between the reconstructed SPEI and other drought indices (PDSI and SPI) in their reconstructed and instrumental versions ($r > 0.50$) underlines the validity of the results obtained here. In addition, it allowed detection of the coincidence in the variation of droughts (Figure 8), particularly the most severe events mentioned above. These results also demonstrate the effectiveness of tree rings in identifying the trend and intensity of historical droughts [18,40].

The spatial field correlation of the reconstructed $SPEI6_{FM}$ showed a close association ($r > 0.6$) with the global SPEI 06 data sets (February to May, Figure 9), indicating high representativeness for much of northern Mexico and parts of the southern United States.

MEI and PDO showed similar associations with the reconstructed $SPEI6_{FM}$ in some cases being greater than the reports by other authors who assessed the association between these indices of ocean–atmosphere phenomena and ring–width index chronologies [17,19,69]. The high frequency peaks (2–4 years) identified through spectral analysis coincided with the range of ENSO (<10 years) [70,71], within which the driest periods affecting northern Mexico have occurred [59]. Although the wavelet analysis showed only sporadic periodicities at frequencies below 4.1 years, this result is important as other authors such as Castruita-Esparza et al. [72] and Martinez-Sifuentes et al. [12] have found that climate variability for northwest Mexico has a memory effect of between 3 and 5 years. This result may indicate the need for more research in this direction.

5. Conclusions

The earlywood residual dendrochronology of *Pinus durangensis* Martinez was significantly related to the six-month cumulative SPEI of the period February-May. This association allowed for the reconstruction of $SPEI6_{FM}$ for a total of 296 years (1725–2020). In addition, this reconstruction made it possible to identify the increase in the recurrence of droughts since 1880.

The climate response analysis indicated that growth in *P. durangensis* is positively influenced by seasonal winter-spring precipitation and low temperatures. However, the negative association of growth with maximum temperature and the SPEI at different scales indicates the high susceptibility of this species to drought over short time scales. This, together with the rising temperatures resulting from global warming, may affect the ecological stability of the populations of this species in the region.

Climatic instability, coupled with the excessive exploitation of *P. durangensis*, has brought this species to near-threatened status. Therefore, we recommend conducting further studies to address the growth and population dynamics of *P. durangensis* and its response to climate change.

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CHAPTER IV: RESILIENCE OF *PINUS DURANGENSIS* MARTÍNEZ IN EXTREME DROUGHT PERIODS: VERTICAL AND HORIZONTAL RESPONSE OF TREE RINGS


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Article

Resilience of *Pinus durangensis* Martínez in Extreme Drought Periods: Vertical and Horizontal Response of Tree Rings

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Abstract: Extreme drought events reduce the productivity of forest ecosystems. One approach for estimating the effects of drought on forests is by assessing their resilience. The objective of this study was to estimate resilience rates at different heights along the tree stem of *Pinus durangensis* Martínez. The radial growth of 200 cross sections extracted at four heights of tree stems (0.07–0.15, 1.3, 6.3, and 11.0–12.0 m) was analyzed and subsequently transformed into ring-width indices (RWI). These indices were correlated with the Standardized Precipitation-Evapotranspiration Index on a six-month time scale (accumulated drought of six months in the period February–May; $SPEI06_{FM}$). Seven extreme drought events were identified (1890, 1902, 1956, 1974, 1999, 2006, 2011), and radial growth before, during, and after each event was determined. Based on ring-width index values, resistance, recovery, and resilience indices were calculated. The results indicated a significant correlation ($p \leq 0.05$) between annual radial increment and climate indices along the stem (0.56 to 0.80). Climatic sensitivity was higher in the lower part of the stem, with mean sensitivity (MS) and expressed population signal (EPS) values of 0.38 and 0.97, respectively. Resistance index values ranged from 0.44 to 0.76 and were better expressed in higher sections of the stem. Resilience indices changed over time. Regardless of the height of the tree stem, the latest extreme drought events (1999, 2006, and 2011) have led to a lower resilience of trees, indicating that their recovery capacity has decreased. Therefore, forestry practices in the study area may consider managing tree density as a strategy to regulate the stress in competition and to increase the tolerance of trees to drought.

Keywords: tree growth; resistance; recovery; tree-rings; stem analysis; SPEI

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1. Introduction

Forest ecosystems have been seriously affected by frequent climate variations in recent decades [1–4]. The intensity of drought events is one of the main drivers of disturbance, leading to a reduction in tree growth [5], and on occasion to the dieback of trees [6–8]. However, the growth recovery of forest ecosystems after a disturbance event varies with the local climate and species [9]. Another factor that also influences this behavior is forest structure, which regulates resource supply, uptake, and use efficiency [10].

In terms of species, it has been reported that those belonging to the *Pinaceae* family (mainly pines) are less resilient than those belonging to the *Fagaceae* family (mainly oaks) in the face of extreme drought events [9]. This finding may be relevant to the prevailing conditions of the Sierra Madre Occidental (SMO) of Mexico [11], which presents the greatest diversity of associations of pines and oaks worldwide [12]. This places Mexico as a secondary center of diversity of the genus *Pinus*, having about 42% of the species and a high percentage of endemism (>55%) [13]. Among these species, *Pinus durangensis* Martínez is one of the most important due to its distribution area (143,000 km^2), wood quality, commercial value, and for being a key component for the conservation of the SMO's biodiversity [14,15]. However, its extensive logging has reduced the abundance of large trees in many areas, placing it on the International Union for Conservation of Nature's Red List of Threatened Species as Near Threatened [16]. In addition, the susceptibility of *P. durangensis* to extreme drought events has been reflected in radial growth rates [17,18], which may compromise its resilience [19].

In view of concerns about the increasing frequency of extreme drought events in recent years, research efforts have focused on understanding the response of forests to extreme drought [20–24]. Significantly, the analysis of pre- and post-disturbance growth has led to the development of indices, such as quantifiable resilience components [25].

The indices proposed by Lloret et al. [26] have been widely used for quantifying tree resilience. These indices include resistance (*Rt*), defined as the capacity of the tree to sustain growth under disturbing conditions, and recovery (*Rc*), representing the ability of the tree to return to its original condition after disturbance. In forest terms, resilience (*Rs*) refers to the ability of the forest to maintain its original functions under extreme disturbance [27].

Currently, indices for quantifying resilience in forest ecosystems have been addressed using two main approaches: dendrochronology [28–30] and satellite imagery [31,32]. Ring-width chronologies, however, provide information on the growth response to drought at the individual tree level [7] and allow estimating resilience indices on scales ranging from decades to hundreds of years.

Although there is increasing use of resilience indices to analyze the response of trees to extreme drought events around the world, studies involving this approach are scarce in Mexico. In addition, studies based on analyzes of resilience indices through tree rings have been based on radial increases at breast height (1.30 m), which may provide an adequate estimate of radial growth during drought along the stem; however, different results may be obtained in terms of resistance and recovery [33]. In this regard, obtaining information about the response of trees to drought requires the use of growth data at different stem heights in tree species [25].

Based on the above, the objective of this study was to estimate the resilience indices at different stem heights of *P. durangensis* trees in a site in northern Mexico. Particularly, we explored the consistency in resilience indices along the stem of *P. durangensis* trees and whether the resilience of *P. durangensis* has decreased in recent decades. To this end, two main hypotheses were considered: (1) resilience indices estimated for extreme drought events differ along the stem height, and (2) the increase in the frequency and intensity of droughts in recent decades has reduced the resilience of *P. durangensis* to drought. These results contribute to a better understanding of the effects of extreme weather conditions on the growth of *P. durangensis*, a species of great ecological and logging importance in temperate forests in Mexico.

2. Materials and Methods

2.1. Study Area

The sampling site is located in the Sierra Madre Occidental (SMO), northwest of the Durango state (Figure 1a). The site is characterized by uneven-aged vegetation, represented by the genera *Pinus*, *Quercus*, *Juniperus*, *Cupressus*, *Pseudotsuga*, *Arbutus*, and *Alnus* [34]. The sampled trees of *P. durangensis* were obtained in an altitudinal gradient of 2573–2829 m a.s.l., which is its optimal distribution (Figure 1b). The predominant aspect was southwest and had an average slope of 12%. The geographical coordinates are 24°48′16.98″–25°12′38.91″ N and 106°12′37.63″–106°12′25.58″ W (Figure 1c). The main soil types are Leptosol, Cambisol, Luvisol, and Phaeozem [35]. The prevailing climate is cold-temperate, with a mean annual precipitation of 850 mm (Figure 1d) and a mean annual temperature of 10 °C (Figure 1e) [36].

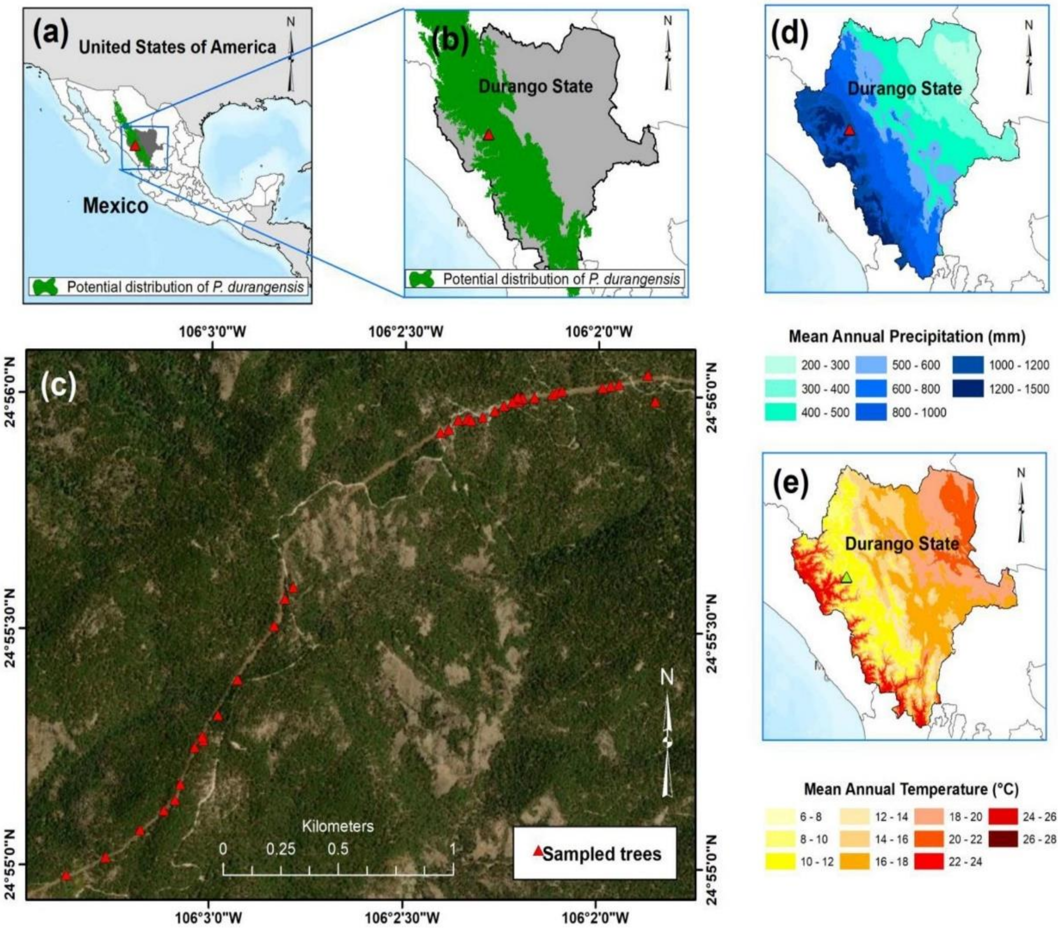

Figure 1. Characteristics of the study area: (**a**) geographic location of the sampling site; (**b**) potential distribution of *P. durangensis* along the Sierra Madre Occidental [37]; (**c**) location of the sampled trees (n = 50); (**d**) mean annual precipitation; and (**e**) mean annual temperature.

2.2. Dendrochronological Information

Fifty *P. durangensis* trees were analyzed, which were selected through directed sampling. Those healthy trees with straight stems and no signs of mechanical damage were chosen. Four cross-sections were extracted from each tree at different heights of the stem. The first section was set between 0.07 m and 0.15 m, the second one at 1.3 m, the third one at 6.3 m, and the last one between 11.0 m and 12.0 m in the height of the stem.

The cross sections were polished and dated based on standard dendrochronological techniques [38]. For each section, the total ring width of two representative radii was measured to an accuracy of 0.001 mm using a Velmex measuring system. Quality in the dating of the ring-width series was checked using COFECHA software [39].

To eliminate biological and geometric trends unrelated to climate, the series were standardized by fitting negative exponential functions. Standardization was carried out using the *dplR* library [40] in R software [41]. This procedure allowed estimating ring-width indices (RWI) for the different heights of the stem. RWI1 is the ring-width index for the first section (0.07 m and 0.15 m), RWI2 for the second section (1.3 m), RWI3 for the third section (6.3 m), and RWI4 for the last section (11.0 to 12.0 m). Those RWI are characterized by being dimensionless, with a mean close to 1.0 and homogeneous variance, but preserving a high portion of the climatic signal [42].

The quality and reliability of chronologies were verified through the mean, standard deviation (SD), mean sensitivity (MS), intercorrelation between series (SI), mean correlation between series (Rbar), first-order autocorrelation (AC1), expressed population signal (EPS) [43,44], and subsample signal strength (SSS) [45]. EPS and SSS are statistics that measure the degree of representativeness of a chronology relative to a theoretical population with an unlimited number of samples. However, the theoretical population is infinitely replicated for EPS, while replication is finite for SSS [46]. In this study, an SSS > 0.85 was used to determine the best replicated period [43].

2.3. Identification of Extreme Droughts

According to Cabral-Alemán et al. [47], the radial growth of *P. durangensis* in the study area is influenced by dominant winter-spring climatic conditions and reported reconstruction of the Standardized Precipitation-Evapotranspiration Index (SPEI) at a 6-month scale (cumulative drought from six months) of February-May ($SPEI06_{FM}$), in the period 1725–2020. In this study, we used the data of $SPEI06_{FM}$ in the period 1880–2020. Based on a statistical criterion, drought events were selected, with extreme droughts defined as the years in which the $SPEI06_{FM}$ values fell out in the lowest fifth percentile [24].

Additionally, the association between the chronologies at different stem heights and the $SPEI06_{FM}$ was calculated with the Pearson correlation analysis using the Minitab 19 software.

2.4. Resilience of Pinus durangensis to Drought

In ecology, the term resilience refers to the ability of natural systems to recover or return to pre-disturbance levels [48]. To optimize the characterization of the response of *P. durangensis* to drought, three resilience components were calculated at different tree stem heights.

The resistance (*Rt*), recovery (*Rc*), and resilience (*Rs*) of a tree to drought events were calculated from the total ring-width index (RWI) based on the formula of Lloret et al. [26], with the *pointRes* library [49] in R software [41]. *Rt* values close to 1.0 denote a high resistance to drought, and *Rc* values less than 1.0 indicate a drop in growth after the drought event. Values of *Rs* equal to or greater than 1.0 indicate the ability to achieve the level of performance before the disturbance. *Rt*, *Rc*, and *Rs* were calculated using Equations (1)–(3). *Rt*, *Rc*, and *Rs* are calculated with Equations (1)–(3).

$$Rt = \frac{G_d}{G_{prev}} \quad (1)$$

$$Rc = \frac{G_{post}}{G_d} \quad (2)$$

$$Rs = \frac{G_{post}}{G_{prev}} \quad (3)$$

where G_d represents radial tree growth (RWI) during drought, G_{prev} is pre-drought growth (mean RWI of four years prior to the drought year), and G_{post} is post-drought growth (mean RWI of four years after the drought year).

The proportion of trees showing high *Rt* and high *Rc* was also calculated. The observed relationship between *Rt* and *Rc* was compared with the hypothetical relationship when full resilience is achieved, and the line of full resilience was calculated using Equation (4) [25].

$$Rc_{h=} \frac{1}{Rt} \quad (4)$$

where Rc_h is recovery assuming a hypothetical full resilience = 1.0

3. Results

3.1. Development of Chronologies

The chronologies estimated for different tree stem heights of *P. durangensis* showed variability in dendrochronology statistics. RWI4 showed peak Rbar and SI values, while the four chronologies greatly exceeded the minimum acceptable EPS value (0.85). RWI1 had the highest MS and AC1 values. SSS values > 0.85 for the four chronologies determined the common period for evaluation, which was 1880–2020 (140 years). Chronology data are shown in Table 1.

Table 1. Dendrochronological statistics for the standard version of the ring-width chronology of *Pinus durangensis* at different tree stem heights.

Chronology	Height (m)		Dendrochronological Statistics							
			Mean	SD	Rbar	EPS	SI	MS	AC1	SSS > 0.85
RWI1	0.07–0.15	1717–2020	0.94	0.35	0.28	0.97	0.60	0.38	0.54	1801–2020
RWI2	1.3	1736–2020	0.95	0.27	0.32	0.98	0.61	0.36	0.36	1797–2020
RWI3	6.3	1797–2020	0.97	0.21	0.33	0.97	0.64	0.32	0.29	1831–2020
RWI4	11.0–12.0	1819–2020	1.00	0.24	0.34	0.97	0.65	0.30	0.46	1880–2020

RWI, ring-width index; SD, standard deviation; Rbar, mean correlation between series; EPS, expressed population signal; SI, series intercorrelation; MS, mean sensitivity; AC1, first-order autocorrelation; SSS, subsample signal strength.

3.2. Relationship between Growth and SPEI

The correlation values between growth data represented by RWI chronologies at different stem heights and drought events represented by $SPEI06_{FM}$ values showed high and significant correlations ($p \leq 0.05$). However, RWI1 and RWI3 were more strongly associated with this index (Table 2).

Table 2. Pearson's correlation analysis between the ring width index (RWI) at different tree stem heights and $SPEI06_{FM}$.

Variable	Pearson's Correlation Coefficient	*p*-Value
RWI1	0.738	0.001
RWI2	0.568	0.001
RWI3	0.803	0.001
RWI4	0.567	0.001

3.3. Identification of Extreme Droughts

The analysis of the variation of $SPEI06_{FM}$ during the period 1880–2020 (140 years) revealed seven years (1890, 1902, 1956, 1974, 1999, 2006, and 2011) with values below the fifth percentile of the distribution. The years resulting from this analysis were classified as extreme drought years. Figure 2a shows the RWI and its graphic relationship with extreme drought events indicated by the $SPEI06_{FM}$ (Figure 2b). The seven years identified as the most severe droughts coincided with variations in radial growth represented by the four chronologies.

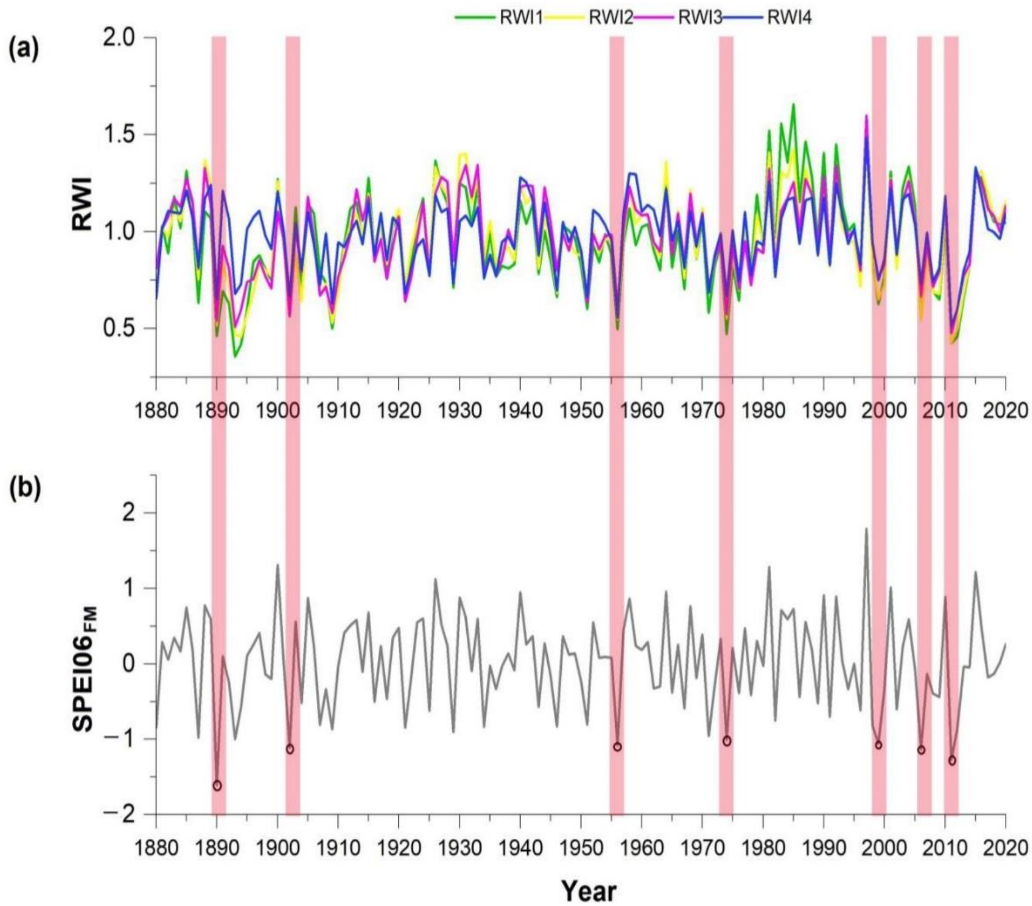

Figure 2. (**a**) Standard version of the ring-width index chronologies at different stem heights in *P. durangensis*, (**b**) SPEI reconstructed for the western region of the state of Durango [47]. Vertical shaded red lines and black circles mark regional extreme drought events.

3.4. Resilience Components

The values of the drought resilience components (*Rt*, *Rc*, and *Rs*) of *P. durangensis* calculated for tree growth (RWI) showed variations between tree stem sections for each extreme drought year. Regarding *Rt*, peak values were found in samples collected for RWI4 (11.0–12.0 m) in the droughts of 1974, 1999, and 2001, with a marked decrease in the 2011 drought. The lowest *Rt* values were observed for RWI2 (1.3 m) and RWI3 (6.3 m) in the 1890 drought (the most severe drought event according to the $SPEI06_{FM}$ reconstruction). Even though an uneven decrease in RWI values was detected for the four stem sections in 1893, corresponding to a low SPEI value, this was not as extreme as the other drought periods and was not selected for further analysis. The *Rc* values increased from 1890 to 1956, then decreased from 1974 to 2006, and increased again in 2011. The four stem sections presented the highest *Rs* values in the 1956 drought, while the lowest values occurred in 1890 (Table 3).

The *Rt* values of the four sections did not reach the reference value (1.0) in any of the drought events, while the *Rc* values were greater than 1.0 in the four sections of all the drought events analyzed. The *Rs* values of the four sections did not reach the reference value (1.0) in the drought events of 1890 and 2006; in 1974, only RWI1 and RWI4 exceeded the value of 1.0; while in 2011, only RWI1 did not reach the value of 1.0 (Figure 3).

Table 3. Mean and standard deviation of resistance, recovery, and resilience indices for each tree stem section of *P. durangensis* in seven selected drought events.

Drought Year		Resistance (*Rt*)				Recovery (*Rc*)				Resilience (*Rs*)			
		RWI1	RWI2	RWI3	RWI4	RWI1	RWI2	RWI3	RWI4	RWI1	RWI2	RWI3	RWI4
1890	Mean	0.51	0.44	0.49	0.64	1.31	1.42	2.34	1.48	0.60	0.57	0.66	0.91
	SD	0.23	0.16	0.13	0.22	0.45	0.67	1.65	0.35	0.27	0.17	0.19	0.29
1902	Mean	0.68	0.59	0.65	0.67	2.28	2.24	2.79	1.79	1.23	1.03	1.19	1.00
	SD	0.32	0.30	0.28	0.29	1.61	1.65	2.63	0.93	0.52	0.41	0.59	0.34
1956	Mean	0.60	0.58	0.64	0.54	2.48	2.59	2.79	2.42	1.39	1.49	1.31	1.20
	SD	0.25	0.22	0.24	0.15	1.40	1.71	4.73	1.29	0.79	1.64	0.49	0.25
1974	Mean	0.56	0.59	0.63	0.75	1.94	1.76	1.61	1.48	1.05	0.96	0.96	1.05
	SD	0.17	0.21	0.23	0.26	0.85	0.75	0.57	0.52	0.43	0.28	0.28	0.27
1999	Mean	0.64	0.68	0.76	0.74	1.98	1.87	1.51	1.50	1.08	1.11	1.03	0.99
	SD	0.30	0.36	0.36	0.33	1.74	1.16	0.82	0.61	0.56	0.64	0.47	0.36
2006	Mean	0.53	0.56	0.64	0.75	1.65	1.62	1.60	1.37	0.79	0.83	0.87	0.98
	SD	0.24	0.20	0.24	0.28	0.70	0.67	1.12	0.51	0.33	0.34	0.29	0.43
2011	Mean	0.51	0.52	0.53	0.56	2.30	2.26	2.12	1.98	1.00	1.02	1.02	1.03
	SD	0.20	0.26	0.19	0.23	1.52	1.15	0.98	0.86	0.41	0.35	0.39	0.35

RWI1, chronology at 0.07–0.15 m stem height; RWI2, chronology at 1.3 m stem height; RWI3, chronology at 6.3 m stem height; RWI4 chronology at 11.0–12.0 m stem height; SD, standard deviation.

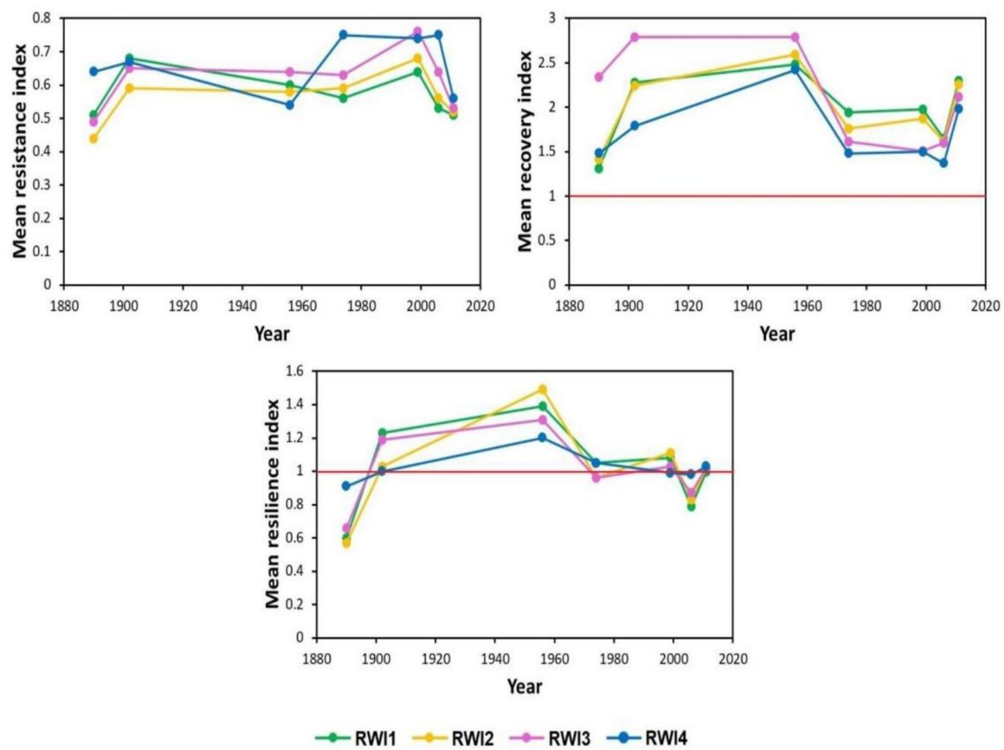

Figure 3. Variation in the resistance, recovery and resilience indices throughout the extreme droughts studied. RWI1 = sampled at 0.07-0.15 m; RWI2 = sampled at 1.3 m; RWI3 = sampled at 1.6 m; RWI4 = sampled at 11.0–12.0 m. The red horizontal lines correspond to mean indices of 1.0 for recovery and resilience, where values over this line imply a full recovery from previous drought conditions, whereas values below 1.0 are indicative that the trees had problems recovering in a four-year period after the dry conditions.

3.5. Line of Full Resilience

The observed values of *Rt* of the 50 trees represent the average for each height in each drought event. The mean values of *Rt* allowed obtaining the values of *Rch*, assuming the line of total resilience (*Rs* = 1.0). During the 1890 drought, the fewest number of trees that reached the line of full resilience occurred. In the 1902 drought, an increase was observed in the proportion of trees that reached the line of full resilience. On the other hand, in the 1956, 1974, and 1999 droughts, RWI1 and RWI2 had the highest number of trees that exceeded the full resilience line. However, in the 2006 drought, a marked drop in tree number was observed, increasing again for the 2011 drought. RWI1 (green dots) generally showed the lowest *Rt* values, which coincided with the highest *Rc* values (Figure 4).

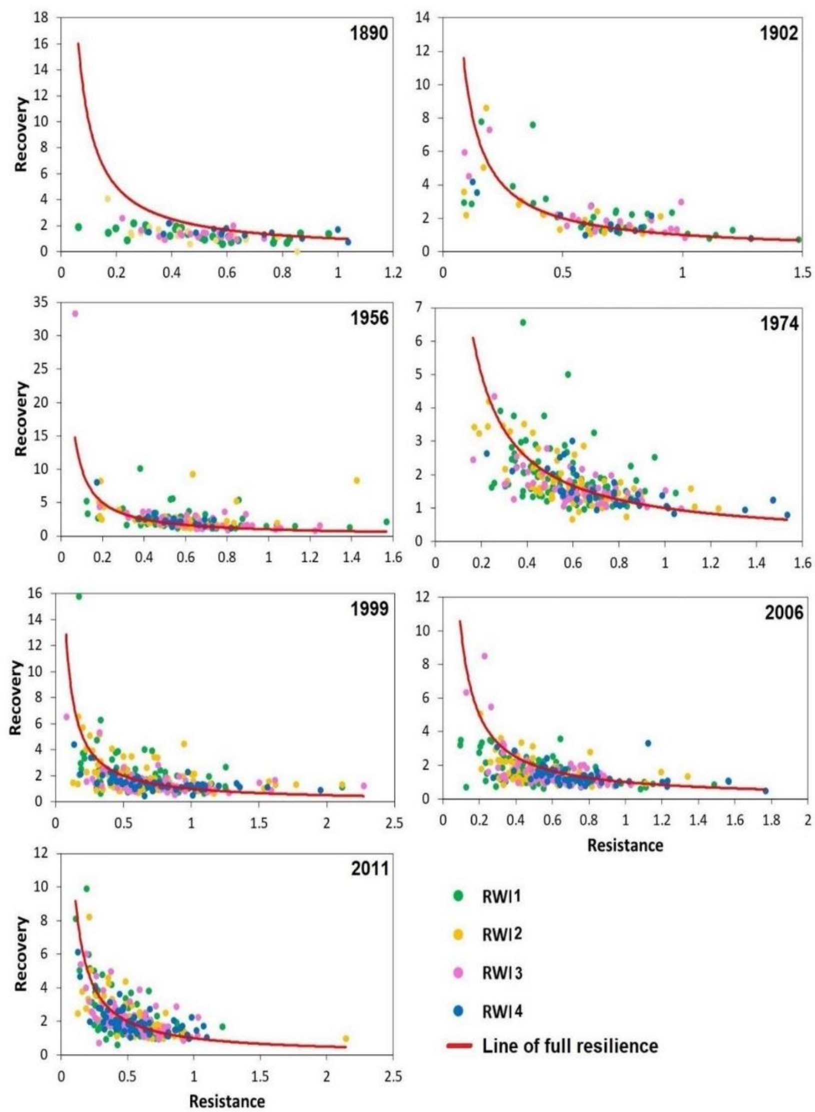

Figure 4. Relationship between the mean *Rt* and *Rc* values observed at different tree stem heights in *P. durangensis* and the hypothetical function representing the line of full resilience at any *Rt* value for each extreme drought year. The dots represent the samples of RWI1, RWI2, RWI3, and RWI4. RWI1 = sampled at 0.07–0.15 m; RWI2 = sampled at 1.3 m; RWI3 = sampled at 1.6 m; RWI4 = sampled at 11–12 m.

3.6. Growth Response of *P. durangensis* to Drought

A marked reduction in growth was found in all four RWI in the 1890, 2006, and 2011 drought events, while the 1956 drought was associated with a slight increase in growth in all four RWI. In the 1902 drought event, an increase in the growth of RWI1 and RWI3 and a growth decrease in RWI2 and RWI4 was found. In the 1974 drought, there was a slight increase in growth for RWI1, RWI2, and RWI3, respectively (Figure 5).

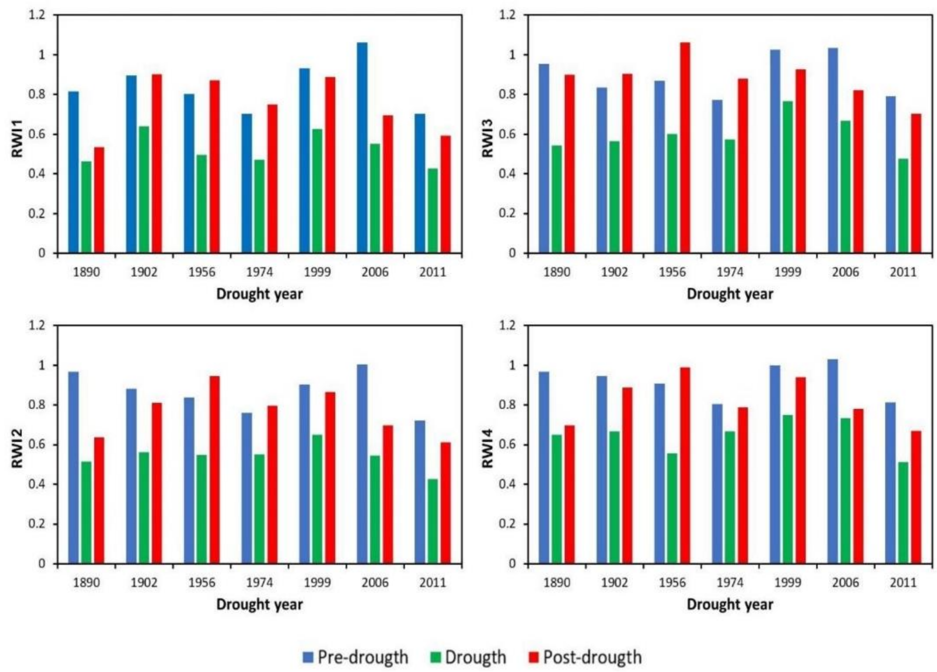

Figure 5. Impacts of seven drought events on forest growth at different stem heights in *P. durangensis* assessed over an average of four years pre-drought, during the drought year, and four years post-drought.

4. Discussion

The results of this study represent the first research of its kind in Mexico. Although these studies generally require destructive sampling and subsequent processing of samples (cross-sections), which is time-consuming and expensive [50,51], they are needed to improve our understanding of the response of tree growth to climate, specifically to extreme droughts. Besides, these elements can be useful for implementing climate change adaptation measures. More importantly, this type of information can be generated more easily in managed forests.

4.1. Dendrochronological Statistics

The dendrochronological statistics indicated high climatic sensitivity in the four series, confirming the potential of this species in the analysis of climatic signals from tree rings. SI values for series collected at different tree stem heights ranged from 0.60 to 0.65 and increased along the stem height. In general, these values suggest an adequate common response between chronologies [52] and are consistent with the report for this species by Villanueva-Diaz et al. [17], who documented an SI of 0.68. In addition, our results coincide with those reported by Martínez-Sifuentes et al. [53], who found an SI of 0.54. MS values ranged from 0.30 to 0.38, reflecting a lower sensitivity as stem height increases. These findings are consistent with data reported from similar studies [54,55].

EPS values for the four series greatly exceeded the minimum acceptable limit of 0.85 and are higher than those reported for coexisting species [56,57]. The assessment period was selected using SSS, considered a more appropriate statistic for determining the common period in chronologies with an intensity threshold of 0.85 [43,46].

4.2. Growth-Climate Relationship along the Stem

Pinus durangensis showed a positive and significant association with $SPEI06_{FM}$ for the four-growth series, with values from 0.56 to 0.80. These results demonstrate the growth response of the species at short time scales, consistent with observations for other conifer species inhabiting temperate zones of northern Mexico [58,59]. The lowest association with $SPEI06_{FM}$ was observed in RWI1 and RWI4, in line with the findings reported by Bouriaud et al. [54], who recorded a lower impact of drought in the upper part of the tree stem. An explanation for the low relationship at this stem height may be related to the proximity of RWI4 to the tree canopy, which is one of the principal carbon (C) sinks. In this portion of the tree, sugars are delivered earlier than in other portions. During drought, C assimilation rates are reduced, and transport is affected, both of which have a greater impact on the lower portion of the stem [33,60].

On the other hand, the highest relationship between growth and climate was observed in the RWI1 and RWI3 sections of the stem, which are considered more sensitive to weather variations than section RWI2, i.e., diameter at breast height (DBH). This indicates that considering only growth at breast height may lead to underestimating the influence of climate on *P. durangensis* growth and, therefore, the impact of climate change on productivity—a process associated with carbon dioxide capture and the adaptation of this species to global warming [61].

4.3. Resilience Indices along the Stem

The seven extreme drought events identified (1890, 1902, 1956, 1974, 1999, 2006, and 2011) coincided with drought periods previously documented for northern Mexico [62]. The response of the four ring-width series in the driest years was similar and consistent with the findings reported for forests of northern Mexico [63].

The result of the analysis of *Rs* indices suggests that the response of *P. durangensis* trees is largely driven by drought intensity, as shown for other species in previous studies [64,65]. The severity of drought events was quantified based on the variability of pre- and post-drought growth, which has been shown to be the main driver of the response of trees to drought [66]. Our results suggest the possibility of a cumulative effect on *P. durangensis Rt* to the 1999, 2006, and 2011 droughts in three (RWI1, RWI2, and RWI3) of the four ring-width series studied. This effect was also evident with a similar variation in *Rc* and *Rs*, with a marked decrease from the 1956 drought in the four-chronology series studied. This may be due to the higher recurrence and intensity of dry periods in northern and central Mexico in recent decades [56,62,67].

The average *Rt* at different stem heights indicated variations from 0.44 to 0.76 (Table 3), indicating that mean radial growth decreased between 56.0% and 24.0% in extreme droughts. This finding is consistent with the one reported by Castrruita-Esparza et al. [68] for *Pseudotsuga menziesii* (Mirb.) Franco, with radial growth reductions of more than 50% under extreme drought. The mean *Rc* by stem height showed values above 1.0 (1.31 to 2.79), indicating that once the drought ended, radial growth increased by 31.0% to 179.0% relative to the growth recorded in the drought year. These results are consistent with those reported for other tree species, such as *Araucaria araucana* (Molina) K. Koch in Argentina [24] and *Pinus ponderosa* Douglas ex C. Lawson in the United States [26]. However, post-drought growth shows a significant decrease relative to pre-drought growth in most cases (Figure 5). This trend may be due to the inherited effects on the long-term post-drought recovery capacity, which may lead to lower productivity as a consequence of reduced radial growth [21].

At the event scale (horizontal averages, Table 3), the 1999 drought resulted in a reduction of up to 76.0% in radial growth. The most remarkable *Rc* response (2.79) occurred after the 1902 drought, while the greatest *Rs* was related to the 1902 and 1956 events

(1.23 and 1.49, respectively) when the trees were young and could recover more rapidly from drought [26,69].

The line of full *Rs* showed that in 1890, most of the trees sampled could not return to the pre-drought growth rates in any series at the different tree stem heights. This event has been reported in different studies as a severe drought associated with La Niña events that lasted for several years [62,70,71]. Therefore, the trees did not recover the pre-drought growth rates. From 1902 to 1974, we recorded an increase in the number of trees reaching pre-drought growth rates, with higher rates in RWI1. However, from 1999 to 2011, the number of individuals achieving pre-drought growth rates decreased again, confirming the significant impact of recurrent droughts in recent decades. The slow growth rate of *P. durangensis*, a species inhabiting temperate zones, can favor *Rt* because slow-growing trees are able to use reserve resources to withstand periods of extreme drought. However, this does not warrant a total post-drought recovery [72–75].

On the other hand, the analysis carried out in this study using tree-ring series at different stem heights supports the hypothesis that the recovery of growth is not homogeneous along the tree stem [25]. The highest values of *Rc* were observed in RWI3 in the first three droughts (1890, 1902, and 1956). However, in the four most recent droughts (1974, 1999, 2006, 2011), RWI1 presented the highest values of *Rc*. In this sense, it has been proposed that under hydric stress, trees may modify their pattern of photosynthate allocation, deriving fewer resources to crown growth and carbon assimilation and a greater allocation to root growth. This strategy captures additional water and, therefore, reduces the growth-limiting effects of this factor [76,77]. However, the practical result of this research indicates that tree-ring sampling at the soil level (0.07–0.15 m) captures the most important information to analyze changes in trees' resilience.

One aspect to be considered in the recovery of tree growth is ecosystem hysteresis since, in the face of climate change effects, forest ecosystems may show a certain lag in recovery (delayed growth response); in some cases, returning to the historical growth rate is no longer possible [11]. It has been observed that the growth recovery of forest ecosystems after a disturbance event varies with local climate and species, with trees of the family *Pinaceae* being the most susceptible and least resilient [9]. Our results showed that it took four years on average for trees to recover the pre-drought growth rate, consistent with Anderegg et al. [9], who reported recovery times between one and four years for chronologies obtained in different parts of the world. On the other hand, it is worth mentioning that after the 1890 drought, it took ten years for trees to reach pre-drought growth levels, a period with no extreme drought events. In contrast, in the case of the 2006 extreme drought event, trees had not fully recovered their pre-2006 growth rate when another extreme drought event occurred in 2011. These findings demonstrate that the high frequency of droughts resulting from climate variations, either naturally or attributed to climate change, may compromise the recovery of *P. durangensis* growth to drought.

4.4. Management Implications

The *Rs* results observed in the present and other studies highlight the need for actions aiming to increase tree drought tolerance. In this regard, forestry has been mentioned as a valuable tool for this purpose [77]. For instance, the growth-climate association has been found to be weaker or decoupled after forest thinning [30]. By increasing the number of resources available for the remaining trees, greater tolerance to extreme weather conditions would be expected [33]. However, some issues related to the benefits of thinning still need to be explained, including how thinning affects climate sensitivity, dependence on growth in the previous year, and the duration of thinning effects [30]. In line with the findings of the present study, further studies should explore the impact of silvicultural activities on drought stress in trees of *P. durangensis* and other species growing in mixed forests in the study area.

Finally, since the *Rs* of trees to extreme drought results from complex interactions acting simultaneously at different spatial and temporal scales [24], future studies should also analyze the resilience of *P. durangensis* along its distribution gradient and consider the factors affecting site quality and the characteristics at the tree level.

5. Conclusions

The growth response to drought differed according to tree stem height in *P. durangensis*. Our results showed that the part of the stem closest to the ground (0.07–0.15 m) exhibited better climate sensitivity. Therefore, the remaining stumps in cutting areas would preserve important dendrochronological information. Drought resistance was generally better in the upper part of the stems. Although recovery was better in the upper parts (RWI3) in the first three drought events, the lower part of the tree stem (RWI1) showed the largest recovery in the last four drought events. In terms of resilience, the latest three drought events have been more frequent and severe, undermining the resilience capacity at different tree stem heights in *P. durangensis*.

The results of the present study refer to *P. durangensis* in the study region. However, they represent a step forward in understanding the behavior of tree growth along the stem, laying the grounds for future studies on this and other tree species in the Sierra Madre Occidental, Mexico.

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CHAPTER V: GENERAL CONCLUSIONS

In addition of being a species with high ecological and economic value in northern Mexico, *Pinus durangensis* was found to have a high dendroclimatic potential. The high positive correlation between the annual radial indices of *P. durangensis* and the SPEI06 from February to May indicates that the growth of the species is limited by the availability of soil moisture from the end of the winter to the spring season. New records of the ring-width series of *P. durangensis* were developed, which allowed a reconstruction of SPEI for near the last three centuries. The SPEI reconstruction for the northwestern region of the state of Durango allowed us to identify extreme drought episodes, trends and increases in their frequency and intensity in the last century. Therefore, the tree-rings of *P. durangensis* are suitable as a proxy for the reconstruction of historical climatic events in this region of northern Mexico.

A decreasing temporal trend in the resilience of *P. durangensis* to drought was detected, which suggests that the cumulative effect of this phenomenon represents a determining factor in the ability of trees to overcome the negative effects of drought on growth. Even though the recovery rates increased in the last two analyzed droughts, the potential recovery could be compromised if the disturbances occur with greater intensity and frequency due to global warming, which could cause an effect known as "dieback" and lead to the final death of individuals of this species.

The results showed that the radial growth of *P. durangensis* along the stem responded differently to climatic variations and, therefore, resilience and its components also showed variations.

The climatic sensitivity of *P. durangensis* decreased at higher stem height, so analyzing radial growth only at breast height (1.30 m) could underestimate the influence of drought on the growth and adaptation of the species to the disturbances caused by climate change. The results of this study are specific to *P. durangensis* in the northwest region of the state of Durango. However, these results constitute a baseline for similar research to be carried out for the same species throughout its distribution area, as well as for other associated tree species present in different sites in the Sierra Madre Occidental.