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Earlywood and Latewood Widths of *Picea chihuahuana* Show Contrasting Sensitivity to Seasonal Climate

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Abstract: The existence of endangered tree species in Mexico necessitates an understanding of their vulnerability to the predicted climate changes (warming and drying trends). In this study, the sensitivity to climate of earlywood (*EW*) and latewood (*LW*) widths of the threatened *Picea chihuahuana* was determined. The response of *EW* and *LW* to climate variables (maximum temperature, minimum temperature, precipitation, evaporation, and a drought index) was analyzed by means of correlation analysis using dendrochronology over the period of 1950–2015. *EW* and *LW* production were enhanced by cool and wet conditions during winter prior to the start of growing season. During the growing season, *EW* and *LW* production increased in response to cool spring and summer conditions, respectively; temperatures and year-round evaporation, excluding summer and the previous drought in the period prior to the growing season. *EW* was sensitive to seasonal drought, which is a concern considering the predicted aridification trends for the study area. These results provide further knowledge on the dendroecological potential of *Picea chihuahuana*.

Keywords: dendroecology; drought; forest; Mexico; radial growth

1. Introduction

Climate variability drives forest productivity and tree growth [1–3]. The implications of forecasted warmer and drier conditions become crucial to predicting forest productivity in Northern Mexico where the frequency of severe drought is expected to increase [4]. This region possesses a floristic diversity recognized worldwide [5], with the presence of endangered conifer species, such as *Picea chihuahua* Martínez, located in relic forests at the Sierra Madre Occidental [6]. *P. chihuahuana* is a tree species endemic to the Sierra Madre Occidental (Northern Mexico), and is currently considered to be in danger of extinction [6]. Approximately 42,600 *P. chihuahuana* individuals are distributed in 40 scattered populations covering less than 300 ha [7,8]. However, knowledge of the ecological responses of these threatened tree species, including the quantification of seasonal radial-growth responses to climate, is still scant [9,10]. We argue that this information is very valuable to improve the conservation of relict or threatened tree species which have to face more arid conditions as those forecasted for Northern Mexico [4].

Dendroecology has been used as a tool to know the temporal responses of trees to their environment, including climate variability [11]. Dendroecological studies allow recovering growth information at annual up to seasonal scales if earlywood width (hereafter *EW*) and latewood width (hereafter *LW*) are separately measured [12,13].

Overall, Northern Mexico is still an underrepresented geographic region for tree-ring research. Nevertheless, some dendroecological and dendroclimatic studies have been carried out for different tree species in Mexico. Pompa-García and Domínguez-Calleros [12] evaluated the response of *EW* and *LW* to drought for a conifer representative of Northern Mexico forests (*Pinus cooperi* C.E. Blanco). Carlón et al. [14] studied the influence of temperature and precipitation on the radial growth of *Pinus pseudostrobus* Lindl. and *Abies religiosa* (Kunth) Schltdl. and Cham. Santillán-Hernández et al. [1] determined the climatic sensitivity of *Pinus pinceana* Gordon and Glend. and its potential for dendroclimatic reconstructions in several regions of Mexico. Lastly, Villanueva-Diaz et al. [15] conducted dendrochronological analysis of old Montezuma cypress (*Taxodium mucronatum* Ten.) to recover climatic information. However, few studies have considered *EW* and *LW* data in Mexican forests, particularly considering threatened tree species, such as *P. chihuahuana*.

Apart from Mexico, in other regions of North America several studies have used tree-ring data at seasonal scales. For instance, Anchukaitis et al. [16] reconstructed the summer temperatures of a maximum density chronology of *LW* density *of Picea glauca* (Moench) Voss. Griffin et al. [17,18] conducted studies to verify the viability of *LW* chronologies of *Pseudotsuga menziesii* Mirb. as drought proxies in southwestern U.S.A. Torbenson et al. [19] analyzed the relationships between *EW* and *LW* series of many tree species across North America. Kerhoulas et al. [20] used tree ring records, local climate data, and oxygen stable isotopes to examine the importance of monsoon precipitation for LW production in mature ponderosa pines (*Pinus ponderosa* Dougl.) from Northern Arizona. In the same way, in Europe, Miina [21] considered *EW* and *LW* series of *Pinus sylvestris* L. and *Picea abies* (L) Karst as a function of climate variability. However, to date in Mexico there has been no study for *P. chihuahuana EW* and *LW* series with respect to year-to-year climate variability.

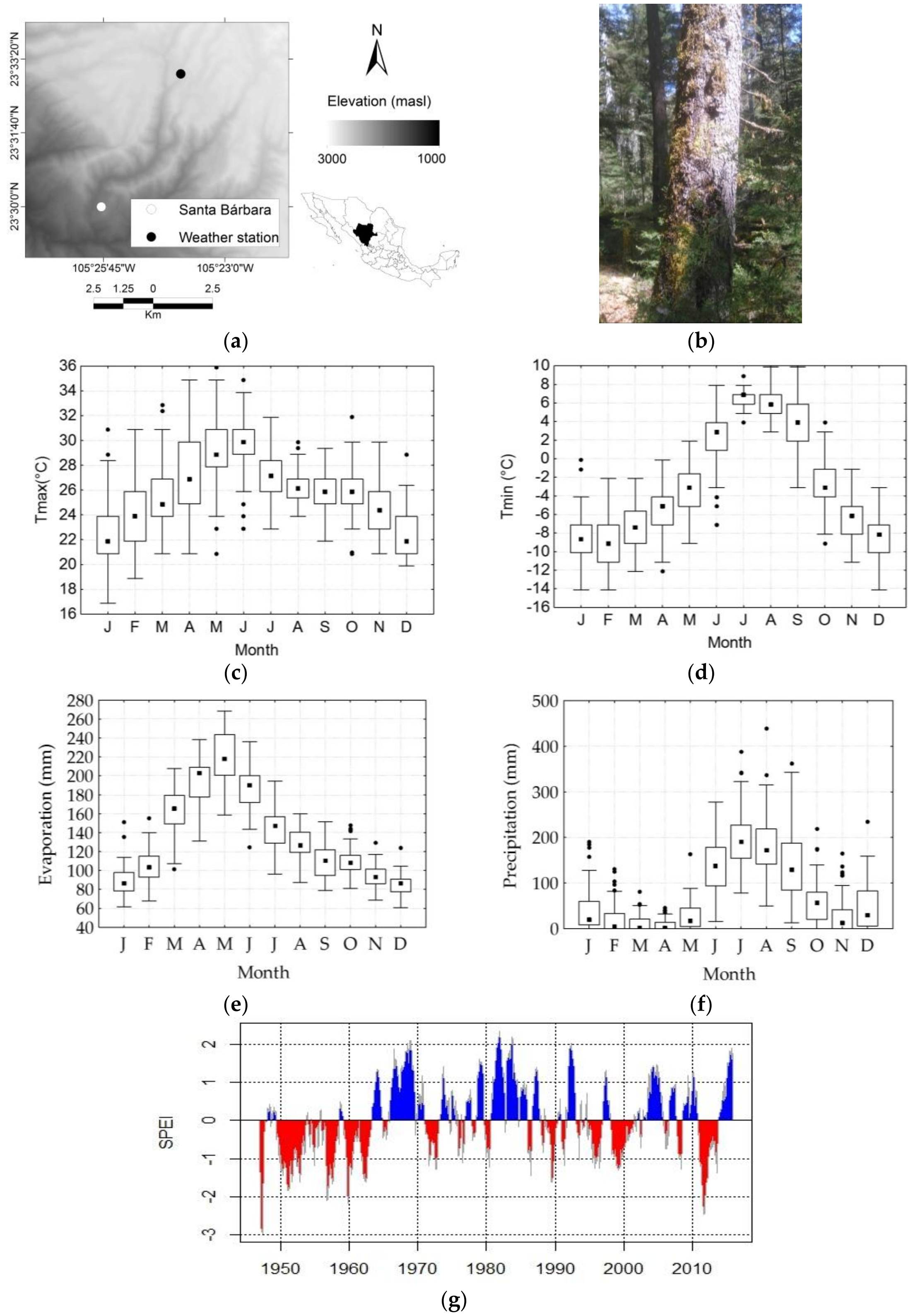
The main objective of this study is to analyze the dependence of *EW* and *LW* of *P. chihuahuana* on climate variability considering the following variables: precipitation, evaporation, drought, and maximum and minimum temperatures. We also analyzed how *EW* and *LW* are influenced by drought severity. Since *EW* and *LW* are formed during different seasons, we expect that they would reflect different climate constraints.

2. Materials and Methods

2.1. Study Area

The study area is located in a protected natural forest known as Santa Bárbara, located at 23°29′ N and 105°25′ W, about 20 km south of the city of El Salto, Durango, Northern Mexico (Figure 1). The Santa Bárbara forest is a suitable place for this study because it is one of the southernmost distribution limits of *P. chihuahuana* [6,22,23], and it is a high-conservation value forest free of recent management changes (e.g., logging) according to the Local Forest Management Program (Ejido El Brillante, Durango, Mexico).

In the study site *Picea chihuahuana* Martínez coexists with *Abies durangensis* Martínez and *Pseudotsuga menziesii* (Mirb.) Franco in an area of approximately 20 ha. The latitude of this site provides a warm climate that is rare for forests where these three species coexist [21]. The climate is temperate-subhumid [24] with a cool and humid summer as a result of the influence of monsoons and characteristic dry conditions in spring and winter. The monthly maximum evaporation values are observed in April (200 mm) and May (220 mm) (Figure 1). Soils in the study area are Cambisol, Lithosol, Regosol, and Phaeozem types [25].



(**a**) (**b**)

(**c**) (**d**)

(**e**) (**f**)

(**g**)

Figure 1. (**a**) Location of the study area, (**b**) photograph of a sampled tree, and (**c**–**g**) monthly climate conditions: (**c**) maximum temperature, Tmax, 1946–2015 period; (**d**) minimum temperature, Tmin, 1946–2015 period; (**e**) evaporation, 1965–2010 period; (**f**) precipitation, 1946–2015 period; (**g**) SPEI drought index, period 1946–2015. Blue and red bars indicate positive and negative SPEI values corresponding to wet and dry conditions, respectively.

2.2. Dendrochronological Methods and Data Processing

Since the tree species under study is endangered, a total of 20 trees were sampled and used for their dendrochronological processing. Two radial cores were extracted at 1.3 m from the base of the trees using a Pressler increment borer. The extracted tree cores were polished using sandpapers of fine grits to highlight their ring boundaries. Tree rings were recognized and visually cross-dated following standard dendrochronological techniques [26].

Climatic conditions in the study area are similar to those recorded in the nearby "El Salto" climate station. Nevertheless, a correction (environmental lapse rate of 6.49 K km $^{-1}$) was applied to temperature data [27].

EW represents the light-colored and less-dense part of the tree ring, whereas *LW* is the darker-color wood forming the last part of the ring [17]. After cross-dating the samples, *EW* and *LW* were distinguished following this criterion. Then, *EW* and *LW* were separately measured from the most recent ring width to the pith along two radii per tree under a binocular microscope with a resolution of 0.01 mm using a measuring LINTAB device (Rinntech, Heidelberg, Germany). The previous visual cross-dating was checked using the program COFECHA (Laboratory of the Tree-Ring Research, University of Arizona, Tucson, AZ, USA), which compares all ring-width series with the master chronology built averaging the annual ring-width data [28]. To remove non-climate-related biological and geometric trends due to the stem enlargement and tree aging, the *EW* and *LW* raw series were standardized with the R statistical software using the library *dplR* [29–31]. Negative exponential functions were fitted to *EW* and *LW* data to obtain the residual series. This conservative detrending was used to preserve as much high-frequency variability as possible while maximizing the climate signal [32]. The first-order autocorrelation was removed from these residuals which where averaged using bi-weight robust means to obtain mean pre-whitened or residual *EW* and *LW* series or chronologies. Mean, standard deviation (SD), and first-order autocorrelation (AC) were calculated for the *EW* and *LW* raw data, the other statistics were calculated using *EW* and *LW* indices. These statistics included: the mean sensitivity (MS), which measures the relative difference in width among consecutive rings [33]; the mean correlation among trees (r_{bt}); and the expressed population signal (EPS). The quality of the chronologies was evaluated through the EPS value, in which values exact or superior to 0.85 correspond to well-replicated periods [34].

Pearson correlation analyses were performed to assess the *EW* and *LW* responses to climate variables by relating residual *EW* and *LW* mean series to monthly climate variables: precipitation, maximum temperatures, minimum temperatures over the period 1946–2015, and evaporation (measured using an evaporimeter) from 1965–2015. The variables were obtained from the nearby climatological station of El Salto 23°47′00″ N, 105°22′00″ W, 2560 m a.s.l. (meters above sea level). To characterize drought severity, we used the standardized precipitation evapotranspiration index (SPEI), a multi-scalar drought index based on the standardized monthly climatic balance computed as the difference between the cumulative precipitation and the potential evapotranspiration, which was estimated using local climate data and the SPEI R statistical package [35,36]. Based on previous studies, we related *EW* and *LW* series with the SPEI calculated at 1–9 month-long scales from January to September [10,12]. Positive SPEI values indicate a positive water balance (wet conditions), whilst negative SPEI values indicate water deficit and dry conditions [35,36].

Finally, field spatial correlations were calculated using Pearson coefficients. In this correlation, the *EW* and *LW* series and six-month long SPEI data (gridded at 0.5° resolution) were related from January to May considering the 0.5° grids covering Mexico and the southern conterminous USA. The KNMI webpage was used for these analyses [37,38].

3. Results

Considering the common and best-replicated 1946–2015 period, the *EW* and *LW* showed similar variability and first-order autocorrelation, but the *LW* showed a lower year-to-year variability (MS) and coherence between trees (r_{bt}, EPS) than the *EW*. The EPS showed values lower than 0.85 (*EW* = 0.84, *LW* = 0.77) due partly to mesic site conditions in which this species grows and the reduced sample size; this being justified considering that *P. chihuahuana* is a protected species and to obtain samples a special permit was obtained that restricted the number of cores extracted (Table 1). *EW* and *LW* showed similar temporal variability (r = 0.70; Figure 2), with increases in 1935 and noticeable decreases during the 1970s and onwards. The total length of the chronology is 115 years.

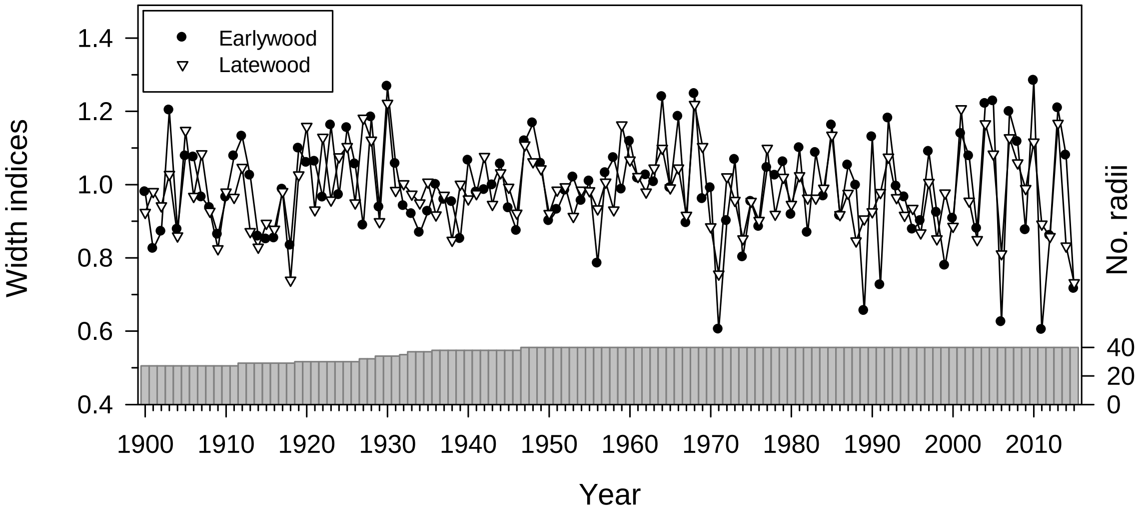


Figure 2. High-frequency variability observed in earlywood and latewood width indices of *Picea chihuahuana* since 1900. The bars show the number of measured radii (right y axis).

Table 1. Dendrochronological statistics for *EW* and *LW* data for the best-replicated period 1946–2015.

	Raw Data		Residual Indices			
Variable	**Mean ± SD (mm)**	**Coefficient of Variation (%)**	**AC**	**MS**	**r_{bt}**	**EPS**
EW	1.22 ± 0.60	49.6	0.75	0.27	0.24	0.84
LW	0.35 ± 0.17	51.4	0.71	0.27	0.18	0.77

SD = standard deviation; AC = first-order autocorrelation; MS = mean sensitivity; r_{bt} = correlation between trees; EPS = expressed population signal.

Precipitation from December–March had a positive relationship with *EW*, while for *LW* it only had a positive relationship in January (Figure 3). Regarding the maximum temperature, a negative association was obtained for *EW* in February and May of the year of tree-ring formation, whereas *LW* showed a negative relationship with June minimum temperatures. January minimum temperatures showed a positive relationship to *LW*, but negative relationships were observed with both *EW* and *LW*, considering June minimum temperatures. *EW* and *LW* showed negative correlations with evaporation data of the previous October, but also in winter (December–February) of the current year, in spring (April, May) in the case of *EW*, and May for *LW*.

The *EW* and *LW* series of *P. chihuahuana* showed positive responses to the SPEI, i.e., *EW* and *LW* production increased when drought severity decreased, with the highest values of correlation observed for three to six-month-long scales, and from January to May. In the case of *EW* we observed a maximum Pearson correlation coefficient of 0.55 (six-month-long SPEI, May) and for *LW* the maximum correlation was 0.28 (Figure 4).

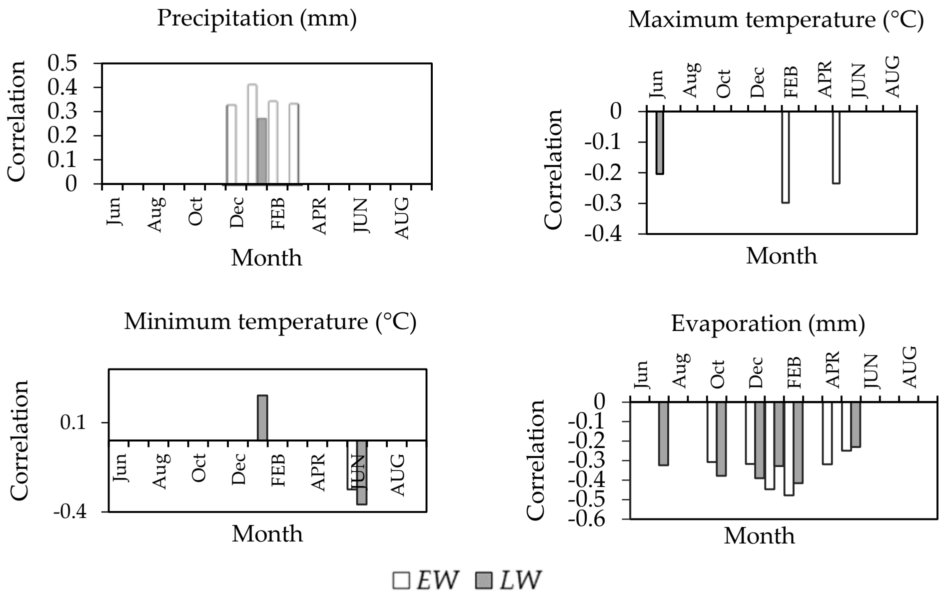


Figure 3. Significant ($p < 0.05$) correlations between earlywood (*EW*, empty bars) and latewood (*LW*, filled bars) indexed width chronologies of *Picea chihuahuana* and monthly climatic data. Months written in lower case letters indicate the prior year, whereas those written in upper case letters correspond to the year of growth. Only correlations significant at $p < 0.05$ are reported.

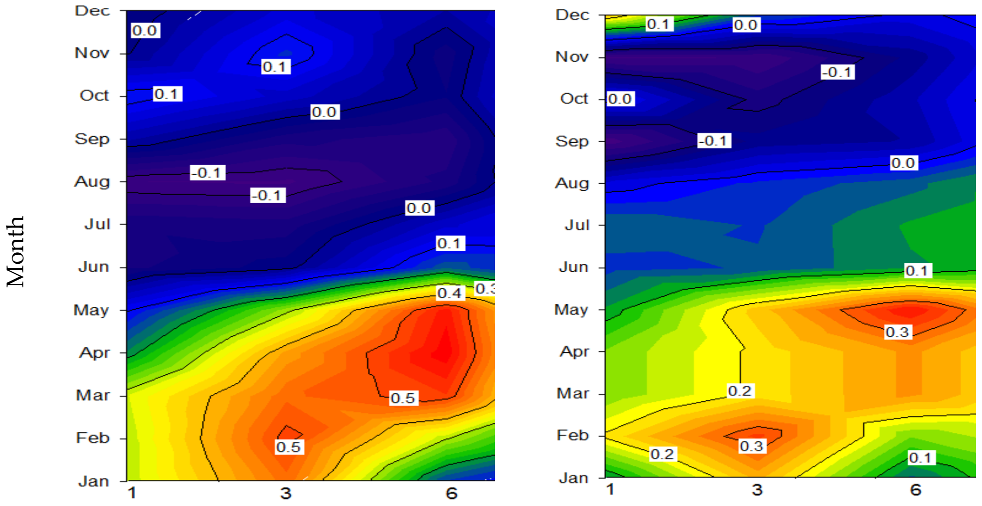


Figure 4. Drought-growth association calculated for *Picea chihuahuana* relating the SPEI drought index with residual earlywood (*EW*) and latewood (*LW*) mean chronologies. The value is assigned to the last month of the cumulative SPEI period.

Finally, the results obtained from the field correlation between *EW*, *LW*, and six-month-long SPEI values showed positive relationships, always stronger for *EW* than for *LW*, and spatially centered in Northern Mexico and the Southern USA (Figure 5). Only the months of April and May are presented because they showed the highest correlations with *EW* and *LW* data. The spatial correlations indicate that large-scale climate phenomena influence the radial growth of *P. chihuahuana* (Figure 5).

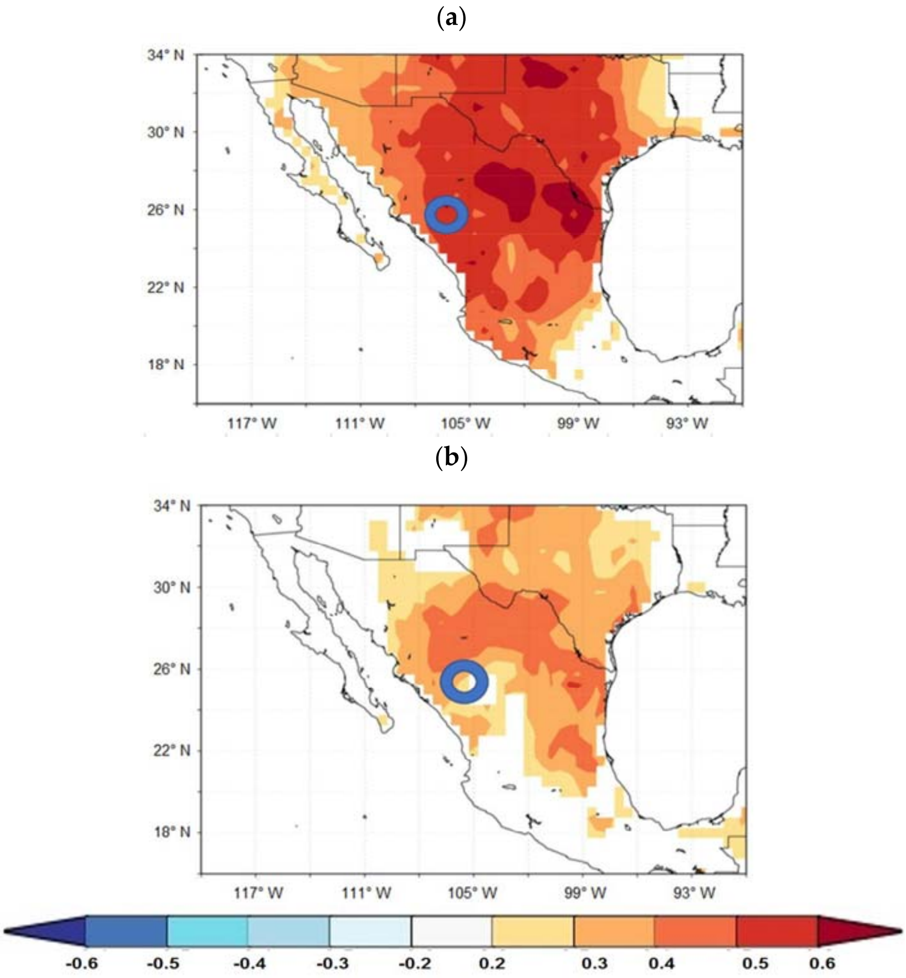


Figure 5. Spatial correlations of *EW* (**a**) and *LW* (**b**) residual chronologies and six-month long SPEI for April (**a**) and May (**b**) across Mexico and the Southern U.S.A. Field correlations show $p < 0.10$ in both cases. The blue circle shows the approximate location of the study site. The color scale shows the correlation values.

4. Discussion

This research constitutes a first approximation towards understanding the dendroclimatic potential of *EW* and *LW* measurements in the relict *P. chihuahuana*, an endangered tree species from Northern Mexico. The common variability between years in *EW* and *LW* (Table 1) resemble that of other conifer species in Northern Mexico, such as *Pinus piceana* Gordon and Glend. [1], or *Pseudotsuga menziesii* Mirb. [10].

The AC values of *EW* and *LW* agree with what it has been reported in other Mexican conifer species, such as *Pinus cooperi* [12], or for other tree species from drought-prone sites in the Mediterranean Basin, such as *Pinus nigra* [39]. The higher coherence between trees considering *EW* data indicates that this type of wood better reflects climate variability as previously found [12,17,40].

The positive relationship of *EW* and *LW* and winter rainfall agrees with what has been previously reported [41]. The positive relationship is due to the fact that, in Northern Mexico, the growth of conifers is influenced by the precipitation of the winter–spring period since much of this rain water is stored in the shallow sub-surface and can be used by trees during the early growing season in late winter and early spring [25,42]. The effect of winter precipitation on *LW* production is remarkable since it is assumed that the latewood is not produced in winter. However, the much later indication that *EW* and *LW* production are related may possibly be due to external processes (soil water storage) or internal mechanisms (improved synthesis of carbohydrates in late winter and spring used for *LW* production) [43,44].

LW showed a positive response to January minimum temperatures, which probably favored cambial activity, and a negative response to June minimum temperatures which can be caused by an enhanced respiration and an increased consumption of carbohydrates, reducing cambial activity [45]. With regard to maximum temperatures, *EW* had a negative response to warm February and May conditions, probably because respiration increased, more carbohydrates were consumed, or evapotranspiration was too high, increasing the vapor pressure deficit and leading to drought stress, which may trigger stomata closure and reduce photosynthesis rates [25,46].

The growth–drought associations were characterized by the positive relationships detected between SPEI and *EW* or *LW* production (Figure 4). These relationships indicate that warm and dry conditions and high evapotranspiration rates lead to reduced growth in *P. chihuahuana*, whereas cool, wet conditions enhance wood production, particularly in the case of *EW*. This agrees with what different authors reported in similar studies conducted in sites subjected to seasonal drought [47–49]. The spatial correlations between *EW*-*LW* chronologies and SPEI (Figure 5) agree with findings published regarding several pine species coexisting in a nearby area [32]. This confirms the existence of large spatial signals between *EW* and drought severity across semi-arid areas of Northern Mexico and the Southern USA confirming the value of seasonal wood production as climate proxies in this region [17,18]. Such broad-scale patterns seem to be connected to the ENSO (El Niño Southern Oscillation) variability since droughts are often connected with La Niña episodes [32,50,51]. These dry periods are forecasted to be longer and more intense according to diverse climate models [52].

Several authors have verified that the winter rains of the year prior to the growing season contribute to the growth of trees. This occurs because rain is usually of low intensity and occurs when evapotranspiration is low, which favors its infiltration into the soil and improves the long-term storage of water in deep soils, resulting in positive soil water balances and enhanced tree growth [40,49,50]. This agrees with the results obtained for this study, which report a positive correlation among winter–spring rainfall and *EW* production. If forecasted climate conditions lead to intensified aridification in Northern Mexico [52], we anticipate a reduction in *EW* production that will lead to a decline in the stem hydraulic conductivity and negatively feedback on forest growth and productivity [35,36,51].

5. Conclusions

Seasonal radial growth of the endangered conifer *Picea chihuahuana* shows a high sensitivity to climate. In this species, the production of earlywood is enhanced by cool, wet winter conditions across Northern Mexico and a low severity of mid-term (five to six-month-long) droughts across Northern Mexico. The production of latewood also depends on earlywood production and on the winter–spring water balance. The latewood is less sensitive to climate variability and shows a less coherent signal among coexisting trees than the earlywood. Similar dendroecological studies could provide valuable data at seasonal and annual resolution of the long-term growth responses of similar threatened tree species to hydroclimate variability. Such tree-ring data can be used to predict the vulnerability of these tree species to the forecasted warmer and drier conditions in drought-prone areas.

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Author Contributions: C.C.-A. developed the experiment; M.P.-G. conceived and designed research; M.P.-G., A.C.A.-H., J.M.Z.-V. and J.J.C. contributed to data analyses. All authors discussed and contributed to the writing of the manuscript.

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