Article

Assessment of the dendroclimatic potential of *Pinus lumholtzii* B. L. Rob. & Fernald

Martha González Elizondo[1*]

María del Socorro González Elizondo[1]

José Villanueva Díaz[2]

Julián Cerano Paredes[2]

[1] CIIDIR-Durango, Instituto Politécnico Nacional. México.

[2] CENID RASPA, INIFAP. México.

[*]Autor por correspondencia, email: martha_gonzel@yahoo.com.mx

Abstract:

Pinus lumholtzii is widely distributed in the Western *Sierra Madre*. It grows mainly in rocky outcrop sites; therefore, its annual growth rings may be sensitive to climatic variables. Ring-width chronologies of *Pinus lumholtzii* from sites in southern *Durango* were developed in order to analyze its dendroclimatic potential. For this analysis, dendroclimatic parameters and response to climatic factors were compared with a chronology of *Pseudotsuga menziesii* previously developed for the same region with proven dendrochronological potential. Our results indicate that *P.*

lumholtzii dendroclimatic chronologies have a good potential. They presented suitable cross-dating, although their sensitivity to environmental factors was lower than that observed in *P. menziesii* chronologies. In addition, the four chronologies showed significant correlations between one another and also compared to the chronologies of *P. menziesii*, which indicates a good response to the regional environmental variables. Furthermore, the correlation between growth rates of *P. lumholtzii* and the regional precipitation was statistically significant and even higher than that obtained for *P. menziesii*. The rainfall reconstruction using ring-width series of *Pinus lumholtzii* was significantly correlated with that developed for *P. menziesii* series. The wide distribution range of *P. lumholtzii* in the *Sierra Madre Occidental*, and its proven dendroclimatic potential, enable the development of a network of chronologies that may be useful for dendroecological studies, as well as for monitoring the regional climate change.

Key words: Tree rings, dendrochronology, Lumholtzii pine, *Pseudotsuga menziesii* (Mirb.) Franco, climate reconstruction, *Sierra Madre Occidental*.

Fecha de recepción/ Reception date: 25 de abril de 2017.
Fecha de aceptación/ Acceptance date: 30 de mayo de 2017.

Introduction

One of the major limitations to the study of the variability of climate and the changes occurring in it is the shortage of instrumental climate records. Even in developed countries, reliable climate records do not date back more than 100 years (Easterling *et al.*, 1999). In Mexico, there are large geographical areas without meteorological data, and very few stations with records prior to 1940 exist (Florescano and Swam, 1995).

An alternative that partially remedies this deficiency consists in the natural climate records or climate "proxies" such as: ice cores, marine sediments, pollen, and tree growth rings. The latter are noted for their higher temporal (annual and even seasonal) resolution. Dendrochronological techniques make it possible to reconstruct the climatic variables of both the periods prior to the available climate records and the geographical areas for which there are no previous data (Villanueva *et al.*, 2000). The main species used in dendrochronology belong to Pinaceae genera (*Pinus*, *Pseudotsuga*, *Abies*, *Picea*, etc.). The enormous wealth of *taxa* of this family existing in Mexico contrasts with the scarcity of dendroclimatic studies conducted in the country (Villanueva *et al.*, 2000; Acosta-Hernández *et al*., 2017).

The detection of species with dendroclimatic potential allows the reconstruction of the climatic factors of the past, which are a basis for the study of climate variability and for the discernment between natural variations and those changes in climate that are related to human activities, as well as for the prediction of climate change in the future (Fritts, 1976).

On the other hand, the temperate forest —the main type of vegetation in which Pinaceae occur— is the most likely to disappear in Mexico, in the face of a scenario of climate change (Villers-Ruiz and Trejo-Vázquez, 1997, 1998).

Given the selective harvesting of species in these forests, natural areas without disturbance that might be used for monitoring changes are rare and little accessible in general (Lammertink *et al.*, 1996). However, the study of certain taxa like *Pinus lumholtzii* B.L. Rob. & Fernald may be a good alternative for dendroclimatic studies. Pine, commonly known as "sad pine" because of its characteristic physiognomy, is quasi-endemic to the *Sierra Madre Occidental* (Western Sierra Madre), where it grows in sites with a poor soil, and has no commercial value (García and González, 1998).

Thus, it can be assumed that its populations are less affected by human impact, compared to those species with economic importance. Furthermore, as a consequence of the poor soil on which the sad pine usually develops, it may exhibit greater sensitivity to environmental factors such as temperature and precipitation. Therefore, it is considered that the studies of the growth rings of *P. lumholtzii* might better reflect the relationship with the natural factors than studies of species of economic importance, in which their relations with environmental factors may be masked by the effect of forest management, forest fires, pests and diseases, among others.

P. lumholtzii has been used in few dendrochronological studies; González-Elizondo (2003) suggests that it may have a potential to record climatic variations at both regional and local levels and to determine that the chronologies of the lower distribution limit were more sensitive to drought than those of the upper limit. Bickford *et al*. (2011) tested the drought sensitivity of radial growth of *P. engelmannii* Carrière and *P. lumholtzii* in an altitudinal gradient in the *Chihuahua Basaseachi* National Park, in a period of 60 years (1945-2004); González-Cásares *et al.*, (2016) included a short chronology (88 years) of the sad pine, in a comparison of its dendrochronological potential with that of other sympatric *Pinus* species in the state of *Chihuahua*; Irby *et al.*, 2013 include growth centers of *P. lumholtzii* to build a composite chronology of *Basaseachi* National Park; in this case, it is a chronology of 225 years based on samples of three species —*P. durangensis* Martínez, *P. lumholtzii* and *P. engelmannii*— collected in climate-sensitive sites.

Although *P. lumholtzii* has been the objet of several dendrochronological studies, in no case has the assessment of their potential been referenced to a taxon of proven dendrochronological utility, such as *P. menziesii* Douglas ex D. Don*;* therefore, the objetive of this study was to evaluate the potential dendroclimatic potential of *P. lumholtzii* in the south of the state of *Durango*, through the implementation of the following goals: 1) to determine the potential for synchronization and dating of its annual growth rings, 2) to determine its sensitivity to environmental factors, 3) to determine the association between the annual radial growth rates of the sad pine and various climatic factors, and 4) to obtain regression models for reconstructing climatic variables in terms of the annual radial growth, and to compare the climatic reconstructions thus achieved with those obtained through similar studies for *Pseudotsuga menziesii* (Mirb.) Franco, in the same region.

As hypothesis, it is suggested that the species has adequate dendrochronological potential for paleoclimatic reconstructions due to the little disturbance to which it has been subjected, as well as to the morphological and soil conditions and the edaphic conditions under which it grows.

Materials and Methods

The field work was carried out in the southern region of the state of *Durango*, which represents, in general, the central area of the latitudinal distribution of *P. lumholtzii* (Farjon, 2013). Two sites adjacent to the road from the city of *Durango* to the *La Flor* sawmill (LFA and LFB), and two more on the road from the municipal seat of *El Mezquital* to the *Los Charcos* sawmill (MEA and MEB) were selected. The populations are located, respectively, in the upper and lower altitudinal limits of the species in each transect (Table 1). The natural vegetation is dominated by *P. lumholtzii,* which commonly forms open forests in sites with strong mother, rock outcrop or with surface stoniness and a poor, usually acid soil (García and González, 1998). At least, two samples (chips) of 40 trees of *P. lumholtzii*, chosen with the point-centered quarter method (Cottam and Curtis, 1956), and with different diameters representative of the populations, were obtained at each site.

Four chronologies of *P. lumhotzii* were built based on traditional techniques in dendrochronology for sample preparation and processing of information (Swetnam *et al.*, 1985; Fritts and Swetnam 1989). The total width (early wood + late wood) of the annual rings was measured with a precision of 0.001 mm with a Velmex measuring system and the *Medir* software (Krusic *et al.*, 1996). The analysis of the quality of the data (dating and measurement) and of the samples (average sensitivity and the presence of outliers) was carried out using the COFECHA software (Holmes, 1996). After analyzing the results of the COFECHA software, certain series with dating problems due to irregular growth, decay or fractioning of the growth centers were discarded in order to include only the most climate-sensitive and those with a common climate response.

Once the quality of the dating and the measurement was verified, the ARSTAN software (Cook and Holmes, 1996), which generates standard chronologies, was utilized. This software standardizes each individual series and removes the variance due to biological factors such as age and radial growth, as well as the variance resulting from differences in productivity between microsites and changes in the environment of the trees unrelated to the climate (Fritts, 1976; Cook *et al.*, 1991). The ARSTAN software maximizes the variance due to environmental factors that affect the population as a whole (*e.g.* climate and atmospheric factors).

In order to remove the influence of the physiological processes related to age, and at the same time preserve the low-frequency variations possibly related to the climatic trends, adjustment of a negative exponential curve or straight line with positive or negative slope was chosen as the first standardization; subsequently, a second standardization was carried out by adjusting a flexible line to preserve 50 % of the variance established at a wavelength of 128 years —a conservative procedure that removes only the monotonic trends (Cook and Peters, 1981). A rate of growth per year was immediately estimated for each individual series, by dividing the real value of the width of the ring between the corresponding value in the curve; thus, if the real growth is equal to or exceeds the estimated value, the generated index will be a value higher than or equal to the unit. Finally, the annual indices of the individual series were averaged to produce the corresponding chronology.

In order to determine the relative dendroclimatic potentiality of the sad pine chronologies, the descriptive statistics obtained for the chronologies of each of the four sites were compared among themselves and with the chronologies previously obtained for *Pseudotsuga menziesii* (Mirb.) Franco in the region (Stahle and Cleaveland, 1993; González-Elizondo, 2003). The response of the chronologies to the climate is reflected mainly in their mean sensitivity values, standard deviation, autocorrelation and signal-to-noise ratio (Fritts, 1976; Speer, 2010). A chronology is considered to have a good dendroclimatic potential if it has the following characteristics: a strong high frequency variation (a high mean sensitivity), a high standard deviation, a low first-order autocorrelation and a high correlation between series (Villanueva, 1995).

The correlation between the four chronologies and between the growth rates of each chronology and the climatic factors (precipitation) was analyzed. Regression models were used to reconstruct the regional mean precipitation from November to August for the 1787-2001 period.

Table 1. Geographical location of the four populations of *Pinus lumholtzii* B.L. Rob. & Fernald studied in the south of *Durango*.

Key	Locality	Coordinates	Altitude (masl)
LFB	Road from *Durango* to *La Flor*	23°42’16” N, 104°44’20” W	2 430
LFA	Road from *Durango* to *La Flor*	23°37’41” N, 104°44’00” W	2 700
MEB	Road from *El Mezquital* to *Los Charcos*	23°22’42” N, 104°20’30” W	2 400
MEA	Road from *El Mezquital* to *Los Charcos*	23°16’53” y 104°20’46” W	2 630

LFB = *La Flor* sawmill B; LFA = *La Flor* sawmill A; MEB = *Mezquital Charcos* sawmill B; MEA = *Mezquital Charcos* sawmill A.

Analysis of the association between the growth rates and the climate

The association between climate variability and the variability in the radial growth of *P. lumholtzii* within the study area was determined according to the precipitation data of four weather stations in the region with more than 30 years of climate records (Table 2).

Table 2. Weather stations closest to the study area with more than 30 years of climate records.

Name	Period	N. Lat.	W. Long	Altitude (masl)	Climate[1]
Las Bayas	1964-2001	23°30′	104°49′	1 840	C(E)(w2)
El Salto	1940-2001	23°47′	105°22′	2 560	C(E)(w2)
Navíos	1964-1999	23°54′	105°03′	2 492	C(E)(w2)
Otinapa	1963-1999	24°03′	104°59′	2 400	C(E)(w1)

The climatic factor and the most important period of the year for the annual growth of *P. lumholtzii* in the study area were identified based on the R-value (Pearson product-moment) and its probability that r = 0 between the annual growth rates of the chronologies for the region and the data of the total monthly and seasonal precipitation and the mean, maximum and minimum temperatures.

Given that the annual growth of the trees is affected both by the climatic conditions during the growth season and by the prevailing conditions in the months leading up to it, 18 months were considered for the analyses of correlation: the 12 months of the current year of growth and the six months prior to the year of growth (July of the previous year to December of the year of growth). Those data of the individual months that were significantly correlated with growth were combined (means in the case of temperatures and amounts in the case of precipitation) in order to obtain the monthly and seasonal climate data, which were in turn correlated with the growth rates.

The 1965–2001 period was selected to explore the association between growth rates and climatic factors, as it corresponds to the common starting period of the meteorological records in the various seasons.

Because reliable climate records are available only for a very short period, the verification process, desirable in this type of study, was ruled out. For this purpose, it would be necessary to divide the number of climate data into two parts, which would be to the detriment of the number of observations required to build predictive models (Briffa *et al.*, 1990). Instead, in an exploratory fashion, correlation coefficients were obtained for different periods in order to get a notion of the stability of the association between growth and the climate. Furthermore, in order to have comparable results to those of previous studies utilizing *Pseudotsuga menziesii* (Stahle and Cleaveland, 1993; Cleaveland *et al.*, 2003), the correlation between growth-climate for the 1965–1993 period used in these studies was also analyzed.

Based on the above results, linear regression models were built to reconstruct the regional precipitation in terms of the growth rates.

Results and Discussion

Synchronization potential and dating

The dating method of graphical representations or skeleton plots (Stokes and Smiley, 1968) proved difficult to implement in this study, due to the large number of false and lost rings detected in samples of *P. lumholtzii*. Therefore, in order to date the growth rings of the samples, the visual method of synchronization was alternatively used, and indicator rings were taken as reference with the support of previously developed chronologies of *P. menziesii* in the region (Stahle and Cleaveland, 1993; González-Elizondo, 2003). This procedure is usual and it allows a quick dating when previous chronologies of the same or different species are available for the region.

The difficulty of synchronization, or cross-dating, is common in dendrochronology. Similar problems have been detected when studying other pine in Mexico, such as *Pinus lagunae* (Passini) Passini, *P. cembroides* Zucc., *P. edulis* Engelm. (Díaz-Castro *et al.*, 2001), and *P. pinceana* Gordon (Santillán-Hernández *et al.*, 2010); as well as

P. hartwegii Lindl. (Villanueva *et al*., 2015), *Juniperus monticola* Martínez (Villanueva-Díaz *et al*., 2016), *Taxodium mucronatum* Ten. (Stahle *et al*., 2011), *Prosopis* spp. (Villalba *et al*., 2000), among others.

258 (62 %) out of a total of 415 processed samples were successfully synchronized and dated. This proportion is lower in older age classes, which indicates that it is more difficult to synchronize and date the samples from old trees (Table 3).

Table 3. Samples obtained, reviewed and dated by age classes, and proportion of samples dated in relation to the obtained and reviewed samples.

	Revised (#)	**Dated (#)**	**%**
Total number of samples	415	258	62
Aged more than 50 years	312	165	53
Aged more than 100 years	180	74	41
Aged more than 150 years	81	36	44
Aged more than 200 years	29	9	31

The percentage of synchronized and dated samples varies from 31 % (aged more than 200 years) to 62 % (of all ages). These figures are comparable and even superior to those cited for *Pinus lagunae* by Díaz-Castro *et al.* (2001), who point out that only 25 % of their samples were dated.

Characteristics of the obtained chronologies

Four chronologies were obtained for *P. lumholtzii* in the south of *Durango*. A total of 50 samples aged more than 200 years (11 of these aged more than 250 years) were collected. However, the oldest individual accurately dated and considered for the construction of the chronologies was aged 216 years; it was collected in the LFA site, where 50 % of the trees aged more than 200 years were located. The chronologies of the two sites at the highest altitude (LFA and MEA) have a greater mean length than those of the sites located at the lower distribution limit (LFB and MEB).

Compared to the chronologies of *Pseudotsuga menziesii* (González-Elizondo, 2003), a species with a recognized excellent dendrochronological potential, the four chronologies of *P. lumholtzii* reveal a mean acceptable sensitivity (0.247-0.379) and a relatively low intercorrelation (0.538 – 0.666), and have a higher proportion of segments that are little correlated with the master chronology (Table 4).

The four chronologies are superior to 100 years, with a common period to all of them extending from 1890 to 2001. The most extensive chronology is that of the LFA site (1787-2002), while the shortest corresponds to the MEB site (1890-2002). The extension of the chronologies is short, compared to those of *Pseudotsuga* (Cleaveland *et al.*, 2003) and of *Taxodium mucronatum (*Stahle *et al.,* 2012); however, it is considered equal to the chronology registered for the sad pine by Bickford *et al*. (2011) and exceeds the age indicated for *Pinus cooperi* C.E. Blanco (Cerano *et al*., 2012), *P. pinceana* (Santillán-Hernández *et al*., 2010) and *Pinus lagunae* (Díaz-Castro *et al*., 2001), as well as the age documented for *P. lumholtzii* by González-Cásares *et al.* (2016). Furthermore, given that most of the ancient forests have disappeared from the region as a result of forest extractions (Lammertink *et al.*, 1996), *P. lumholtzii* trees aged more than 250 years constitute an excellent alternative for extending dendroclimatic reconstructions, at least those of the last two centuries.

Analysis of the dendroclimatic potential of the obtained chronologies

A comparative analysis of the data of *P. lumholtzii* and *P. menziessii* according to the quality test of the COFECHA software indicates a high number of segments that might point out possible errors of dating in two of the chronologies of the sad pine, although, in fact, they were growth problems in certain series of sad pine, which are also reflected in the lower intercorrelation between the individual series that they comprise and have repercussions on their mean sensitivity.

Analysis of the sensitivity of the chronologies to environmental factors

Based on the statistical parameters that reflect a response to environmental factors (mean sensitivity, autocorrelation, standard deviation, signal-to-noise ratio), the chronology of MEB exhibits the best dendroclimatic potential, followed by the chronology of LFA. According to the same parameters, the chronology of LFB would be the one with the lowest potential (Table 4).

Table 4. Comparative summary of the descriptive statistics of the four chronologies of *Pinus lumholtzii* B. L. Rob. & Fernald developed for the south of *Durango*.

Statistical parameters	**MEA**	**MEB**	**LFA**	**LFB**
Mean sensitivity	0.2163	0.3049	0.2479	0.1627
First-order autocorrelation	0.1366	0.1871	0.0553	0.3338
Correlation between samples	0.396	0.448	0.302	0.286
Signal-to-noise ratio	7.693	22.76	9.445	8.329
Variance in the first eigenvector (%)	45.40	48.75	34.93	33.57
Standard deviation of the common interval	0.192	0.286	0.201	0.189
Period	1811-2002	1890-2002	1787-2002	1830-2001
Number of years/trees/samples	192/33/39	113/38/39	216/42/48	172/35/39
Common period	1910-1980	1970-2001	1920-1977	1922-1998
Number of years/trees/samples	71/12/14	32/28/28	58/22/25	77/21/22

Chronologies of *P. lumholtzii* = MEA, MEB, LFA, LFB, related in Table 1.

The chronology of MEB had the highest values for mean sensitivity, standard deviation, correlation between samples, signal-to-noise ratio and proportion of variance in the first eigenvector. All these parameters are associated with a high dendroclimatic potential. However, a limitation of this chronology is its short extension and its relatively high autocorrelation, although in practical terms it is similar to that of the other series, which indicates a delayed effect of both favorable and unfavorable environmental conditions affecting the growth in the following year. This masks the effect of the climate of the year of growth; however, this value is comparatively lower than the chronologies of other species, which sometimes have up to two years of autocorrelation —a problem that is eliminated in the residual version of the chronology, which involves the use of autoregressive methods and the generation of a robust mean (Cook *et al.*, 1987).

Conversely, the chronology of LFB is characterized by statistical parameters that are associated with a low dendroclimatic potential: lower values for mean sensitivity, standard deviation, correlation between samples, and proportion of variance in the first eigenvector. The signal-to-noise ratio of this chronology does not seem to differ from the one registered for the two remaining chronologies: MEA and LFA. These values indicate a relatively greater influence of local environmental (non-climatic) factors on the radial growth in the study sites, compared to the MEB site (with a much higher signal-to-noise ratio). Nevertheless, the behavior of this parameter is not limiting for the obtainment of climate information from any of the chronologies, since the ratio was positive for all of them.

In sum, according to the values of the statistical parameters related to the dendroclimatic potential, the chronologies with the highest and the lowest potential, respectively, are MEB and LFB, while the intermediate values of the two remaining chronologies —MEA and LFA— seem to indicate an intermediate dendroclimatic potential.

On the other hand, a comparative analysis of the values of the statistical parameters related to the dendroclimatic potential between the four *P. lumholtzii* and five *P. menziesii* chronologies available for the region suggests a good dendroclimatic potential for *P. lumholtzii*. The low number of chronologies documented up to the date of the study for the two taxa considered in the region (5 and 4, respectively) did not allow for a statistical comparison of the values of the parameters in question. However, their visual analysis suggests: 1) that the mean sensitivity and standard deviation values of the *P. lumholtzii* chronologies are generally lower than those of *P. menziesii*, although certain chronologies of *P. lumholtzii* reach the mean values registered for *P. menziesii* in these parameters. That is to say, in general *P. lumholtzii* evidences a lower sensitivity than *Pseudotsuga*; however, certain pine chronologies are as sensitive as the average chronologies of *Pseudotsuga*. And 2) that the chronologies of *P. lumholtzii* reach values as high as those of *P. menziesii* for the correlation between samples and between trees, the signal-to-noise ratio and the proportion of variance explained by the first eigenvector. This means that, in general, the chronologies of *P. lumholtzii* have a strong common signal and, as a result, a good potential for climatic reconstructions.

Correlation between chronologies

As for to the association between chronologies, the correlation analysis of the 1890-2001 period (112 years) between the four sad pine chronologies and the five previous chronologies of *P. menziesii* (Table 5), indicates that they all correlate significantly; this agrees with the findings of González-Cásares *et al.*, (2016), who determined that the chronology of *P. lumholtzii* correlates significantly with those of *Pinus arizonica* Engelm., *P. durangensis* Martínez, *P. engelmannii* Carrière and *P. leiophylla* Schiede ex Schltdl. & Cham. for the common period from 1970 to 2015.

Table 5. Correlation between chronologies for the common 1890-2001 period ($p < 0.001$).

	MEA	**MEB**	**LFA**	**LFB**	**BAY**	**BAN**	**TEU**	**SAL**	**BAR**
MEA		0.71	0.82	0.59	0.79	0.70	0.67	0.49	0.52
MEB	0.71		0.65	0.53	0.59	0.57	0.75	0.38	0.49
LFA	0.82	0.65		0.77	0.78	0.71	0.72	0.54	0.55
LFB	0.59	0.53	0.77		0.51	0.57	0.66	0.49	0.54
BAY	0.79	0.59	0.78	0.51		0.68	0.55	0.48	0.45
BAN	0.70	0.57	0.71	0.57	0.68		0.72	0.29	0.67

TEU	0.67	0.75	0.72	0.66	0.55	0.72		0.33	0.63
SAL	0.49	0.38	0.54	0.49	0.48	0.29	0.33		0.28
BAR	0.52	0.49	0.55	0.54	0.45	0.67	0.63	0.28	

Chronologies of *Pinus lumholtzii*: MEA, MEB, LFA and LFB; chronologies of *Pseudotsuga menziesii*: BAY, BAN, TEU, SAL and BAR.

The chronologies that best correlate with each other are those of the two *P. lumholtzii* populations at the upper distribution limit (LFA and MEA). They are also the ones that show the highest correlation with the rest, of both pine and spruce. The chronology least correlated with the rest is that of *P. menziesii* in the *El Salto* region (SAL). It should be noted that this exhibits lower correlations with the rest of the chronologies of *Pseudotsuga* than with those of the sad pine. The relatively high correlation between chronologies suggests similar responses to environmental factors affecting at a regional level. It also allows for the construction of regional or composite chronologies (a combination of two or more site chronologies) that might better reflect the response to environmental factors of regional influence.

Correlation with climatic factors

The highest correlations between the growth rates of each of the four chronologies and the total precipitation of the individual months correspond to the months of November of the previous year to May of the current year of growth. The rainfall of August of the year of growth also exhibits high and significant correlations with the growth rates of the four chronologies (Figure 1).

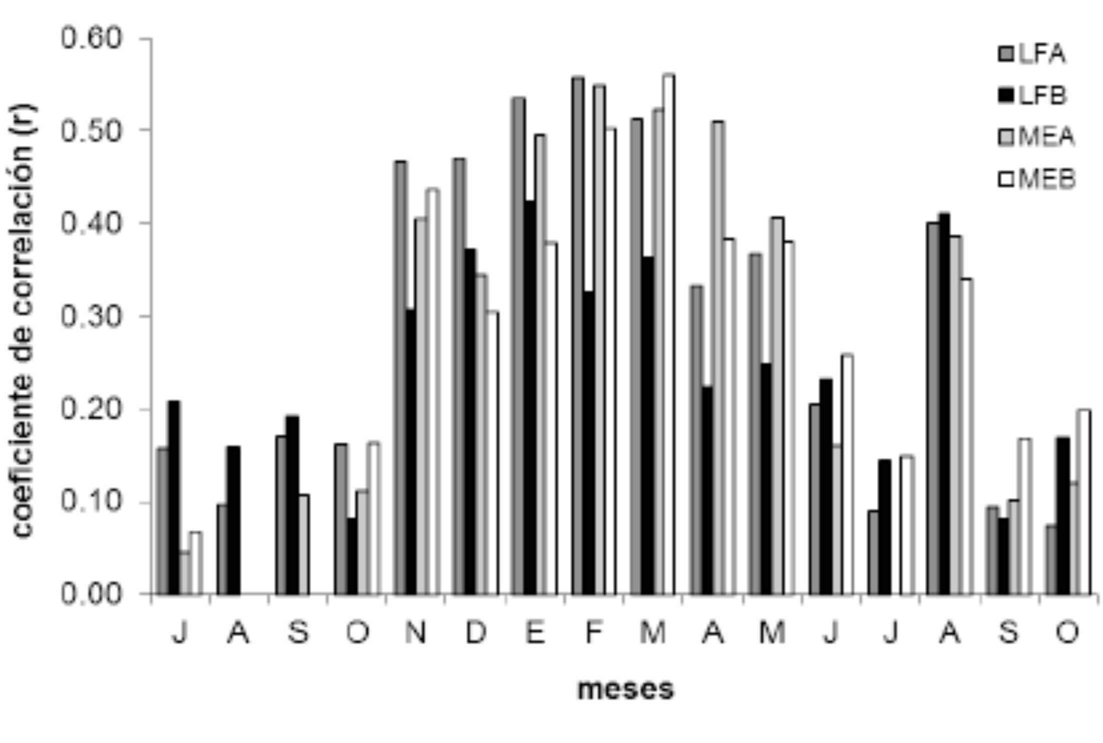

Figure 1. Correlation between the growth rates of each of the four chronologies of *Pinus lumholtzii* B. L. Rob. & Fernald and regional monthly rainfall (average of four weather stations). The continuous period significantly associated ($p<0.01$) with the growth was November of the previous year to May of the current year of growth.

The total seasonal precipitation of various combinations of months exhibits higher correlations than that of the individual months. For example, while the highest correlation coefficient with the monthly rainfall has a value of 0.56 (chronology of MEA, month of March), the total precipitation in the period from November to May, as well as from November to August, has a correlation with the rates of growth of *P. lumholtzii* of up to 0.76 (1965-2001 period). The four chronologies follow the same pattern of association with the precipitation; the precipitation from November to October, from November to August and from November to May is the one the that best explains the growth (Table 6).

Table 6. Correlation coefficients (r) between the annual growth rates of the four sad pine chronologies and the regional mean precipitation of three different periods[1].

Period	Years	MEB	LFA	LFB	MEA
Nov-Oct	1965-2001	0.66	0.67	0.58	0.62
	1965-1982	0.94	0.86	0.77	0.84
	1983-2001	0.49	0.54	0.49	0.45
	1965-1993	0.85	0.73	0.52	0.75
Nov-Aug	1965-2001	0.69	0.76	0.63	0.69
	1965-1982	0.87	0.91	0.76	0.85
	1983-2001	0.56	0.68	0.63	0.54
	1965-1993	0.82	0.8	0.59	0.77
Nov-May	1965-2001	0.65	0.76	0.55	0.71
	1965-1982	0.83	0.89	0.69	0.83
	1983-2001	0.58	0.76	0.59	0.68
	1965-1993	0.69	0.75	0.48	0.72

[1] = The correlation analyses were computed considering the climate records for different periods between 1965 and 2001.

The results obtained in the study sites agree partially with previous reports for *Pseudotsuga* in the region (Stahle and Cleaveland, 1993; Cleaveland *et al.*, 2003; González-Elizondo, 2003; González-Elizondo *et al.*, 2005); while the annual growth of *Pseudotsuga* is associated with the winter-spring rainfall, the growth of *P. lumholtzii* seems to be determined by the precipitation of a whole year (November of one year to October of the next). It should be noted, however, that this pattern is dynamic because, as can be seen in Table 6, the growth-climate correlation varies over time. This difference is very obvious when comparing the coefficients of correlation between the growth rates and the climate of the 1965-1982 and 1983-2001 periods, which seems to indicate that the radial growth of *P. lumholtzii* is determined to a much larger extent by the rainfall of the first period than by that of the second. In addition, there seems to have been a change in the rainy season that affects the growth, since for the 1983-2001 period the highest correlations with the precipitation were detected with precipitation periods that differed from those shown in Table 6 (*e.g.* January to March and February to May). This circumstance is of great importance for the climate reconstruction using regression models, because the reconstructed precipitation will coincide more or less with the real precipitation according to the period selected for building the model.

The comparative correlation between the growth rates of each of the four sad pine chronologies and the precipitation coincides with the statistical parameters of these chronologies (Table 4). The chronology best correlated with the precipitation proved to be that of MEB, which is also the one that has the best statistical parameters related to the dendroclimatic potential. While, the chronology least correlated with the precipitation was that of LFB, which in turn exhibits the most adverse values for the statistical parameters.

Reconstruction of the precipitation

In order to obtain comparable results to those of previous studies in the region, the precipitation was reconstructed using regression models, based on the instrumental data of the years 1965 to 1993 for the regional mean precipitation from November of the year prior to the growth season to August of the year of growth.

The precipitation from November to August accounts for up to 68 % of the variance in the rates of growth of both *P. menziesii* (a species with a highly recognized dendroclimatic potential) and *P. lumholtzii*. (Table 7). The association existing between the reconstructions of the precipitation for both species is remarkable, even though there are two short periods of evident discrepancy, around 1790 and around 1840 (Figure 2).

Table 7. Statistics of the regressions between different chronologies and regional mean precipitation (1965-1993).

Chronology	r	r^2	Model[1]
BAY (*Pseudotsuga menziesii*)	0.82	0.68	$Y_i = 101.85 + (624.94)X_i$
LFA (*Pinus lumholtzii*)	0.80	0.63	$Y_i = -32.41 + (705.61)\ X_i$
MEB (*Pinus lumholtzii*)	0.82	0.68	$Y_i = 166.93 + (516.33)\ X_i$

[1] = Models for the reconstruction of the regional precipitation (November to August), where Y_i is the reconstructed value for the year *i*, and X_i is the growth rate of the chronology for the year *i*.

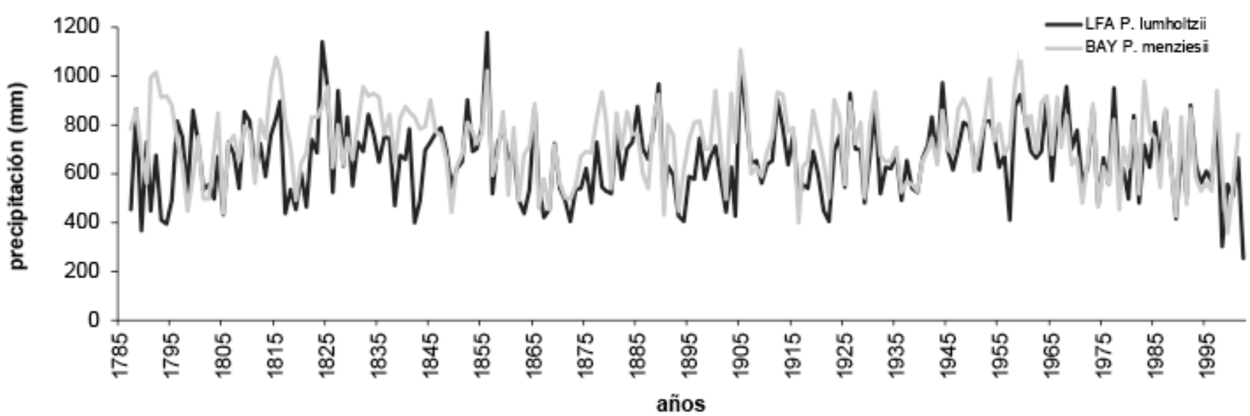

Figure 2. Regional average precipitation (1787-2001) reconstructed from the growth rates of a chronology of *Pinus lumholtzii* B. L. Rob. & Fernald (LFA) and one of *Pseudotsuga menziesii* (Mirb.) Franco (BAY).

Conclusions

The results of this study indicate that *Pinus lumholtzii* has an excellent dendroclimatic potential because: 1) it was possible to date 40 % of the collected samples, which indicates a good potential for synchronization and dating (certain references cite 25 % for species considered to have a good potential); 2) the chronologies of *Pinus lumholtzii* present statistical parameters related to sensitivity to environmental factors, although in general they are less favorable, although still comparable, than those of the chronologies of *Pseudotsuga menziesii*; 3) the chronologies of *Pinus lumholtzii* have high and significant correlations between themselves and with those of *Pseudotsuga menziesii* in the region. This is a reflection of the responses to environmental factors of regional influence on growth; 4) the correlation between the growth rates of *Pinus lumholtzii* and regional precipitation was statistically significant and even higher than the one shown by *Pseudotsuga menziesii*, and 5) the reconstruction of precipitation based on the rates of growth of *Pinus lumholtzii* is significantly correlated with the reconstruction of the precipitation for the same period based on the growth rates of *Pseudotsuga menziesii*.

Therefore, the construction of a network of growth chronologies through its area of distribution in the Western Sierra Madre would be very helpful, both for the study of the climate (variability and change) and for the monitoring of those changes in geographical distribution and growth patterns that may be related to climate change.

Acknowledgments

This research was funded by the *Instituto Politécnico Nacional*, through the project "Evaluation of the dendroclimatic potential of *Pinus lumholtzi*i Rob. & Fern." (CGPI: 20040673). The authors are grateful for the comments and suggestions of two anonymous reviewers who helped improve the manuscript.

Conflict of interest

The authors declare no conflict of interests.

Contribution by author

Martha González Elizondo: selection of the sampling sites, obtainment of the growth cores, development of the analysis and its interpretation, and drafting of the manuscript; María del Socorro González Elizondo: site selection, description of the vegetation and assistance in the collection of the samples and in the field work in general; José Villanueva Díaz: analysis of results and drafting of the manuscript; Julián Cerano Paredes: preparation of the samples, dating of the growth cores, and measurements for the generation of the time series.