

# Dendrochronological reconstruction of long-term precipitation patterns in Basaseachi National Park, Chihuahua, Mexico

## Reconstrucción dendrocronológica de patrones de precipitación de largo plazo en el Parque Nacional de Basaseachi, Chihuahua, México

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### ABSTRACT

The purpose of this study was to reconstruct the precipitation at Basaseachi National Park (BNP) in Chihuahua, Mexico. Tree-ring samples from pine species including *Pinus durangensis*, *P. lumholtzii* and *P. engelmannii* were collected in and near BNP and they were cross-dated with existing chronologies. Ring widths of each sample were measured and models to remove non-climatic trends from the data were applied. The relationship between precipitation from the weather station in Yécora, Sonora, and the ring width indices were modeled using a bivariate linear regression ( $r^2 = 0.59$ ,  $p < 0.01$ ). It was found that precipitation from the months of October, December, February and April was most highly correlated with tree ring growth. The reconstruction extends 225 years from 2007-1782. During this time period there were thirteen severe droughts, ten of which affected large areas in northern and central Mexico.

### KEY WORDS:

Climate, dendrochronology, drought, *Pinus*, precipitation reconstruction.

### RESUMEN

El propósito de este estudio fue generar una cronología de anillos de crecimiento lo más extensa posible y usarla como un método indirecto para el desarrollo de una reconstrucción de precipitación estacional en el Parque Nacional de Basaseachi (BNP), Chihuahua, México. Para el desarrollo de la cronología, se colectaron núcleos de crecimiento de ejemplares de tres especies de pino, ubicados tanto dentro como fuera del BNP. Las muestras se fecharon con cronologías existentes y cercanas al área de estudio. Se midió el ancho de anillos de cada una de las muestras y se aplicó un procedimiento de estandarización para remover tendencias biológicas y geométricas. Con los índices dendrocronológicos y datos de precipitación de la estación climática Yécora, Sonora, se generó un modelo de regresión lineal bivariado que tuvo una varianza significativa ( $r^2 = 0.59$ ,  $p < 0.01$ ). La precipitación de los meses de octubre, diciembre, febrero y abril fue la más correlacionada con el grosor de los anillos. La reconstrucción se extendió 225 años, período 2007-1782. Durante este tiempo ocurrieron trece sequías severas, diez de las cuales afectaron grandes áreas en el norte y centro de México.

### PALABRAS CLAVE:

Clima, dendrocronología, *Pinus*, sequía, reconstrucción de precipitación.

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## INTRODUCTION

Megadiverse ecosystems are those in which the magnitude of species richness is one to two orders higher than that of most temperate zones (Brehm *et al.*, 2008; McCune, 1988). Many of these ecosystems are being damaged by human land use practices such as fire suppression, logging and livestock grazing. Additionally, global warming is currently affecting the climate in these regions, adding to the disturbance within the ecosystems and this trend is expected to become more pronounced in the near future (Rosenzweig *et al.*, 2007). From a conservation perspective, megadiverse ecosystems require an increased level of understanding about climatic variability over time as well as climate's influence on the hydrologic cycle and the growth of dominant species (Villanueva-Díaz *et al.*, 2009).

The Sierra Madre Occidental (SMO) in Northwestern Mexico is an example of a megadiverse system (Bye, 1995). The SMO holds some of the most extensive and diverse pine-oak forests remaining in the world, yet there is relatively little protection of these ecosystems (Bye, 1995; Heyerdahl and Alvarado, 2003). The aquifers and surface runoff provided by the SMO sustain life for over six million people living in the states of Sonora and Chihuahua. Basaseachi National Park (BNP) is of interest for conservation because it contains the second tallest waterfall in Mexico (246 m) and draws thousands of tourists annually, stimulating the local economy and providing protection for a small area of forest on the canyon rim.

The study of historical climatic variability is important for understanding current and future climatic trends as well as their relationship with social and economic stability (Timmerman *et al.*, 1999;

Villanueva-Díaz *et al.*, 2007). Instrumental weather data in Mexico is short and incomplete, thus it is necessary to obtain information about past climate from a proxy source. Climate reconstructions provide useful information on the range and variability of precipitation, which can aid in resource management, restoration, and conservation efforts (Villanueva-Díaz *et al.*, 2007). Several tree-ring chronologies exist for northwestern Mexico, compiled by Stahle and Cleveland (1993), Villanueva-Díaz and McPherson (1996), Biondi (2001), Díaz *et al.* (2002), Cleveland *et al.* (2003), González-Elizondo *et al.* (2005), Villanueva-Díaz *et al.* (2009); Cerano-Paredes *et al.* (2009).

These chronologies range from 320 to 607 years long. Most of the existing chronologies in the SMO were constructed from *Pseudotsuga menziesii* because trees of this species are long-lived and sensitive to climate. However, in northern Mexico, this species is restricted to the highest elevations, northern slopes, and canyon bottoms. Pine species, in contrast, are widespread. By using pine species including *Pinus durangensis*, *P. lumholtzii* and *P. engelmannii*, it is possible to expand the number of areas available for climate reconstruction as well as provide a better regional understanding of past climate.

## OBJECTIVES

The objectives of the present study were to (1) develop the oldest possible chronology using tree-ring records from pine trees in and around Basaseachi National Park (BNP), (2) model precipitation to develop long-term climate reconstructions from the proxy tree-ring data, and (3) evaluate historical patterns of drought and its relationship to the El Niño Southern Oscillation (ENSO).

## METHODS

### Study Site

The study site is located in a pine-oak forest in and around BNP in Chihuahua, Mexico (Fig. 1 y 2), centered at about 108,2° West, 28,2° North (Fig. 3). Elevation ranges from approximately 1720 to 2300 m. The climate can be characterized as arid to semi-arid with summer monsoonal rains. Average annual precipitation in this area is approximately 700 mm (ERIC II, 2000). The majority of the soil is classified into Leptosols and Regosols. Species present in this region include *Pseudotsuga menziesii* (Shwerin), *Pinus durangensis* (Martínez), *P. lumholtzii* (Robinson and Fernald), and *P. engelmannii* (Carrière) (Spellenberg *et al.* (1996), species authorship from Farjon and Styles (1997) and Uchytíl (1991)). Much of the forest in the Sierra Madre Occidental has been heavily

logged (Cortés Montaña and Cruz Gaisardo, in press). Logging started in the area in the late 1800's and proceeded through the 20<sup>th</sup> century and as a result, only a small fraction of the original vegetation remains intact (Lammertink, 1996). Overgrazing has also been an issue in the area (Valero *et al.*, 2001). Frequent, low intensity fires are important disturbance agents in these forests, which burned every 4-5 years before fire exclusion began in the 1940's (Heyerdahl and Alvarado, 2003 and Fulé *et al.*, 2005).

### Sample Collection

Tree species used in this chronology include *Pinus durangensis*, *P. lumholtzii* and *P. engelmannii*. Cores from large mature trees growing in climatically sensitive areas characterized by shallow, rocky soils and steep terrain were extracted



Figure 1. Pictures taken at the study site, Basaseachi National Park (BNP), Chihuahua. Top- looking out from Cascada Basaseachi, samples were taken on the rim as well as the canyon bottom.



Figure 2. *Pinus lumholtzii*.

(Villanueva-Díaz *et al.*, 2007). Using increment borers, two cores were removed from each suitable tree. The cores were taken 40 cm from the ground. To extend the length of the chronology, several cross-sections from old trees collected during a companion fire history reconstruction study in the same area were used (Yocom *et al.*, unpublished data). All wood samples were air-dried, cores stored in paper straws, and cross sections wrapped in plastic wrap for transport.

### Laboratory Analysis

All cross sections and cores were glued to wood mounts and sanded with increasingly finer grades of sandpaper until cells were clearly visible under a microscope (Grissino-Mayer, 2001). Using existing chronologies, the samples were visually crossdated and with skeleton plots (Fritts,

1976; Stokes and Smiley, 1968). Tree-ring widths were then measured to the nearest 0,001 mm using a stereo-zoom microscope and a Velmex sliding-stage micrometer. To check the cross dating accuracy, the program COFECHA was used (Holmes, 1986; Grissino-Mayer, 2001). Using the program ARSTAN, non-climatic trends, were removed including the general decrease in ring width as the tree ages, and autoregressive growth persistence, by applying a negative exponential growth curve (any  $k$ ) followed by autoregressive modeling. The residual chronology was used, which represents the maximal interannual variability after removing the influence of autocorrelation, for the final reconstruction.

To determine the correlation between monthly precipitation and annual tree-ring growth, residual ring-width indices were compared with monthly precipitation and temperature data using the program Den-

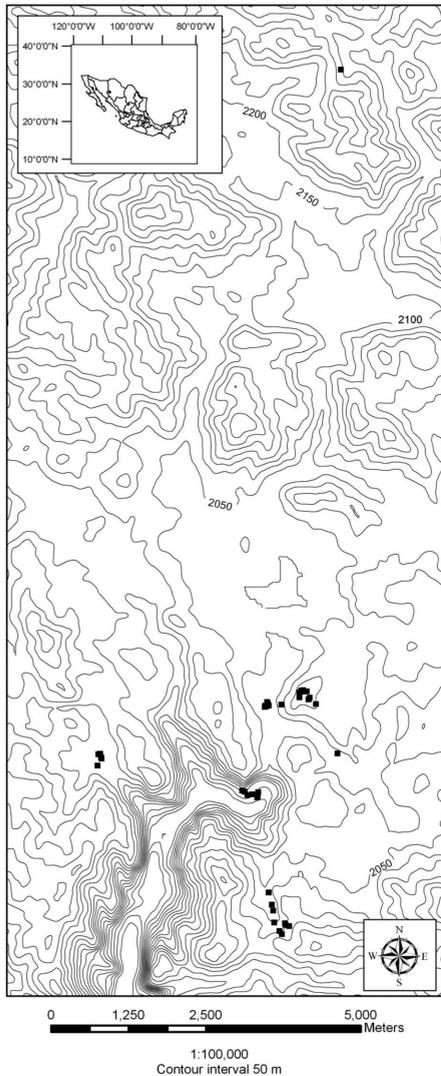


Figure 3. Sampling sites in and around BNP.

droClim 2000 (Biondi and Waikul, 2004; ERIC II, 2000). This was a resampling  $p$ -value. The highest association of tree ring indices and precipitation was Oct-Apr, thus precipitation from these months was used for the final reconstruction. In selecting a weather station precipitation data from three different weather stations were compared with similar

elevations and in relatively close proximity to BNP. There is a weather station, at the park but the data were too short and incomplete to be used. The weather station at Yécora, Sonora was chosen because the association between ring width indices and precipitation was the highest of all the stations that were considered and the station had a longer, more complete data set than the others.

A least-squares regression was calculated between meteorological records of October-April precipitation and the residual ring-width chronology to find the correlation of precipitation with tree-ring width (Fritts, 1976). The precipitation data and tree ring indices were split into two periods: a calibration period and a verification period. The weather data gathered at the Yécora station spanned the time period between 1971 and 2004. The data were split into two periods: 1971-1987 and 1988-2004. Each period served as a calibration and validation period, in successive analyses. The alpha level was 0,05. The regression equation developed in the calibration period was applied to the ring-width indices of the verification period. The reduction of error (RE) was calculated as well as the coefficient of efficiency (CE) for the model. These two statistics are used to compare estimated data with values assumed to be equal to the calibration period mean (Briffa *et al.*, 1988). Positive values indicate reasonable skill in the reconstructions (Fritts, 1976). The CE differs from the RE in that it is a measure of the common variance between the actual and estimated data over the verification period whereas the latter is a measure of variance over the calibration period (Briffa *et al.*, 1988). The average expressed population signal (EPS) was also calculated. The EPS is used to express the degree to which a particular sample chronology portrays a hypothetically perfect chronology with higher values being more favorable (Wigley *et al.*, 1984).

To create the final reconstruction, all the data were combined and a least-squares regression calculated between October-April precipitation recorded for the entire period of the weather station record and the ring-width indices. Past precipitation was estimated by applying the model to the full data set back to the year 1782.

The effect of ENSO on precipitation was examined by correlating the NINO3 data set with the ring-width index. To determine major drought periods, a three year running average was calculated and identified periods where precipitation was less than 86% of the 225 year average.

## RESULTS AND DISCUSSION

### Chronology

Pine trees from Basaeachi National Park proved to be useful for developing a multi-century precipitation reconstruction. The final chronology contained 44 trees and the series intercorrelation was 0,61. The climate reconstruction was extended back 225 years, covering the time period between 1782 and 2007. The EPS for the series was 0,87. For this chronology, the average EPS exceeds the critical level of 0,85 determined by Wigley *et al.* (1984).

### Precipitation Reconstruction

Precipitation occurring in the previous winter, during the months of December and February, was most highly correlated to tree ring growth, with values of 0,43 and 0,50 respectively. In addition, October and April precipitation were found to have a positive correlation with tree growth at 0,27 and 0,24 respectively. Because these months had the highest correlations, total precipitation occurring between the

months of Oct and April was used for the final reconstruction. There were no statistically significant correlations between tree growth and temperature. Although they were not significant, the values suggest a negative correlation between temperature and annual tree-ring growth (Biondi and Waikul, 2004).

The calibration period (1971-1987) had a statistical significance of  $r = 0,79$  ( $r^2 = 0,63$ ) and the verification period (1988-2004) had a statistical significance of  $r = 0,74$  ( $r^2 = 0,55$ ) (Fig. 4). The RE derived from the model was 0,67, and the CE was 0,63 indicating high skill in the reconstruction (Table 3). The RE and CE calculated with reversal of the calibration and verification periods were 0,63 and 0,55 respectively again indicating high skill in the reconstruction (Table 3).

The linear regression representing the total time period of weather data (1971- 2004) and corresponding tree ring indices had a correlation of  $r = 0,77$  ( $r^2 = 0,59$ ), meaning that approximately 59% of the variability in tree ring growth was explained by precipitation data. The linear regression used to calculate precipitation values for the total reconstruction was:  $Y = -244,85 + 499,03X$  where Y is the amount of October-April precipitation (in mm) and X is annual tree-ring width index. The model parameters were highly significant (Tables 1 and 2).

### Effects of ENSO

ENSO is known to have a large effect on precipitation in northern Mexico (Cleveland *et al.*, 2003; Stahle and Cleveland, 1993). Generally in this region, El Niño is associated with higher winter precipitation while its counterpart La Niña is associated with winters producing less precipitation (Magaña *et al.*, 2002). No significant correlation was found upon comparing ENSO patterns with winter

Table 1. Linear regression model used to calculate the total reconstruction model is  $Y=\alpha_0+\alpha_1X$ .

<i>Period</i>	<i>Coefficients</i>	<i>t ratio</i>	<i>Prob&gt; t </i>	<i>Standard Error</i>	<i>R<sup>2</sup></i>
1971-2004	$\alpha_0 = -244,85$	-3,38	0,0019	72,3374	0,59
	$\alpha_1 = 499,03$	6,72	<0,0001	74,2628	

Table 2. Analysis of Variance of model used for the reconstruction.

<i>Source</i>	<i>DF</i>	<i>Sum of Squares</i>	<i>Mean Square</i>	<i>F Ratio</i>	<i>Prob &gt; F</i>
Model	1	403998	403999	45,1556	<0,0001*
Error	32	286298	8947		
Total	33	690296			

Table 3. Reduction of error, coefficient of efficiency and final model.

	<i>Calibration (1971-1987 Verification (1988-2004</i>	<i>Calibration (1988-2004 Verification (1971-1987</i>	<i>Final model</i>
Calibration R <sup>2</sup>	0,63	0,56	R <sup>2</sup> = 0,59
Verification R <sup>2</sup>	0,56	0,63	
Reduction of error	0,67	0,63	y= 244,85+499,03x
Coefficient of efficient	0,63	0,55	

precipitation but ENSO extreme years tend to match up with periods of uncharacteristically high or low precipitation, which is consistent with the study by Stahle and Cleaveland (1993). From 1782 to 1970, there were 13 years classified as La Niña extreme events (Stalhe and Cleaveland, 1993). Reconstructed precipitation for each of these 13 years was less than or equal to 90% of average precipitation (Table 4). There were nine El Niño events during this same time period. Of the nine years, reconstructed precipitation was higher than average for all but two years: 1844 and 1964 (Table 4).

### Drought

This reconstruction identified three drought periods not present in similar studies: 1902-1904, 1943-1946 and 1959-1967. One likely explanation for the appearance of these droughts at BNP is the lower elevation relative to the elevations of previous study sites. The identification of unique drought periods at BNP further demonstrates this area's sensitivity to climate patterns

and can aid resource managers in preserving the natural resources in the area. The five driest years identified by this reconstruction in order of increasing severity were 1909, 1982, 1798, 1887 and 2000. The total reconstruction identified thirteen droughts lasting more than three years in duration occurring during the past 225 years (Fig. 5). Severe droughts identified by the reconstruction are listed in Table 5. The most prolonged drought lasted 16 years and occurred between the years of 1835 and 1851. Most of the drought periods identified by the reconstruction are also present in other reconstructions conducted in northern Mexico with the exception of the three periods listed above (Villanueva *et al.*, 2007). Many of these drought periods can be linked to social and economic hardship in Mexico. The first of was the period between 1785 and 1786, although the reconstruction obtained here only shows 1785 to be below average. This is known as "*El Año del Hambre*" (The Year of Hunger) as it resulted in extreme food shortages and an outbreak in epidemic disease throughout Mexico (Therrell, 2005).

Table 4. List of ENSO extreme years from Stahle and Cleaveland (1993) and percent of average precipitation from our model that fell during these years at the study site.

<i>La Niña Extremes</i>		<i>El Niño Extremes</i>	
<i>Year</i>	<i>% precip (of ave)</i>	<i>Year</i>	<i>% precip (of ave)</i>
1789	45	1792	126
1801	76	1844	73
1805	52	1869	108
1855	76	1881	101
1862	84	1919	121
1887	0*	1931	195
1904	46	1944	113
1909	13	1958	201
1917	90	1964	90
1921	79		
1925	37		
1934	37		
1956	59		

\* Ring width too small for application of the model.

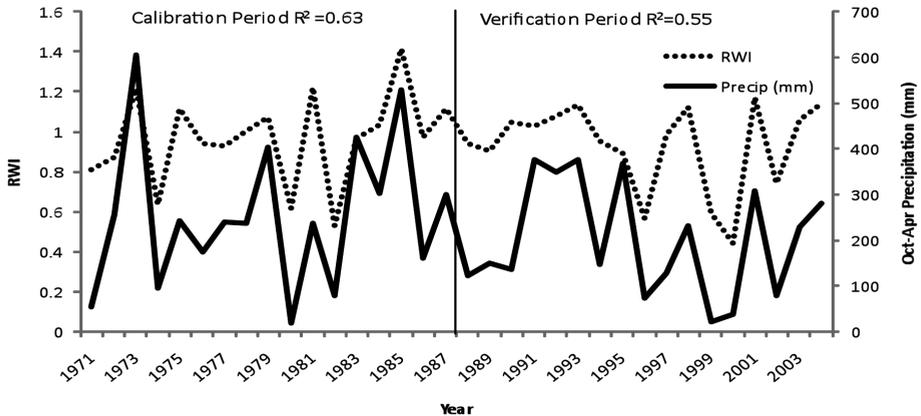


Figure 4. Observed and reconstructed precipitation during 1971-2004. The calibration period lasts from 1971- 1987 and the verification period from 1988-2004.

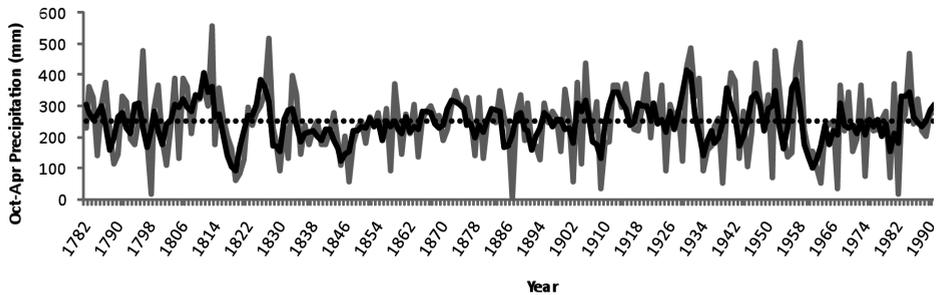


Figure 5. Reconstructed precipitation for the full 225 years from 1782-2007. The grey line represents calculated Oct-Apr precipitation values (in mm) and the black line represents a smoothing filter of the precipitation values. The horizontal dashed line is the 225-year average calculated from annual precipitation values.

*El Año del Hambre*, in conjunction with another drought lasting from 1798-1810 throughout northern and central Mexico, is believed to have instigated higher food prices and food shortages which may have ultimately contributed to the Mexican War of Independence (Florescano and Swam, 1995; Cerano *et al.*, 2009). The longest drought during the past 300 years in Chihuahua and Sonora took place between the years of 1841 and 1870 (Díaz *et al.*, 2002 and Cleveland *et al.*, 2003). Our reconstruction from Basasea-

chi did show a decrease in precipitation during this general time period but the drought was most intense between the years of 1835 and 1851. One of the most severe droughts pointed out by this reconstruction occurred between 1909 and 1911. This drought was felt by much of northern Mexico and caused massive food shortages, leading to social discontent. It is for this reason that the drought has been hypothesized to be a major contributor to the Mexican Revolution (Cerano *et al.*, 2009).

Table 5. Droughts lasting three years or more where the average precipitation for the entire time period did not exceed 86% of the 225 year average.

3-4		>4	
Year	% of	Year	% of
1788-	6	1817-	5
1892	6	1829-	6
1902	7	1835-	7
1907	7	1934-	6
1943-	7	1959-	6
1954-	6	1994-	6
1971-	8		

The 1950's represent an entire decade of drought throughout northern and central Mexico and the southwestern United States (Díaz *et al.*, 2002 and Cleveland *et al.*, 2003 and Breshears *et al.*, 2005). Drought years in the Basaseachi area during this decade occurred in 1950-1951, 1954-1956 and in 1959 (Table 5). This drought is also known to have had a major social and economic impact throughout Mexico (Cerano *et al.*, 2009).

Finally, the most recent drought highlighted by the chronology occurred between 1994 - 2002. The year 2000 was the driest year in the past 225 years. This drought was even greater in southeastern Chihuahua where it lasted through 2005 and was one of the most severe droughts in the past 300 years (Cerano *et al.*, 2009).

## CONCLUSIONS

Pine chronologies tend to be shorter and less well-correlated with climate than *P. menziesii* chronologies, but they are useful for reconstructing climate in areas where *P. menziesii* are sparse. A winter-spring precipitation reconstruction for BNP that exten-

ded back to 1782 was developed. Climatic fluctuation was associated with the positive and negative phases of El Niño/Southern Oscillation. This reconstruction identified periods of drought similar to those identified in the rest of northern Mexico, but episodes of local climatic variability were also noted. Additional collection in high elevation pine forests would be useful to expand the individual grid in Mexico and contribute to a greater understanding of climate and its effect on dominant species in the respective ecosystems.

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