Basal area increase forecast, *Picea chihuahuana* Martínez through time series analysis as climate variability indicator

**Abstract**

Tree ring series of ring width can be transformed into basal area increments (BAI) for analysis of past trends in tree growth and building models to forecast future growth. In this study, we use time series analysis of BAI to identify periodicity and forecast tree growth of *Picea chihuahuana* Martínez growing in the Sierra Madre Occidental of Mexico. Results showed significant (P<0.05) correlation between BAI and precipitation. We found periodicities in tree growth of 7, 14, 23, and 27 years in Chihuahua spruce. The type of ARIMA model was (1,1,0) with a periodicity of 27 years to forecast BAI for the next decades. The forecast of BAI by the model indicate decreased tree growth in the short period (five years) and a recovery at years 2041 and 2055. According to the model, future tree growth will not reach average growth rates (22-cm2 year-1) in the next decades, which suggest that recent climate changes may worsen the condition of forest in North Mexico. Time series analysis of BAI as illustrated here is a powerful prediction tool to project future changes in tree growth, climate variability and climate change.

**Keywords:** dendrochronology, tree ring, forest growth, climate change

**Introduction**

The Chihuahua spruce (*Picea chihuahuana* Martínez) is an endemic and endangered species with a restricted habitat and small populations that are found in the Sierra Madre Occidental in the Mexican states of Durango and Chihuahua. Due to the increased variability of the climate in the last three decades, more understanding on the relationship of tree growth and climatic variables is needed. Forest growth depends on stand age, stand density, tree species composition, soil quality and climate, the different factors are reflected in the ring width. Because tree ring measurements can be transformed into basal area measurements, the practical use of tree ring series from wood cores can help to understand tree growth and climate relationships.

Although some reports have indicated that ring width measurements may underestimate tree growth due to vertical fluctuations in annual growth along the bole, tree ring series at the breast height are highly sensitive to climate variation and are related to forest productivity.

Because of recent increased climate variability, more understanding in the response of tree growth in relation to climate is needed, and tree ring series analysis along with basal area measurements will be important for tree growth forecasting. The standard procedures for time series analyses were developed by Box & Jenkins and its application in describing radial tree growth was proposed in the 80’s, along with techniques to identify periodicities or cyclical patterns (spectral analysis) in tree growth. More recently, the use of time series analysis has showed to be useful not only to describe the metrics of tree rings but also to describe past tree physiological processes through stable isotope measurement. Additionally, these techniques can be used in the analyses as an indirect source of climate, to investigate the impact of atmospheric circulation patterns and climate change.

Planning the use of water resources, determine the frequency of hydroclimatric events (droughts) and its socioeconomic impact on population, and to analyze weather conditions, impact of food shortages, epidemics diseases, social and political conflicts. The present study includes an analysis of ring-width series of Chihuahua spruce (*P. chihuahuana*) which are long-lived climate sensitive specie present in specific habitats along the Sierra Madre Occidental. Currently, the species was considered in danger of extinction, and is included under protection of Mexican norm NOM-059-2010. This paper aims to analyze basal area increment (BAI) of Chihuahua spruce derive from tree ring measurements at the breast height.

Hypothesis were  

i. BAI of *P. chihuahuana* in the Sierra Madre Occidental of Mexico show a periodic component, and  

ii. The periodicity found for *P. chihuahuana* can be described and forecasted with a time series model.

**Methods**

**Study site**

The study site is located in the Sierra Madre Occidental of Mexico (WSM) in the Bocoyana municipality in the state of Chihuahua (Figure 1), in coordinates 27° 57’ 19.64’’N, 107° 45’ 9.38’’W. The habitat of *P. chihuahuana* is restricted to slopes of 35% to 80%, the altitude ranges from 2,150 to 2,990m, and aspect of N, NE and NW. The climate is temperate sub-humid with mean annual temperature of 9–12 °C, temperature of the coldest month of 3.8–7.3 °C, temperature of the warmest month of 13.9–17.6 °C, and precipitation range from 600 to 1300mm. In the study site *P. chihuahuana*, does not form pure stands but it is mixed in associations with, Douglas-fir, *Pinus arizonica*, *Pinus durangensis*, and *Pinus ayacahuite*, which have been also reported in other studies.  

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Basal area increase forecast, Picea chihuahuana Martínez through time series analysis as climate variability indicator.

Wood core sampling

In summer of 2012, fourteen-increment cores of Chihuahua spruce was collected in a mixed conifer forest stands. Healthy and long-lived trees were carefully selected by their circular section of the bole and were sampled with a 12mm Haglöf borer. The samples were taken in transversal direction to the slope at 1.3m above the ground. The cores were taken in opposite direction of the circular section of the stems. The average age of the sampled trees was 141years. At this age, basal increments of Chihuahua spruce plateau and remain constant up to the age of 300 years.

Sample core measurement

Increment core samples were measured at the Laboratory of Dendrochronology from Instituto Nacional de Investigaciones Forestales Agrícolas y Pecuarias (INIFAP) in Gomez Palacio, Durango. Samples were air dried and polished with sand paper for better contrast of tree rings. Ring width was measured with a Velvex measuring system with a 0.001mm precision. Increment cores samples were processed following standard dendrochronology techniques.21

Basal Area Increment (BAI)

Basal area increments (BAI) for each tree was computed according to22,23 equation

\[ BAI = \pi \left( R_n^2 - R_{n-1}^2 \right) \] (1)

Where: BAI is basal area increment, \( \pi \) is 3.1416, R is stem radius (cm) and n is the year of ring formation. BAI increases from juvenile to mature stages, providing a reliable indicator of forest productivity as long as the tree is not close to biological senescence, which for the study species occurs at about 400 years. In order to construct the representative series of the study sites, the BAI values at a yearly resolution for all samples were averaged.

Spectral analysis

A spectral analysis was performed to identify cycles of BAI. The time series was decomposed into the sum of sine and cosine waves with different amplitudes and lengths.24,25

\[ x_t = \frac{a_0}{2} + \sum_{k=1}^{m} \left( a_k \cos(\omega_k t) + b_k \sin(\omega_k t) \right) \] (2)

Where: \( x_t \) are the data, \( a_k \) is the mean term: \( a_0 = 2\pi \), m is the number of frequencies in the Fourier decomposition, \( \omega_k \) are the cosine coefficients, \( \theta_k \) are the Fourier frequencies: \( \omega_k = \frac{2\pi k}{m} \), and \( b_k \) are the sine coefficients. The Fisher’s Kappa and Bartlett’s Kolmogorov-Smirnov statistics were computed for the BAI chronology assuring that the series and the spectrum were not “white noise” and were statistically significant. In addition, spectral density graphs and periodogram versus period were developed and tested to determine the presence of significant low-frequency cycles. The spectral density estimate was produced by smoothing the periodogram.

ARMA and ARIMA Box-Jenkins Models

ARMA (p, q) Box-Jenkins models rely on second-order stationary; the presence of p autoregressive terms (AR) and q moving average parameters (MA) help to explain the behavior of the response variable,11 equation 3.

\[ \phi_p(B)Z_t = \theta_q(B)u_t \]

\[ Z_t = \phi_1 Z_{t-1} + \ldots + \phi_p Z_{t-p} + \theta_1 u_{t-1} + \ldots + \theta_q u_{t-q} \]

Where: \( Z_t \) is the mean deviation in time t of an equally spaced stationary series; \( \phi_p \) and \( \theta_q \) are autoregressive terms \( \left( \phi_p(B) = (1 - \phi B - \ldots - \phi B^p) \right) \); B is a backshift operator; \( \theta_q \) and \( \theta_q \) are moving average terms \( \left( \theta_q(B) = (1 - \theta B - \ldots - \theta B^q) \right) \); and \( u_t \) represents randomly independent variables with zero mean and variance \( \sigma^2 \) (white noise). Second-order stationary models are mean \( \left( \mu \right) \), variance \( \left( \text{Var}(Z_t) = \sigma^2 \right) \) and covariance \( \left( \text{Cov}(Z_t, Z_{t+m}) = \gamma_m \right) \) not time dependent. Although in practice most time series are not stationary, due to the presence of some kind of trend, nonconstant variance or by the influence of some factor such as type semi-deterministic seasonality. One extension to the ARMA models is the class of autoregressive integrated moving average or ARIMA process with \( d \)th difference. The d term is the number of times the series must be differentiated to be stationary. The stochastic trend can be removed applying a difference operator \( (\nabla d) \):

\[ X_t = \nabla^d Z_t; \text{ Where } \nabla^d = (1-B)^d \] (4)

Where: \( X_t \) is the d times differenced series to be transformed into stationary and \( Z_t \) is the original series.26 The augmented Dickey-Fuller test of unit root proves that the time series is stationary, testing the hypothesis \( H_0: \rho = 1 \) and \( H_1: \rho < 1 \). If nonstationarity is associated with a variable variance we can use a transformation of power type \( \ln \sigma \).27 It should be noticed that when it is necessary to remove trend and variable variance, the transformation of actual values into logarithm is required before the differentiation. Cyclical effects ARIMA models can be proposed under the following general model ARIMA (p, d, q) \( x \in \left( P, D, Q \right) \) (equation 5),

\[ \phi_p(B) \Phi_P(B^C) \nabla^d \nabla^D \chi(Z_t) = \theta_q(B) \Theta_Q(B^C) u_t \] (5)

where \( \phi_p \) (B) is the noncyclic AR operator, \( \theta_q \) (B) is the noncyclic MA operator, \( \Phi_P \) (B) is the cyclic AR operator of.
Basal area increase forecast, Picea chihuahuana Martínez through time series analysis as climate variability indicator

Stationarity of the process

When the time series are not stationary according to the Dickey-Fuller test, we use the first difference of the natural logarithms of the original series to find the Stationarity. This transformation is convenient to decrease heteroscedasticity and suggested when the mean of series changes overtime as was seen in this study.

Estimation of ARIMA model components

The ARIMA modeling involves the comparison of estimated autocorrelation function graphs (ACF) and partial autocorrelation function (ACFp) with theoretical ACF and ACFp. The pattern of decay of those functions and the lags with significant values are components suggesting the order of parameters for the ARMA model. In this study, the ACF to determine the moving average (MA) was used order (q); and the ACFp was used to determine the order (p) of the autoregressive model. Complementarily, the smallest canonical correlation method was used. This process is helpful to identify the orders of a stationary and nonstationary ARMA process. In general, this method consist in identifying a rectangular pattern of a table which has the eigenvalues of a matrix product of the vector \( Y_{m,t} = Z_1, Z_{t-1}, \ldots, Z_{t-m} \) where \( Z_t \) is time series, such that \( m = p_{\text{min}}^{\ldots, p_{\text{max}}} \) and \( j = q_{\text{min}}^{\ldots, q_{\text{max}}} \). Where \( m \) and \( j \) identify the possible order of the AR and MA process, respectively.

Finally, the estimation of parameter was performed using conditional least squares (CLS). The CLS estimates are conditionals to the original series to find the Stationarity.

Results and discussion

Tree ring series and BAI

Fourteen samples were obtained in the study site. The correlation to BAI and precipitation from January to July was high (0.70, \( P<0.01 \)). The inter-correlation series computed with COFECHA was 0.68, the average mean sensitivity was 0.23. The sample of trees captured a significant ratio of 0.90 in ARSTAN. Mean BAI was 21 cm² year⁻¹ (Std=±4). The result in Chihuahua spruce is similar to that reported for stands of Norway spruce of 22-year-old, which was 24 cm² year⁻¹. In western Oregon where trees with ages from 100 to 300 years Douglas-fir plateaued at 50 cm² year⁻¹. In general, there was a trend to reduce BAI over time, which is not an unexpected result because healthy and dominant young trees with average diameters of 75 centimeters and average age of 141 years. A decadal analysis indicated reductions in BAI, with respect to the previous decade, 16, 15, and 20% in the decades of 1860-1879, 1890-1909, and 1940-1959. Favorable periods resulted in an increased BAI of about 15% above the mean value (Figure 2). Reduction in BAI has been reported for other forests suggesting that water and nutrient are the main stress factors. A strong link between growth diameter and moisture has been found for P. menziesii at the Eastern Sierra of Mexico with larger deviations in diameter growth according to extreme wet and dry episodes.

Spectral analysis and periodicity

The Fisher’s Kappa (\( P<0.05 \)) and the Bartlett’s Kolmogorov-Smirnov statistic (\( P<0.0001 \)) were statistically significant, indicating that the series and their spectra are not white noise and the analysis is unbiased. Results suggested periodicities at 7, 14, 23 and 27 years in Chihuahua spruce (Figure 3). The cycles are in agreement with some droughts recurrence reported for northern Mexico, that have agreement with global circulatory events with El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) cycles found. These results can be due to the high sensitivity of the study species to climatic variations due to global events. Possibly, this quasi periodicity may be associated with solar activity, as the sunspot cycle varies from 8 to 14 years, while the average solar magnetic cycle is 22 years.

BAI transformation and stationarity

Dickey-Fuller Unit Root Tests and the autocorrelation function (ACF) of the original series showing nonstationarity (Table 1). The transformation of the BAI into natural logarithm and its first difference (\( Y_t \)) allowed that the series became grouped around the mean with a homogeneous variance. The logarithmic transformation

Basal area increase forecast, Picea chihuahuana Martínez through time series analysis as climate variability indicator

is convenient to decrease heteroscedasticity and the dth difference is suggested when the mean of series changes overtime. The ACF of the original Chihuahua spruce BAI chronology decays insignificant levels in seven years, (Figure 4); suggesting that the growth of the previous seven and three years influences current tree growth and diameter. Transformation and first-differencing is shown to result in greatly altered ACF, with significant negative autocorrelation at lag 1 year (Figure 4).

### Table 1: Augmented Dickey-Fuller Unit Root Tests of the BAI chronology in Chihuahua spruce

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**Figure 4** Original (4A) Transformed; (4B) Basal area increment chronology of P; (4C&D) Chihuahua, with autocorrelation functions (ACF); The dotted line represents 95% of confidence intervals.

**Identification and estimation ARIMA models**

The pattern of decay for ACF and ACFp of the transformed BAI suggested ARIMA (1,1,1) in Chihuahua spruce (Figure 5). The features of the process were defined by the spike at lag 1, then cut off to zero, and if the spike is negative then θ>0 (ACF) and by the exponentially negative side (ACFp). This result was consistent with the smallest canonical (SCAN) correlation method and the proposed ARIMA models was (1,1,1) for Chihuahua spruce. After considering the ACF, ACFp the selected ARIMA (1,1,1) model in Chihuahua spruce the model had a moving mean parameter (q) involving random shocks, which is different from the AR(1) or ARMA (1,1) models that are frequently proposed to the ring-width series. The selected models were evaluated with the periodicities found and without them to test their significance. Considering t and P values, in Chihuahua spruce the significant model was at (C=27); the model for (C=7) was not significant. The estimation of the moving average (θ) was positive with values of 0.84 and 0.87, while the cyclic moving average term (Θ) varied from 0.49 to 0.50 (Table 2). For forecasting purposes the selected model was ARIMA (1,1,1) x (1,1,0)27. Two reasons support this selection:

- Its statistical strength is reflected in the significance of its terms, no correlated residuals, the Akaike’s information criterion (AIC) AND Schwartz’s Bayesian criterion (SBC) lowest values and reliable fitting of the data
- The periodicity of 27 years may be related to global circulatory patterns as it has been reported by other authors.

**Figure 5** Autocorrelation function (ACF), (5A) and partial autocorrelation function (ACFp); (5B) of the transformed basal area increment chronology of P. chihuahuana. The dotted lines represents 95% confidence intervals.

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The approach used in this study shows potential to be used with other forest species to investigate climate change effects at landscape scales. The trends in tree growth we found are similar to that reported by other authors which indicated that extreme drought events like the ones in 1893 and 1952, 1981,1982,1998 were geographically important North Mexico and Southwest USA. Basal area increment series should be reconsidered as proxy variable to study climate change effects particularly for sensitive forest species. Indeed, the standardization process in dendrochronology proposes to standardize in terms of the stable BAI observed in the middle age of forests species. Our tree sample showed four phases of maximum tree growth, which were decreasing overtime (approximately 1899-1926, 1929-1957, 1959-1973 and 1980-2011). The implications of these results are the expected impacts of climate variation in the short-term future. The forecast of the model proposed is not considering implicitly climate variation and the trend for reduced tree growth may be an indication of a generalized response of the forest in other parts of the world. Additionally, used dendrochronology and time series analysis to determine past frequency of spruce budworm outbreaks according to climate variability in southern British Columbia found that, since the 1500s, outbreaks have been periodic, with a mean return interval of 28 years (95% Confidence Interval 21–35 years). They report that the number of outbreaks per century, since the 1800s, was constant, with 3–4 outbreaks per century. Our study shows these results and the different periodicities in the BAI series for Chihuahua spruce for twenty century in the study region.

**Forecast of basal area increment**

With the best statistical ARIMA model for each species, the forecast for BAI was performed at two time horizons, 15 and 80 years with the SAS 9.3 software, with the following equations. The model selected was ARIMA (1,1,1)x(1,1,0)27; with the following equations:

\[ \phi(B) \Phi(B^c) \nabla^d \nabla^D (Z_t) = \theta(B) \Theta(Q) (B^C) u_t \]

where:

\[ \ln (y_t) = \hat{Y}_t \]

\[ \nabla^d = 1 Y_t = Y_{t-1} - W_{t} \]

\[ \nabla^D = W_t = W_{t-1} - Z_{t-27} = Z_{t} \]

\[ Z_t = \Phi \Phi Z_{t-27} - \Phi_1 \Phi_2 Z_{t-28} = \theta_1 u_{t-1} + u_t \]

Substituting the estimated coefficients:

\[ Z_t = 0.506 Z_{t-1} - 0.506 X_{t-28} = 0.873 (B) u_t \]

The forecast in the model subtracts 50% of the same component of the previous year, 45% of the occurred 27 years ago and adding 23% of the occurred 28 years ago and subtracts a random component of the past year (97%). The reduction forecasted for BAI in the period 2011 to 2025 was about 97% with average of 42 cm² year⁻¹, and significant recovery for the period 2025 to 2028 (Figure 6). For this period, the projected growth will be below the historical mean (21 cm² year⁻¹) proposing a reduction in growth for 2090 (Figure 7).

**Figure 6** Forecast of BAI P. chihuahuana of from the ARIMA model. The black line is for real measurements and red line for estimation. The white area defines the confidence interval at 95%.

**Figure 7** Extended forecast of BAI P. chihuahuana from the ARIMA model. The black line is for real measurements and red line for estimation. The white area defines the confidence interval at 95%.

The forecast in Douglas-fir was estimated with the following equations:

\[ \sigma_p(t) \sigma_p(t) \nabla^d \nabla^D (Z_t) = \sigma_q(t) \sigma_q(t) \Theta(Q) (B^C) u_t \]

Where:

\[ \nabla^d = \nabla^d Y_t = Y_{t-1} - Z_{t-1} \]

\[ \nabla^D = Z_{t-1} = W_{t} \]

\[ \nabla^2 Z_t = W_{t-27} = Z_{t-27} \]

\[ \nabla^3 Z_t = \theta_1 \theta_1 Z_{t-1} + \theta_2 \theta_2 Z_{t-27} = \theta_1 u_{t-1} + u_t \]

Substituting the estimated coefficients:

\[ Z_t = 0.506 Z_{t-1} - 0.506 X_{t-28} = 0.873 \]

The model weights BAI based on the function of random shocks, subtracting 76% of the same component of the previous year, 45% of the occurred 60 years ago and adding 34% of the occurred 61 years ago.
ago. The forecast indicates reductions of 72% in BAI with average of 15 cm²·year⁻¹, and a recovery about the year 2025 (Figure 6). However the projected growth in 2025 for this specie is below the historical mean (54 cm²·year⁻¹) suggesting a net reduction in growth for the next 75 years. Because our results are assuming that the frequency of other stressing agents of the forests, such as pests and fires remains constant, the health of the studied forest may be compromised with concomitant negative effects from other factors. Tree growth trends found here for both species suggest a progressive decrease in tree growth for the next decades. Under natural conditions all forest species show decreased tree growth as trees get old. However, our sample was composed of young trees and we were expecting predictions of future tree growth reaching in some years rates above the average. These result have implications if we take into account recent changes in climate variability.¹° Biologically, the forecast indicates that if mean annual temperature increase and precipitation decreases in the Wet Sierra Madre as predicted by some authors,¹¹ these forests will be under risk in the next decades. Thus, the new management of these forests would be optimizing water resources to maintain healthy forests.

### References

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### Table 2 Adjustment of models for *P. chihuahuana*

| Model          | Parameter | Standard error | T value  | Pr>|t| | Variance estimation | Standard error of the estimation | AIC    | SBC    |
|----------------|-----------|----------------|----------|----------|---------------------|---------------------------------|--------|--------|
|                | $\theta$  | $\varphi$      | $\phi$  | $\theta$|            |                                 |        |        |
| *P. chihuahuana*|           |                |          |          |                     |                                 |        |        |
| ARIMA(1,1,1)   | 0.840     | --             | 0.073   | 11.47    | <0.0001            | 0.015                           | 0.122  | -223.99-217.78 |
|                | --        | 0.490          | 0.116   | 4.21     | <0.0001            | --                              | --     | --     |
| ARIMA(1,1,1)   | 0.445     | --             | 0.176   | 2.55     | 0.0116             | 0.023                           | 0.152  | -143.27-134.09 |
|                | --        | 0.048          | 0.197   | 0.25     | 0.8059             | --                              | --     | --     |
|                | --        | --             | 0.074   | -6.63    | <0.0001            | --                              | --     | --     |
| ARIMA(1,1,1)   | 0.873     | --             | 0.071   | 12.23    | <0.0001            | 0.024                           | 0.156  | -116.46-107.68 |
|                | --        | 0.506          | 0.120   | 4.21     | <0.0001            | --                              | --     | --     |
|                | --        | --             | 0.088   | -5.10    | <0.0001            | --                              | --     | --     |

### Conclusion

Time series analysis of BAI of Chihuahua spruce in the Sierra Madre Occidental allowed identifying periodicity in tree growth, which matches with global atmospheric events like El Niño Southern Oscillation and Pacific Decadal Oscillation. The forecast for BAI indicates decreased tree growth in the present decade and in the future until 2060 and, is possible that Chihuahua spruce forests will be under risk if the variability in precipitation and temperature are affected by the possible climate change. The projections of tree growth in the long-term will not be as high as that seen in the 1930 and 960s (30.14 and 30.61 cm²·year⁻¹). The use of time series analysis for BAI can be helpful to predict future changes in tree growth and to propose management and conservation practices.

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### Conflict of interests

The authors declare no conflict of interest.

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