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VARIABILIDAD CLIMÁTICA, EFICIENCIA DE USO DE AGUA INTRÍNSECA Y CRECIMIENTO DEL AREA BASAL EN BOSQUES DEL NORTE DE MÉXICO

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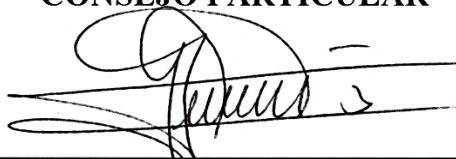PARA OBTENER EL GRADO DE:

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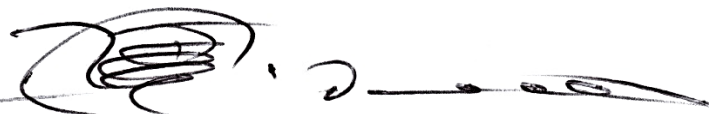**MONTECILLO, TEXCOCO, EDO. DE MÉXICO**

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La presente tesis titulada: **VARIABILIDAD CLIMÁTICA, EFICIENCIA DE USO DE AGUA INTRÍNSECA Y CRECIMIENTO DEL ÁREA BASAL EN BOSQUES DEL NORTE DE MÉXICO**, realizada por el alumno **LUIS UBALDO CASTRUITA ESPARZA**, bajo la dirección del Consejo Particular indicado, ha sido aprobada por el mismo y aceptada como requisito parcial para obtener el grado de:
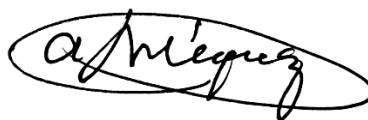
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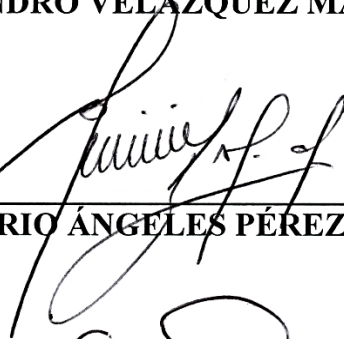**CONSEJO PARTICULAR**

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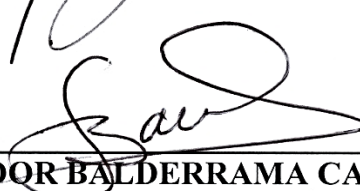
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RESUMEN GENERAL
VARIABILIDAD CLIMÁTICA, EFICIENCIA DE USO DE AGUA INTRÍNSECA E INCREMENTO DEL AREA BASAL EN BOSQUES DEL NORTE DE MÉXICO ANTE CAMBIO CLIMÁTICO

Luis Ubaldo Castruita Esparza, DR.

Colegio de Postgraduados, 2014

Esta investigación se centró en las respuestas fisiológicas de *Pseudotsuga menziesii* (Mirb.) Franco, *Abies concolor* (Gordon & Glend.) Lindl., *Abies durangensis* Martínez, y *Abies guatemalensis* Rehder ante los recientes cambios en la concentración de CO_2 atmosférico y variabilidad climática. A partir de las series de anillos de crecimiento de cada especie, seguido de estudios retrospectivos sobre el estado hídrico, eficiencia de uso de agua intrínseca y el crecimiento radial. También, se llevaron a cabo pronósticos de incremento en área basal para *Picea chihuahuana* Martínez. Este documento se estructura en seis capítulos, cuatro de ellos fueron escritos en formato de manuscrito científico. Estos manuscritos fueron escritos en inglés para facilitar su futura publicación en revistas internacionales.

Primer artículo: Este estudio es sobre la relación entre el crecimiento de *P. menziesii* y la variación de la precipitación en la Sierra Madre Occidental de México. La cronología de 150 años confirmó que el crecimiento de esta especie estaba fuertemente relacionada con la precipitación acumulada de enero a julio. La dinámica de crecimiento de *P. menziesii* describe ciclos relacionados con la periodicidad e índices del fenómeno El Niño Oscilación del Sur (ENSO por sus siglas en inglés). Se encontró correlación significativa entre los índices de anillos y el incremento de área basal, lo que sugiere que hay un alto potencial para reconstruir la dinámica de crecimiento pasado para algunas especies forestales.

Segundo artículo: Este estudio analiza los cambios en eficiencia de uso de agua intrínseca de *P. menziesii* como resultado del aumento del CO_2 atmosférico, durante el siglo pasado. El análisis se separó en periodos secos y húmedos para conocer como las especies forestales enfrentan los eventos extremos. *P. menziesii* respondió de manera similar a otras especies forestales en el mundo con una disminución en discriminación ($\Delta^{13}C$) e incremento en la eficiencia de agua intrínseca (iWUE). Sin embargo, estos cambios no se asociaron a un mayor crecimiento de los árboles, lo que indica que el aumento de EUAi observado fue el resultado de un ajuste en la relación de la fotosíntesis y conductancia estomática, sin evidencia del efecto de fertilización por CO_2. En los

últimos 150 años, el incremento de área basal de *P. menziesii* ha experimentado una disminución hasta del 50% (resistencia), y requiere de seis a diez años (resiliencia) para recuperar las tasas de crecimiento anteriores. Cuando las condiciones de humedad son favorables, el área basal se incrementó hasta en un 17% y mostró una "memoria" del efecto favorable a lo largo de tres años. El Abeto Douglas es una especie sensible, indicadora y de importancia ante el posible cambio climático regional en los ecosistemas forestales del norte de México.

Tercer artículo: Se examinó la respuesta en eficiencia del uso de agua intrínseca debido al aumento de CO_2 atmosférico en tres especies de *Abie*s. El estudio abarcó tres sitios distribuidos de 15 a 30º de latitud N. Como lo muestran otras especies forestales en el mundo, *A. concolor*, *A. durangensis*, y *A. guatemalensis*, muestran evidencias de dilución de ^{13}C en la atmósfera. Sin embargo, el enriquecimiento ^{13}C fue mayor en *A. concolor*, lo cual es consistente con el ambiente más seco donde la especie crece. La composición de isotopos de oxigeno ($\delta^{18}O$) en el último siglo no se ha visto afectada, lo que sugiere que la fuente de agua no ha cambiado. No obstante, *A. guatemalensis* mostró una firma $\delta^{18}O$ inferior en 5‰ con respecto a otras especies. Esto se explica por las condiciones de humedad más altas durante el año y menor enriquecimiento de evaporación en la hoja. En el siglo pasado el aumento en EUAi fue el siguiente: *A. durangensis* (31%), seguido por *A. guatemalensis* (28%) y *A. concolor* (21%). Estos incrementos se encuentran dentro del rango observado por otros autores. Los cambios en la discriminación ^{13}C y la EUAi no fueron mayores en el lugar más seco, como se estableció en la hipótesis.

Cuarto artículo: Dado que *P. menziesii* mostró crecimiento periódico y cíclico asociado a los índices del ENSO, se probó la construcción de modelos de predicción de crecimiento en *Picea chihuahuana* Martínez y *P. menziesii*, en base a la series de tiempo del incremento en área basal. La primera especie mostró parámetros importantes y altas correlaciones entre las muestras individuales. En el Abeto Douglas se observó periodicidad a 7, 21 y 60 años. El período de 60 años fue más consistente en relación a los índices del ENSO, este patrón ha sido reportado por otros autores. Con la periodicidad de 60 años y la serie de incremento en área basal se construyó un modelo ARIMA (0,1,1). El modelo predice reducciones progresivas en incrementos de área basal en los bosques de la Sierra Madre Occidental. Aunque se prevé ciertos grado de crecimiento de los árboles, la recuperación de las tasas de crecimiento no alcanzarían 60 cm^2 año^{-1}, tasa observada en décadas anteriores. Si las predicciones del modelo en este estudio son una reflexión del cambio climático, el crecimiento de los bosques estaría en riesgo en las próximas décadas, ya

que de acuerdo a las predicciones de los modelos de cambio climático indican una mayor frecuencia de las sequías, plagas y enfermedades como se ha observado en las últimas décadas en los ecosistemas forestales del norte de México. La tendencia de crecimiento reducido en el futuro trae la pregunta sobre el cambio en la silvicultura en los bosques del area de estudio, enfocándose en las estrategias de manejo de densidades del rodal de acuerdo a la disponibilidad de recursos que lleven a la salud de los bosques para resistir los efectos del clima.

Palabras clave: Dendroecología, isótopos, cambio climático, productividad forestal

GENERAL SUMMARY
CLIMATE VARIABILITY, INTRINSIC WATER USE EFFICIENCY AND BASAL AREA INCREASE OF FORESTS IN NORTHERN MEXICO TO CLIMATE CHANGE

Luis Ubaldo Castruita Esparza, DR.

Colegio de Postgraduados, 2014

This research focused on physiological responses of *Pseudotsuga menziesii* (Mirb.) Franco, *Abies concolor* (Gordon & Glend.) Lindl. *Abies durangensis* Martínez, y *Abies guatemalensis* Rehder under the recent changes in atmospheric CO_2 concentration and climate variability. It started with the tree ring time series for each species, followed by retrospective studies on the water status, intrinsic water use efficiency and tree growth. Also, prognostics for basal area increment were carried out for *Picea chihuahuana* Martínez. This document was structured in six chapters, four of them were written in a scientific manuscript format. These manuscripts were written in English to facilitate their future publication in international journals.

First manuscript: This study is about the relationship between tree growth of *P. menziesii* and the variation in precipitation in the Western Sierra Madre of Mexico. A 150-year tree chronology confirmed that the tree growth of this species was strongly related to the cumulative precipitation from January to July. Tree growth dynamics of *P. menziesii* describes cycles related to indices and periodicity of El Niño Southern Oscillation (ENSO). A significant correlation between the tree ring indices and basal area increment was found, which suggests that there is a high potential to rebuild past dynamics of tree growth for some forest species.

Second manuscript: This study analyzed changes in intrinsic water use efficiency of *P. menziesii* as a result of the increase in atmospheric CO_2, during last century. The analysis separated wet and dry periods to know how the forest species faced extreme events. *P. menziesii* responded similarly to other forest species in the world decreasing discrimination ($\Delta^{13}C$) and increasing intrinsic water use efficiency (iWUE). However, these changes were not associated to higher tree growth, which indicated that the increase in iWUE observed was a result an adjustment of the ratio photosynthesis to stomatal conductance, with no evidence of the effect of CO_2 fertilization. In the last 150 years the basal area increment of *P. menziesii* has undergone decreased up to 50% (resistance), requiring six to ten years (resilience) to recover previous tree growth rates. Where moisture conditions were favorable, basal area increased up to 17% and showed a "memory" of the beneficial effect for three years. Douglas fir is a sensitive species and an important indicator in the possible regional climate change in forest ecosystems in northern Mexico.

Third manuscript: The response in water use efficiency due to the increase of atmospheric CO_2 for three species of *Abies* was examined. The study included three sites along the 15 to 30° N. latitude. As found in other tree species in the world, *A. concolor*, *A. durangensis*, and *A. guatemalensis*, showed evidence of dilution of atmospheric ^{13}C. However, the ^{13}C enrichment was higher in *A. concolor*, which is consistent with the drier environment where the species grows. Wood ^{18}O composition has not affected in last century, suggesting that no changes in the source of water. Nonetheless, *A. guatemalensis* showed a $\delta^{18}O$ signature lower in 5‰ with respect to other species. This is explained by higher moisture conditions and lower evaporative enrichment in the leaf. In the last century the increase in iWUE was as follows: *A. durangensis* (31%), followed by *A. guatemalensis* (28%) and *A. concolor* (21 %). These increases are within the range observed by other authors. Changes in the ^{13}C discrimination and iWUE were not higher at the driest site, as was established in the hypothesis.

Fourth manuscript: Because *P. menziesii*, showed a cyclical tree growth associated to the ENSO indices, the building of forecast models was tested to predict tree growth for *Picea chihuahuana* Martínez and *P. menziesii*, based on the time series of basal area increments. The first species showed more significant parameters and higher correlations among individual tree samples.

The periodicity for Douglas-fir was observed at 7, 21 and 60 years. The 60-year period was more consistently related to the ENSO indices a pattern that has been reported by other authors. With the 60-year periodicity for the basal area increment series an ARIMA model (0,1,1) was built. The model predicts progressive reductions in basal area increments for the forest of the Western Sierra Madre. Although some degree of tree growth recovering is forecasted, growth rates would not reach 60 cm^2 $year^{-1}$, a rate observed in previous decades. If the predictions of the model in this study were a reflection of climate change, then tree growth would be at risk in the next decades, as the predictions of climate change models indicate higher frequency of droughts, pests and diseases as was observed in the last decades in the forest ecosystems of northern of Mexico. The trend of reduced tree growth in the future brings the question about the change in the silviculture for forests of the study area, focusing in strategies to manage stand density which according to the availability of resources, lead to the required forest health to resist to resist the climate effects.

Key words: Dendroecology, isotopes, climate change, forest productivity

DEDICATORIA

A mis padres, **María Isabel e Ismael** por su paciencia y amor incondicional en cualquier situación, gracias amados padres, disfruto infinitamente cada día cuando estoy a su lado.

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CAPÍTULO I
INTRODUCCIÓN GENERAL

Los cambios que el hombre ha causado recientemente en la composición de gases en la atmósfera, particularmente en la concentración de CO_2, están impactando de diversas formas sobre el crecimiento de los bosques del mundo (Bonan, 2008). En el último siglo las concentración de CO_2 en la atmósfera pasaron de 300 to 400 ppm (NOAA, 2014). Dada la diversidad de especies arbóreas y climas en el mundo, se espera que las repuestas de los bosques varíen latitudinal y altitudinalmente (Battipaglia *et al.*, 2013). Una forma en que impacta el incremento en las concentraciones de CO_2 atmosférico, es en el cierre de estomas de la vegetación. A su vez, este impacto puede manifestarse en una reducción en la transpiración y cambios en la tasa de fijación neta de carbono. Por la disminución en la transpiración el escurrimiento superficial en bosques húmedos y boreales podría incrementar hasta en un 22% (Peters *et al.*, 2013)

Respecto a las predicciones en la vegetación hay pronósticos de un incremento en la productividad primaria neta debido al ahorro de agua y mayor disponibilidad de CO_2 (Peters, Wythers *et al.,* 2013). Si la disponibilidad de CO_2 se traduce en mayor tasa fotosintética y la transpiración se mantiene o decrece, entonces la cantidad de agua requerida por unidad de biomasa, que es la eficiencia de uso de agua, aumentará (Keenan *et al.*, 2013).

Otro posible escenario es que, el aumento de temperatura generado por mayor capacidad de la atmósfera para la absorción de energía radiante de onda larga, conduzca a un estrés hídrico y como resultado la productividad primaria neta decrezca. El mayor efecto de del incremento en la temperatura sobre el estrés hídrico, a pesar de mayor disponibilidad de CO_2, seria en ambientes secos (Linares and Camarero, 2012). También se pronostica que con mayores concentraciones de CO_2 y un incremento en la eficiencia de uso de agua, los ecosistemas entren en estado de desbalance entre la cantidad de nutrientes que demandan y la disponibilidad del suelo para proveerlos, ante esta situación, aun con mejor eficiencia de uso de agua los ecosistemas se podría estresar nutricionalmente (Gomez-Guerrero *et al.*, 2013). La respuesta de la vegetación a los cambios de la atmósfera también se verá influenciada por la alteración de otros ciclos como el del nitrógeno debido a una estimulación del crecimiento en las primeras fases de la saturación de nitrógeno (Leonardi *et al.*, 2012).

Pronosticar con certeza el comportamiento de la vegetación y encontrar el método más indicado es difícil por las características fisiológicas de cada especie y la variación espacial del suelo y el

clima. Sin embargo, los estudios para estudiar el comportamiento de la vegetación ante el cambio climático se separan en tres grandes grupos, (*i*) estudios bajo cámaras controladas, (*ii*) técnicas de dendrocronología combinadas con isótopos de ^{13}C y (*iii*) experimentos con carbono enriquecido al aire libre (FACE por sus siglas en inglés). Los estudios con cámaras controladas son de corto plazo y es posible que no den oportunidad a la aclimatación de las plantas para conocer su verdadero comportamiento a largo plazo (Ainsworth and Long, 2005; Gagen *et al.*, 2011). Los estudios con carbono enriquecido baja atmósferas abiertas requieren una inversión importante y por esa razón se limitan a un número reducido de condiciones ambientales y tipos de bosques (Battipaglia, Saurer et al., 2013). Sin embargo, este tipo de experimentos se está incrementando en número y en superficie para representar las condiciones reales de un bosque (Ainsworth and Long, 2005). La combinación de métodos dendrocronológicos con isótopos es un procedimiento intermedio que permite reconstruir los cambios en crecimiento de la vegetación en escalas de siglos y bajo diferentes condiciones ambientales (Andreu-Hayles *et al.*, 2011; Nock *et al.*, 2011; Peñuelas *et al.*, 2011; Gomez-Guerrero, Silva et al., 2013).

La investigación realizada en este trabajo tiene su fundamento en técnicas dendrocronológicas y el uso dual de isótopos. Las técnicas mencionadas, además de permitir el estudio del crecimiento y la eficiencia de uso de agua, proveen la información básica para estudiar la relación entre variables del clima como la temperatura y la precipitación con el crecimiento radial. Las relaciones del clima y crecimiento de los árboles permiten reconstruir el clima del pasado e identificar los eventos más importantes en condiciones de humedad. También ayuda a conocer los umbrales a los que los bosques han disminuido su crecimiento (resistencia) por la variabilidad climática y el tiempo que les toma para regresar a las condiciones previas (resiliencia) (Lloret *et al.*, 2011).

Los métodos dendrocronológicos también proveen información sobre comportamiento de crecimiento de los bosques, lo que nos permite identificar si existe periodicidad en los ritmos de crecimiento y hasta qué punto dichos periodos se asocian con variaciones climáticas y eventos atmosféricos globales como el ENSO.

Considerando la frontera del conocimiento sobre el comportamiento de los bosques ante los cambios recientes de la atmósfera, el presente estudio presenta cuatro capítulos en forma de manuscritos para publicación, el primero para comprender la variabilidad climática en bosques de *P. menziesii* y su relación con la precipitación, así como con las diferentes periodicidad y ciclicidad que presenta el ENSO. El segundo manuscrito analiza los cambios en la eficiencia de uso de agua

y crecimiento de *P. menziesii* tomando en cuenta las respuestas en periodos húmedos y secos. Para contribuir al conocimiento de las técnicas combinadas de isótopos, se estudian los cambios en las variables fisiológicas de acuerdo a periodos húmedos y secos a través del tiempos y en relación al modelo semi-cuantitativo (Scheidegger *et al.*, 2000) para conocer si los cambios en la eficiencia de uso de agua se deben a cambios proporcionales de fotosíntesis y conductividad estomática (A/g_s) o la disminución de g_s. El tercer manuscrito analiza los cambios en eficiencia de uso de agua y firmas de ^{18}O en madera de tres especies de *Abies*, *A. guatemalensis, A. duranguensis* y *A. concolor* distribuida a lo largo de un gradiente latitudinal en el Pácifico mexicano. El cuarto manuscrito presenta un análisis de periodicidad en crecimiento del área basal de *P. menziesii* y *Picea chihuahuana* Martínez. Los manuscritos de esta investigación se escribieron en inglés ya que se planea su publicación en revistas internacionales. Sin embargo, como capítulo final se presentan en español las conclusiones sobre los principales hallazgos de la investigación.

1.5 OBJETIVOS

a) Objetivo general

Analizar la dinámica de crecimiento de especies forestales de clima templado en relación a la variabilidad climática e investigar su comportamiento fisiológico ante el reciente incremento de dióxido de carbono en la atmósfera. Así como proponer pronósticos de crecimiento de area basal para los bosques del norte de México.

b) Objetivos específicos

- Construir y analizar una cronología de incremento de area basal en *Pseudotsuga menziesii* a fin de conocer la dinámica de crecimiento y su correlación con los índices del ENSO en los bosques del oeste de Chihuahua.
- Analizar mediante un análisis dual de isótopos de ^{13}C y ^{18}O los cambios en variables fisiológicas relacionadas con el estatus hídrico considerando en eventos secos y húmedos extremos en el Abeto douglas.
- Estudiar la respuesta en crecimiento de especies forestales de clima templado con relación al incremento de CO_2 atmosférico a través del tiempo.

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- Investigar mediante análisis de isótopos y régimen de humedad la respuesta en el tiempo del género *Abies* ante el incremento de CO_2 en el Pácifico Mexicano.
- Analizar la periodicidad en incremento del área basal de *Picea chihuahuana* y *Pseudotsuga menziesii* mediante el modelado y pronostico de series de tiempo, en bosques del norte de México.

1.6 HIPÓTESIS

a) Los incrementos en área basal de arbolado joven de *Pseudotsuga menziesii* no muestran diferencias significativas a través del tiempo.

b) Los incrementos en área basal de *Pseudotsuga menziesii* no se correlacionan significativamente con variables climáticas o fenómenos atmosféricos globales como el ENSO.

c) Las variables fisiológicas evaluadas mediante un análisis dual de isótopos (^{13}C y ^{18}O) no muestran diferencias significativas a través del tiempo en el Abeto douglas y no se correlacionan con el incremento de CO_2 en la atmósfera.

d) Los árboles del género *Abies* en la latitud norte han sido más afectados por los cambios de CO_2 en la atmósfera que los árboles del sur de México, y el análisis separado de los regímenes de humedad (seco/húmedo) muestran diferencias significativas en el tiempo a lo largo del Pácifico Mexicano.

e) El incremento del area basal de *Picea chihuahuana* y *Pseudotsuga menziesii* en los bosques del norte de México carecen de periodicidad y no es posible el modelado y pronóstico mediante series de tiempo.

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CAPÍTULO II
CLIMATE VARIABILITY AND BASAL AREA INCREMENT OF *Pseudotsuga menziesii* (Mirb) Franco IN NORTH MEXICO

2.1 RESUMEN

Las especies forestales como *Pseudotsuga menziesii* (Mirb) Franco son sensibles a la variabilidad del clima y proporcionan información esencial respecto a la respuesta futura de los ecosistemas forestales frente al cambio climático. Entender la variabilidad del clima y sus efectos sobre el incremento de área basal (IAB) puede contribuir con información adicional para la gestión forestal. El objetivo de este estudio fue desarrollar una cronología de abeto Douglas para el oeste de Chihuahua y relacionar ésta con la variabilidad climática y el IAB como un índice de crecimiento. Se utilizaron anillos de crecimiento y registros de precipitación disponible para reconstruir la precipitación de los últimos 150 años (1850-2010). Los resultados mostraron una correlación altamente significativa (R^2=0.37 p<0.001) entre el IAB y la precipitación invernal. También hubo correlación estadística entre el IAB y los índices de El Niño 3.4 (ENSO, por sus siglas en inglés) (r = 0,45, P <0,01). La correlación significativa de IAB con los índices del ENSO y la precipitación sugiere que la respuesta de los bosques al cambio climático se puede predecir.

Palabras clave: Dendrocronología, Abeto douglas, Anillos de crecimiento, Precipitación, ENSO

2.2 SUMMARY

Forest species like Douglas-fir (*Pseudotsuga menziesii* (Mirb) Franco) are highly sensible to climate variability providing essential information to understand response of forest ecosystems to climate variability. In this work, a 150 y chronology of Douglas-fir sowed that tree ring width and basal area increment (BAI) are useful to understand tree growth and climate variability. The significant correlation (p<0.05) between tree ring and precipitation allowed the reconstruction of the precipitation of the study sites in the las 150 y (1850-2010). The accumulated precipitation from January to July was the most significant period to explain changes in forest productivity (R^2=0.37 p<0.001). There was also a statistical correlation between BAI and the El Niño 3.4 indices (ENSO) (r = 0.45, *P*<0.01). The significant correlation of BAI to ENSO indices and precipitation suggests that the response of forest to climate change could be predicted.

Keywords: Dendroecology, Douglas-fir, Tree growth, Precipitation, ENSO

2.3 INTRODUCTION

Basal area increment (BAI) provides indirect information of forest productivity due to the ever-increasing diameter of trees (Rubino & McCarthy, 2000). Basal area growth in trees typically follows a sigmoidal pattern; increasing rapidly from young to middle age, plateaus and remains level during a protracted period of middle age and then declines, as trees become older (Kazcka *et al*., 2009; Weiner and Thomas, 2011). In dendroclimatology, BAI measurements are used as a proxy variable to establish relationships between forest growth and climate variability (Briffa *et al.*, 1998). In some circumstances when forest species highly sensitive to climate variation are involved, BAI measurements at 1.3 m above the ground are more accurate to represent forest productivity than radial measurements or tree ring indexes (Pedersen, 1998; Johnson and Abrams, 2009; Bouriaud *et al.,* 2005). The conversion of ring width into BAI is also a recommended practice to avoid the aging effects on trees (Poage & Tappeiner, 2002, Jump *et al.*, 2006) but the circular shape of the trunk section is an important requirement. The combined analysis of radial (tree ring index) and basal measurements can improve the relationship between climate and tree growth.

Douglas-fir *(P. menziesii)* is the tree species of wider distribution in North-America with natural stands from Canada to central México (Hermann & Lavender, 1999). This tree species has been widely used for dendroclimatic purposes due to its sensitivity to climate. Some Douglas-fir individuals in north Mexico live up to 600 years, providing useful information on climate variability and tree growth trends (Villanueva *et al.*, 2006). Tree rings of Douglas-fir are so related to climate that there is a strong relationship between ring width and winter-spring and summer precipitation; even global circulatory events like El Niño South Oscillation (ENSO) warm phase (Stahle *et al.*, 1998) and the Northameican Monsoon System (Griffin *et al.*, 2013) leave a fingerprint in the tree rings of this species.

The objectives of this study were: 1) to build and analyze tree ring and basal area increment chronologies for Douglas-fir; 2) to relate tree ring width and basal are to climate variables; and, 3) to correlate ENSO indices to tree chronologies and forest productivity of Douglas-fir western Chihuahua forest.

2.4 MATERIALS AND METHODS

2.4.1 Study area

   The study area is located in northwestern Mexico in the state of Chihuahua on the Sierra Madre Occidental (SMO). The study sites are in the municipalities of Madera (MAD) and Balleza (BAE), and geographically located at 29° 19' 21.96"NL and 108°12'40.28"WG; 26°27'59.14"NL and 106°21'14.95"WG, respectively (Figure 2.1). Douglas-fir populations were located along an elevational gradient from 2678 to 2715 m. Climate classification is Cb '(w2) x', temperate sub-humid with cool summer (García, 1998). Annual average temperature ranges from 5 to 12°C, temperature of the coldest month ranges from -3°C to 18°C, and temperature of the warmest month is 22°C. Annual rainfall varies from 385 to 780 mm with a precipitation for the driest summer month lower than 40 mm and a winter seasonal percentage rainfall of 5 to 10% of the annual precipitation. Soil units in the study area according to the World Reference Base for Soil Resource for Soil Resource (WRBSR) are Leptosols and Pheozems, comparable to Entisols and Mollisols in the Soil Taxonomy Classification (WRBSR, 2006).
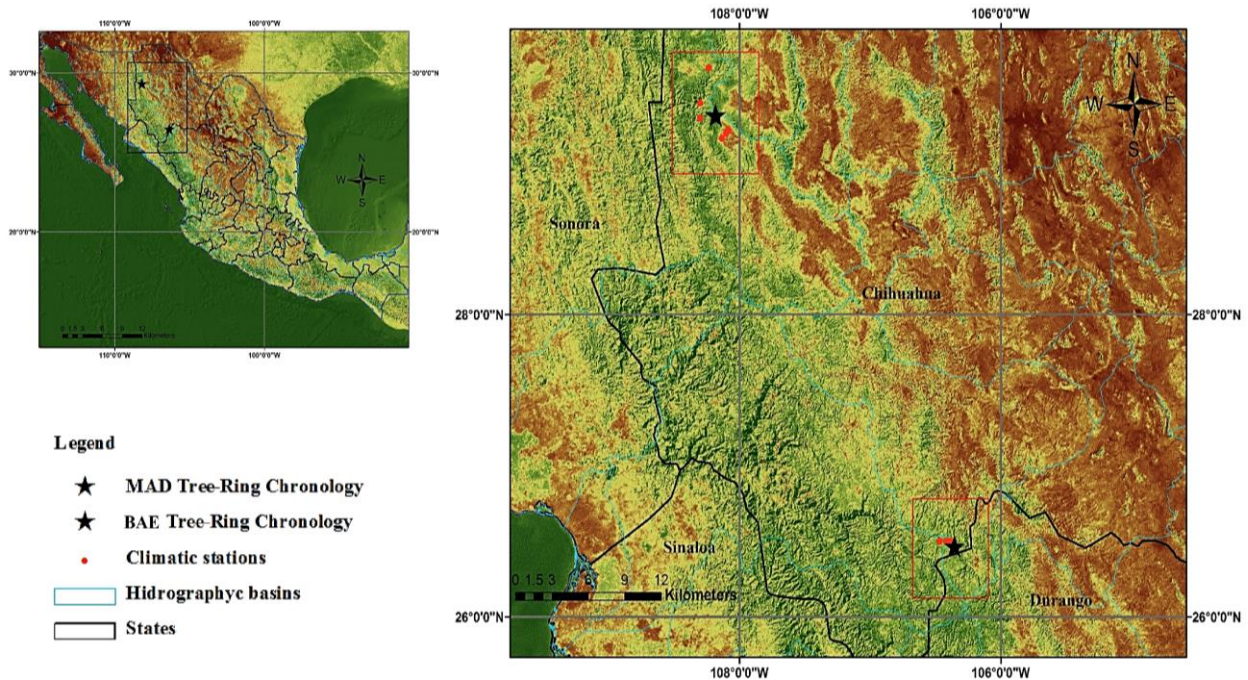
Figure 2.1 Geographical location of the sampled sites.

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Douglas-fir forests are rarely found in pure stands, and usually are intermixed with other conifer species from the genus *Pinus, Abies*, *Picea, Cuppressus, Juniperus* and broadleaves species of *Quercus, Arbutus, Alnus, Populus, Prunus, Acer,* among others. It prefers shady, moist places of canyons with north, northeast or northwest facing slopes, where solar radiation and evapotranspiration are lower (Villanueva Díaz *et al.*, 2008).

2.4.2 Wood core sampling and BAI determination

The trees were selected along an altitudinal gradient from 2710 to 2740 m. The site selection considered the presence of healthy mature Douglas-fir specimens. Two increment cores were collected at breast height from each selected tree using a Haglöf increment borer of 12 mm internal diameter and 14 inches in length.

A total of 40 wood increment cores were taken from mature and healthy trees. Increment cores from young trees were included in the sample size to facilitate dating of the most recent period. Each sampled tree was geographically located with a GPS (Gramin ®). Increment cores were labeled with the site name, species, altitude, latitude, dbh, and additional ecological information. Cores were wrapped in aluminum foil for protection and transportation. In laboratory, the wood cores were dried up at room temperature for seven days to reduce moisture content, and then mechanically polished with sandpaper in grains from 120 to 1200 to better visualize annual ring bands.

Samples were processed with standard dendrochronological techniques. Ring widths were measured to the nearest 0.001mm with a Velmex measurement system (Robinson & Evans, 1980). The quality control of dating was done with the COFECHA software, (Holmes, 1983), and biological trends unrelated to climate were removed with the ARSTAN program. Ring-width indices were produced by dividing each measured value by the estimated value from a fitted negative exponential curve or straight line (Cook & Holmes, 1984). The ARSTAN program generated three versions of ring width chronologies: Standard, Residual and Arstan (Cook, 1985), in this study, the standard version was used. To highlight low frequency events at decadal scale a cubic smoothing spline was fitted to the ring-width indices (Cook & Peters, 1981). Ring-width measurements were then transformed into BAI with the circle equation. The bole section of

Douglas fir has generally circular shape and the selected trees for this study met that criteria. The equation to compute BAI was as follow:

$$BAI = \pi \ (R_n{}^2 - R_{n-1}{}^2)$$

Where R is the radii of the stem at breast height (1.30 m) and "n" is the year when the tree ring (early and late wood) was formed.

To analyze the relationship between the chronology and climatic data, eighth nearby weather stations were used to integrate a representative regional climatic record obtained from the database of the Mexican Institute for Water Technology. A response function analysis was investigated by using DENDROCLIM2002 software (Biondi & Waikul, 2004) that allows identifying the months with higher correlation to ring with indexes and the "memory" effect of past years.

Once the months of higher correlation were identified, a regression equation was calculated to relate climate data and ring indexes. Half of the data used for calibration and half for verification (Fritts, 1991). Given that both subperiods were statistically significant, we used the total climate record to derive a linear regression equation and then used it to reconstruct precipitation on the total length of the chronology. A decadal flexible spline was fitted to the seasonal precipitation data to highlight low frequency events (Cook & Peters, 1981).

The climate reconstruction was compared to ENSO indices, region 3.4 (Trenberth, 1997, Magaña & Víctor, 1999) to analyze its relationship to climate variability. In northern Mexico, ENSO in its warm phase (El Niño) is associated with higher rainfall conditions in winter, while its cold phase (La Niña) tends to favor drier winters, leading to severe droughts (Magaña *et al.*, 2003, Caso *et al.*, 2007). In this context, to analyze the influence of ENSO on precipitation variability the reconstructed precipitation was correlated with ENSO indices using MATLAB 6.5 software (Matlab, 2002). Finally, for the analysis of BAI between wet and dry years, a t-test was performed with SAS 9.3 software (SAS, 2011).

2.5.1 Ring width chronology and parameters

Two ring width chronologies of Douglas-fir with a length of 160 years were developed, the sample depth was 40 radii. The chronologies were dated with series inter-correlation of 0.67 and 0.70 for MAD and BAE sites, respectively. The association between chronologies was significant 0.40 $P<0.001$ and indicating the reliability to integrate the collections in a single representative chronology (Figure 2.2).
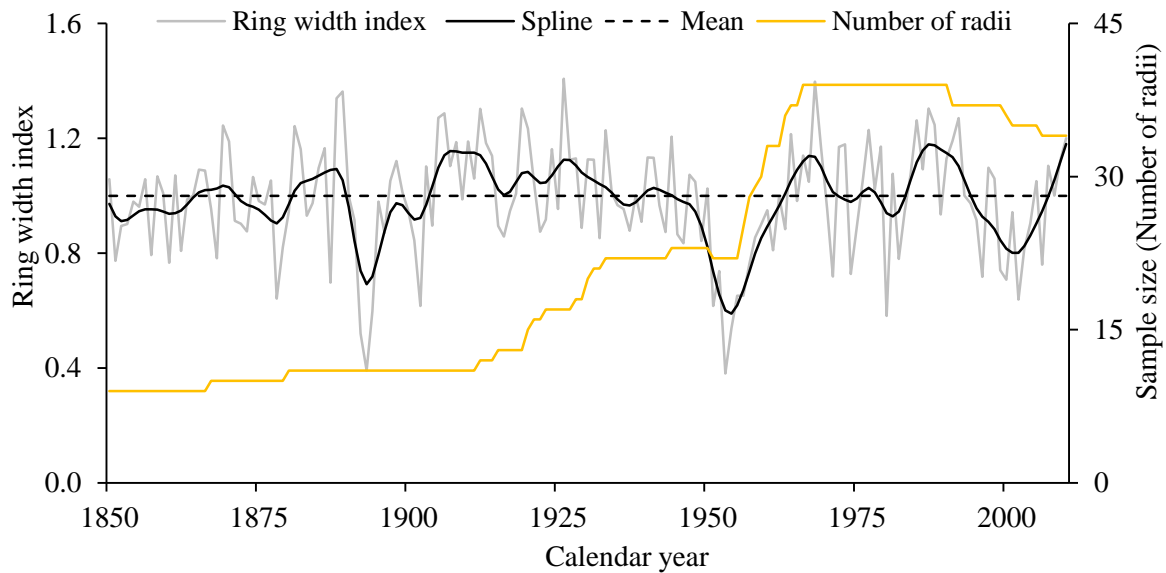
Figure 2.2 Douglas-fir standard ring width chronology representative for two locations (MAD, BAE) in western Chihuahua, covering the period 1850 to 2010.

Some statistical parameters of the Douglas-fir chronology for Chihuahua were similar to some previously developed for the Sierra Madre Occidental, Sierra Madre Oriental and Transvolcanic Belt in México (Table 2.1). However, the mean sensitivity values were better for locations in the Sierra Madre Oriental and Transvolcanic Belt, which may be an indication of greater inter-annual climatic variability.

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Table 2.1 Statistics of Douglas-fir Chronologies Mountain ranges in Mexico.

Statistic	Sierra Madre Occidental (This study)	Sierra Madre Occidental (Villanueva *et al.,* 2008)	Sierra Madre Oriental (Villanueva *et al.,* 2008)	Transvolcanic Belt (Villanueva *et al.,* 2008)
Mean sensitivity[1]	0.18–0.30	0.13–0.34	0.23–0.38	0.21–0.35
Standar deviation	0.19–0.31	0.20–0.31	0.27–0.33	0.22–0.24
Skewness[2]	0.07–0.38	0.07–0.47	0.05–0.62	0.05–0.25
Kurtosis[3]	-0.05–0.31	-0.06–2.32	-0.04–2.10	-0.05–0.54
First–order autocorrelation[4]	0.01-0.19	0.03–0.39	0.05–0.49	0.07–0.35
Second–order autocorrelation	0.02–0.18	0.02–0.16	0.02–0.17	0.09–0.10
Autoregresive variance (%)	0.0-0.14	0.2–19.0	3.5 – 23.0	0.0 – 15.0

[1]The Mean sensitivity is related to the change in growth from one year to the next [2]Skewness is a measure of symmetry in a normal distribution; [3]Kurtosis concerns if data is concentrated on a peak or have a more uniform behavior (flattened) on a normal distribution. ; [4]Autocorrelación is a measure of the tendency of a species to produce similar growth from one year to another, this trend decreases with time.

2.5.2 Response function

The response function from DENDROCLIM2002 (Biondi & Waikul, 2004) indicated that the precipitation of July, August, September, October and December of the previous year, and January, March, April, May, June, and July of the current year significantly correlated (p<0.05) to the tree width index (Figure 2.3).
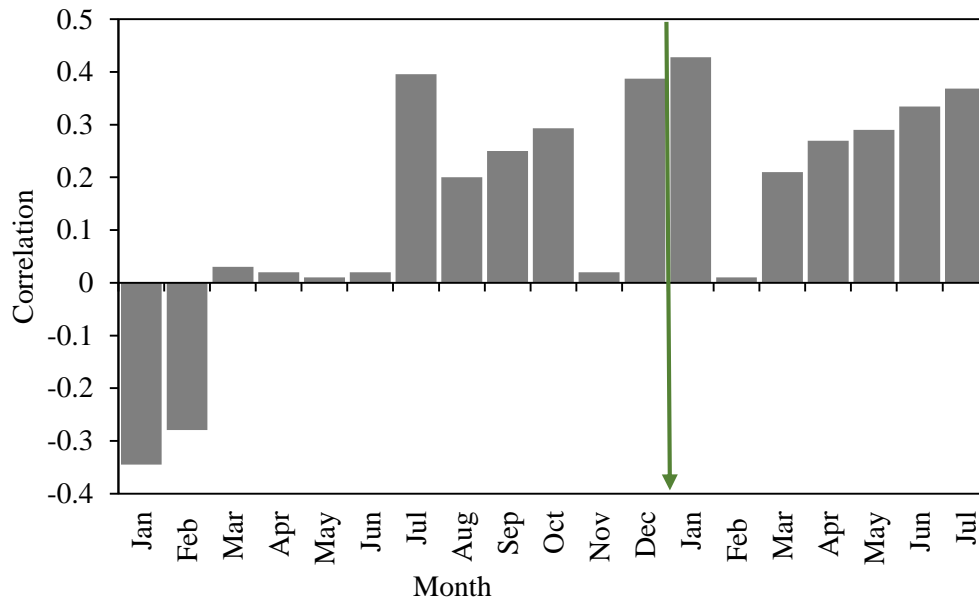
Figure 2.3 Correlation between the ring width chronology and precipitation from the previous
    to the current year from 1968 to1988.

The response function indicated a negative correlation ($P> 0.05$) between the ring width index and the precipitation of January and February of the previous year (Figure 2.3), contrasting with a significant ($P<0.05$) and positive correlation for the months from January to July of the current year. On the other side, we also found that considering the accumulated the accumulated precipitation from December of the previous year through July to the current year, significantly explains the variability of the tree ring index.

One possible explanation for the significant and higher correlation between the precipitation of winter (December previous year and January current year) and tree index may be that the rain intensity in the cool season are lower than that of the spring, as the monsoonal climate predominates in the forests of Mexico (Magaña *et al.,* 2012). High intensity rainfall events of summer may exceed the infiltration capacity of soil producing higher runoff and preventing water storing in the soil profile (Garcia, 1978). The amount of water stored in the soil profile is reflected on radial and basal area growth of forest species during the next growing season (Sarris *et al.*, 2013). The negative correlation between tree growth of the current year and winter precipitation of the previous year, may a reflection of the sequence of wet a dry periods, after a year with higher precipitation than the average, a regular or dry year comes next (Magaña, *et al.,* 200).

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2.5.3 Precipitation reconstruction

The standard ring width chronology was significantly associated with seasonal January-July precipitation for the period 1968 to 1988 (r= 0.79, p<0.001, n=20), showing the highest potential of our data for climate reconstruction (Figures 2.4 and 2.5).
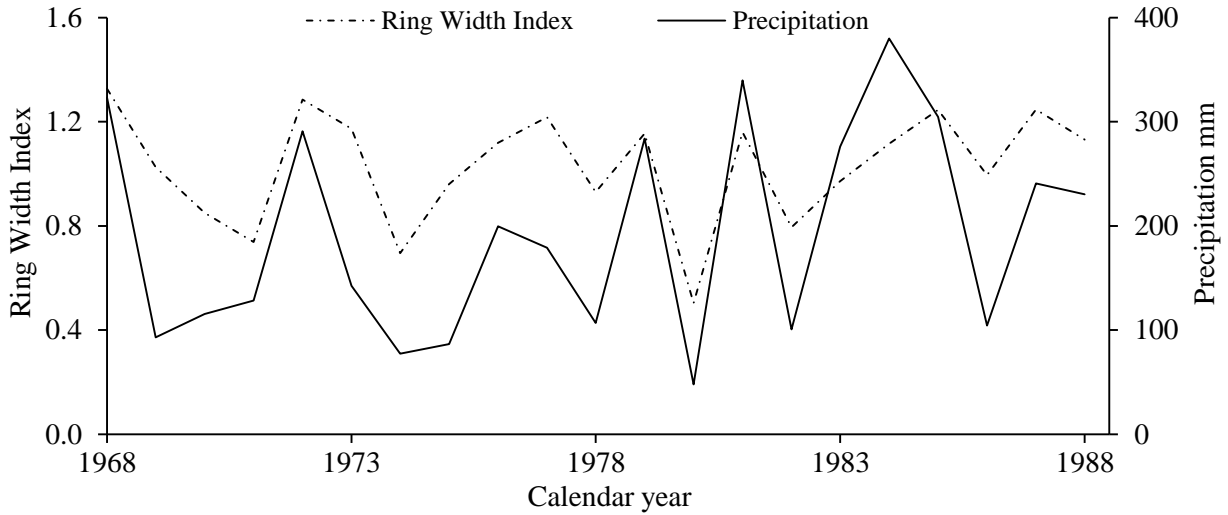
Figure 2.4 Association between ring width indices and accumulated January-July precipitation for the period 1968 to 1988.
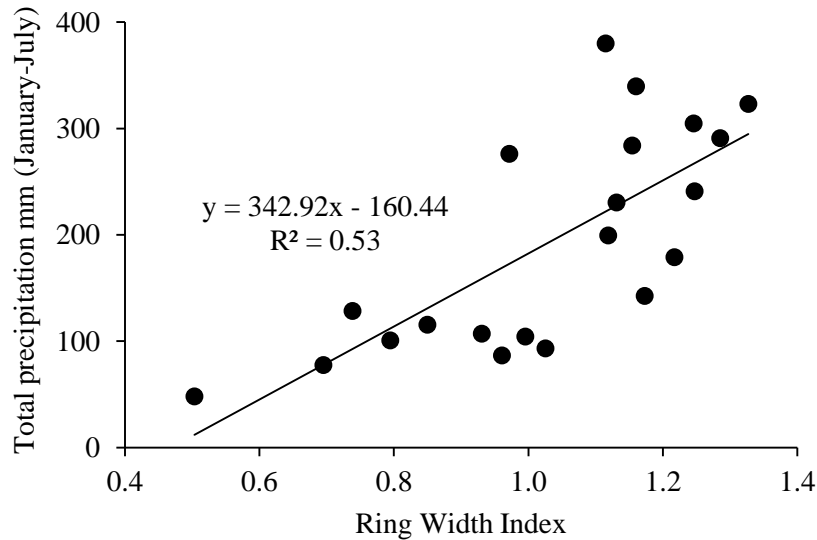
Figure 2.5 Scatter plot of the linear regression model showing the relationship between ring width indices and accumulated January-July precipitation for the period 1968 to 1988.

2.5.4 Calibration and verification

A linear regression model between ring width indices and seasonal precipitation was developed using the Statistica softwareV10. Half of the climate records were used for calibration (1979-1988) and half reserved for verification (1968-1978), (Fritts, 1991). The statistical values derived from the VERIFY5 subroutine, indicated that calibration and verification procedures were statistically significant ($P<0.05$) for the correlation, reduction of error, "t" value, and first significant difference. Therefore, the regression model was considered statistically valid for reconstruction purposes.

According to the model, ring-width indices explain 54% of seasonal winter-spring precipitation variability for this region (Figure 2.6). The linear regression model was as follow:

Yt=-160.4+342.9*Xt

Where: Yt= Reconstructed seasonal January-July precipitation for a given year (mm).

Xt=Tree-Ring Width Index.
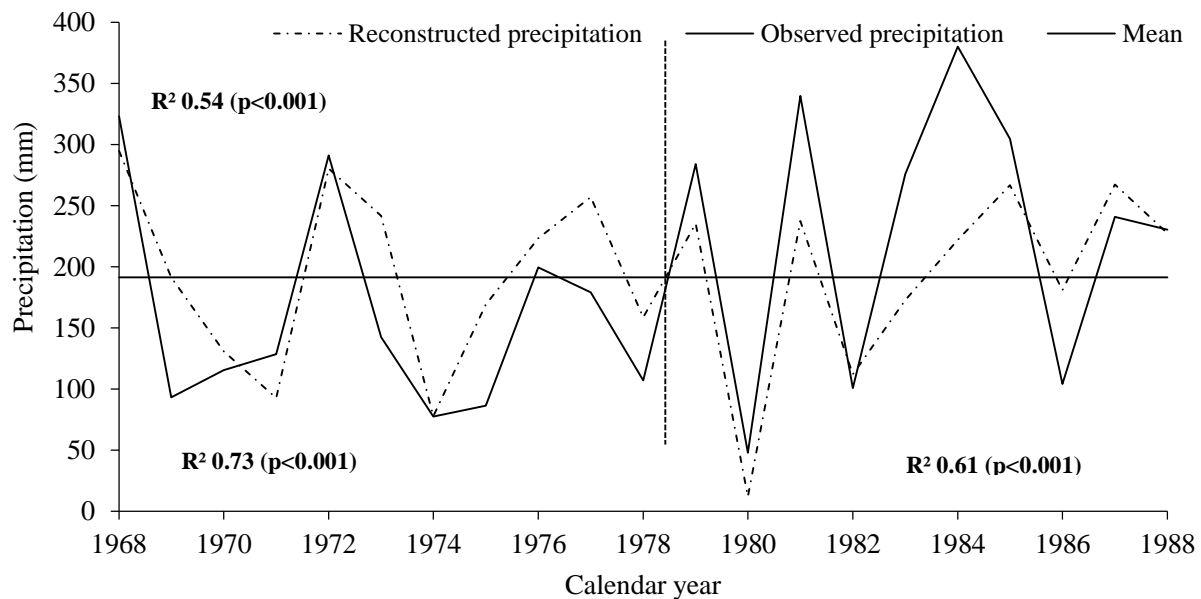
Figure 2.6 Observed precipitation (solid line) and reconstructed (dotted line) for the
accumulated rainfall from January to July.

2.5.5 Analysis of climate variability

Dry and wet episodes reconstructed from 1850 to 2010, showed that the driest periods took place from 1878 to1882, 1891 to1895, 1951 to 1955, and 1998 to 2002, and some particular dry years were 1860, 1938, and 1980. Seven wet episodes were detected from 1884 to1888, 1908 to1912, 1926 to 1930, 1965 to1970 and 1985 to1989. The ENSO phenomena has a significant influence on the precipitation of western Chihuahua as was demonstrated by the significant association found between the reconstructed precipitation and ENSO indices (r = 0.47, $P<0.01$) (Figure 2.7).
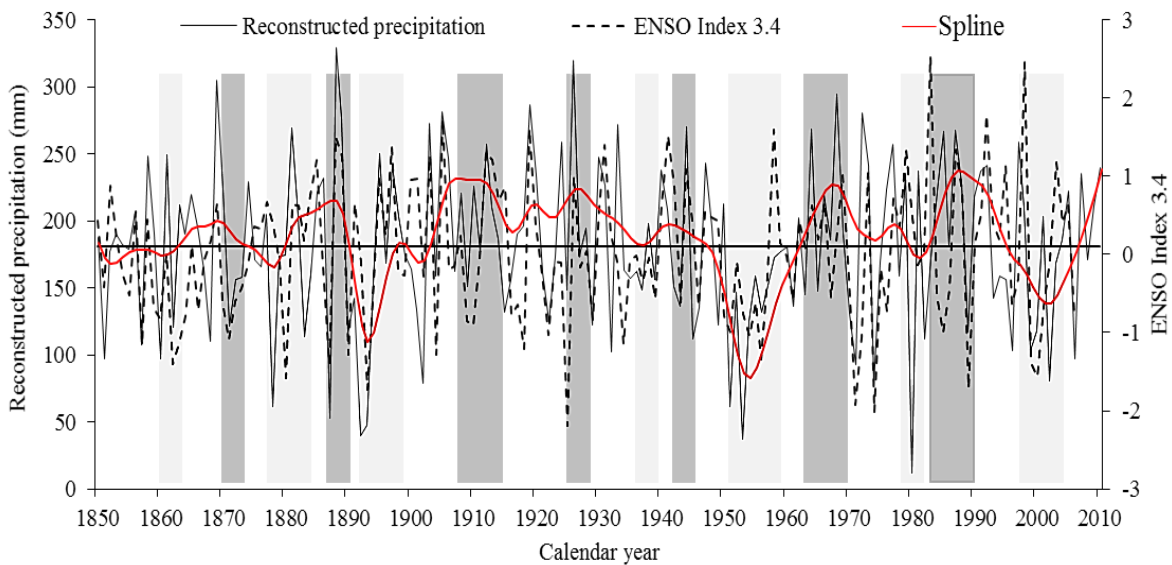
Figure 2.7 Reconstructed January-July precipitation for western Chihuahua. The red line is a flexible curve highlighting low frequency events at decadal scale. Dry episodes are in light gray and wet in dark gray.

2.5.6 Verification of the reconstruction

Historical colonial documents confirm some of the droughts detected in this reconstruction produced food scarcity in Chihuahua and other parts of northern Mexico, as was the 1850´s drought (García-Hernández, 1997 , Enfield & and Fernández-Tejeda, 2006.) A drought episode from 1906 to 1912 produced a low supply of basic grains and starvation in most of Mexico (Florescano, 1980), however in our reconstruction that period indicated above average rainfall. The 1950´s

drought that extended over the Southwestern United States (Stahle *et al.*, 2009) represents one of the driest periods affecting northern Mexico in the 20th century (Cleaveland *et al.*, 2003). This drought had severe impact on the social and economic stability of the region favoring migration from rural to urban areas (Cohen *et al.*, 2013). Subsequent dry periods took place from 1970 to1977, and 1997 to 2011, where only the years 1978 to1982 and 1992-1993 showed wet conditions (Florescano, 1980). The recent drought (1997-2012) has had severe impact in food production and affecting livestock and water availability.

2.5.7 Reconstruction and BAI

The lack of studies relating droughts with tree rings indices and BAI in forests of Mexico limits the interpretation of our tree chronology. However, the followings events with a geographical impact can be related. The drought from 1970 to 1986 reduced BAI in different regions of the USA, high temperatures preceded by severe winters affected the growth of *Quercus* spp.*, Cayra* spp.*, Acer* spp.*, Betula* spp.*,* causing an estimated mortality of 12% (Millers *et al.*, 1989). A similar situation took place for other species in North Carolina (Olano & Palmer, 2003) and Minnesota (Faber-Langendoen & Tester, 1993). Our chronology (Fig 2) includes mostly average tree growth values and a low peak in 1982. The period of 1985-1992 was characterized by a multi-year drought in California, USA and Baja California, Mexico, affecting the vigor of some species as *Pinus jeffreyi* and *Abies concolor,* causing 15% of mortality due to the presence of mistletoe (*Arceuthobium*), and bark beetles (*Dendroctonus ponderosae*) affecting around 56,000 ha in the montane mixed conifer with mortality estimated at 40% and reduction of 13% on basal area, (Macomber & Woodcock, 1994, Savage, 1997). The chronology found here is not consistent with this period (1985-1992), as this period had favorable condition in our study sites (Figure 2.2).

Drought and warmth across western North America in the last decade have led to extensive insect outbreaks and mortality in many forest types throughout the region, affecting ~20 million ha and many tree species since 1997 from Alaska to Mexico (Raffa *et al.*, 2008, Allen *et al.*, 2009). In northern Mexico, pest and disease problems have caused that many mature and old growth Douglas-fir stands be affected and killed (Villanueva Díaz *et al.*, 2008).   In addition, for the last decade drought and forest fires, producing a decrease in vigor, which favors the attack of pests, beetles and defoliators, have afflicted forest ecosystems in Mexico. The area affected in Chihuahua State has increased from 14,506 ha in 2002 to 25,662 ha in 2012 and 75,000 ha in 2013, the most

affected species have been *Pinus leiophylla, Pinus arizonica, Pinus durangensis, Pinus engelmannii and Pseudotsuga menziesii* (Narváez, 2013). The negative effects of the last years from 1997 to 2005 are consistent with our chronology, showing a low peak in 2002 with a reduction 20% (Figure 2.2).

2.5.8 Spectral analysis

The spectral analysis of wavelet coherence to ENSO is shown in figure 2.8.
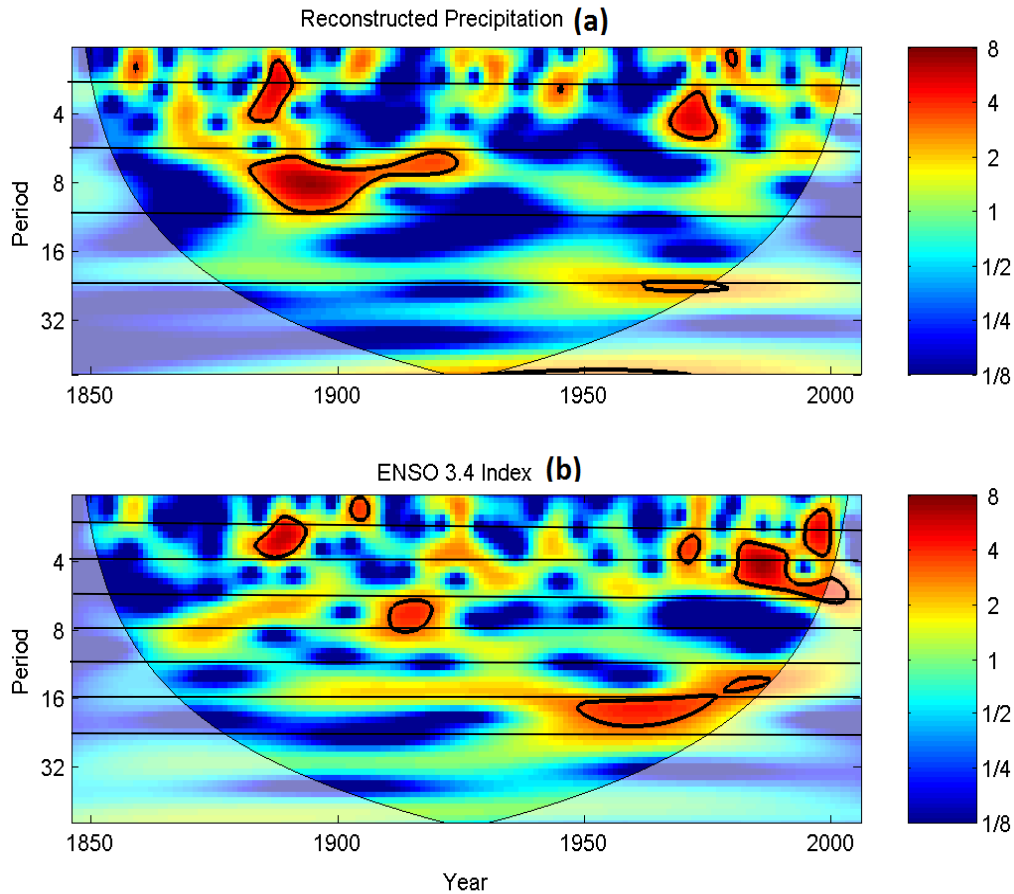
Figure 2.8 Significant frequencies in the reconstructed precipitation series (a) and the ENSO 3.4 index (b). The red spots limited by a black line are significant (p <0.05).

The wavelet spectrum for the reconstructed precipitation (Figure 2.8a) showed significant ($P<0.05$) areas from 1 to 7, 8 to 11, and 22 to 24 years, whereas the ENSO wavelet spectrum (Figure 2.8b) showed irregular frequencies from 2 to 15 and 20 to 24 years. The association

between these two variables were identified by wavelet coherence analysis. Significant areas of coherence between reconstructed precipitation and the ENSO 3.4 index were found for the period 1850 to 2006 at frequencies of 2, 4, 6, 8, 11, 22 and 24 years (Figure 2.9).
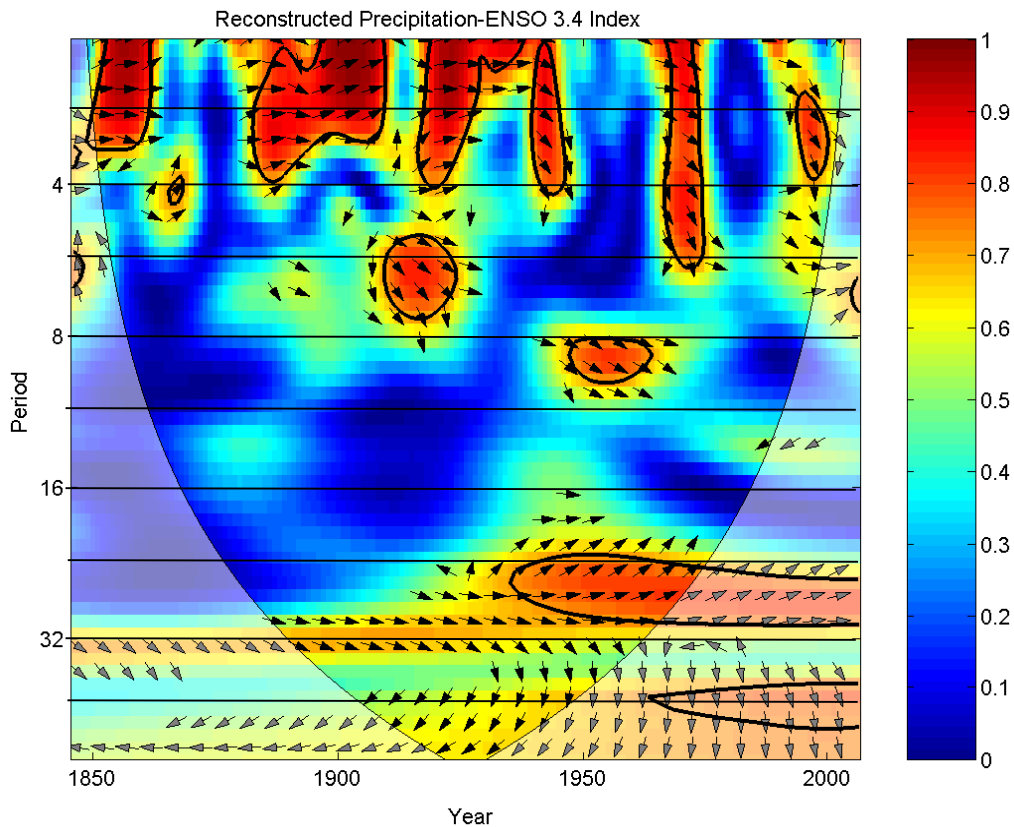
Figure 2.9 Wavelet coherence domain between the reconstructed precipitation and the
ENSO 3.4 index.

The red spots bounded by a black line indicate a significant ($P<0.05$) relationship between the two variables (Figure 2.9). The horizontal arrows pointing to the right indicate that both phenomena are in phase (positive relationship); on the contrary, the arrows pointing to the left suggest antiphase or a negative relationship. The vertical arrows indicate that the phenomena is out of phase. Dry and wet episodes that occurred in western Chihuahua from 1925 to 1950 and from 1950 to 2000 were significantly influenced by the occurrence of ENSO, in episodes of 4, 7 and 11 years, respectively. The most intense La Niña events in the analyzed period that decreased precipitation in western of Chihuahua were those of the year's 1848 to1857, 1886 to1895, 1947 to 1956 and 1995 and 2004. Similarly, wet episodes related to the warm ENSO phase were recorded from 1876 to1885, 1906 to 1915, 1963 to 1972, 1983 to 1992 and 1998 to 2002).

2.5.9 Basal area increments (BAI) and influence of El Niño Southern Oscillation

The ring width chronology, period 1850–2010, shows an ENSO signal with a positive correlation with precipitation, Ring Width Index and BAI (r = 0.30 *P*<0.001) (Figure 2.10). Douglas-fir productivity based on BAI changed along time showing five major productive peaks in years 1865, 1910, 1926, 1966 and 1987, declining substantially thereafter but remaining relatively stable since 1960. In contrast, we observed four low productivity peaks, 1878, 1893, 1953, and 2000.

The reduction of BAI on dry episodes ranged from 3 to 40%, whereas in wet episodes there was a gain of about 20% (Figure 2.11). There are significant differences in absolute BAI between dry and wet episodes, but there was also an unequivocal pattern of recent growth decline, particularly after the 1950's (Figure 2.10). Growth decline has prevailed in recent decades; a situation that may not be different for other forest ecosystems of northern México.
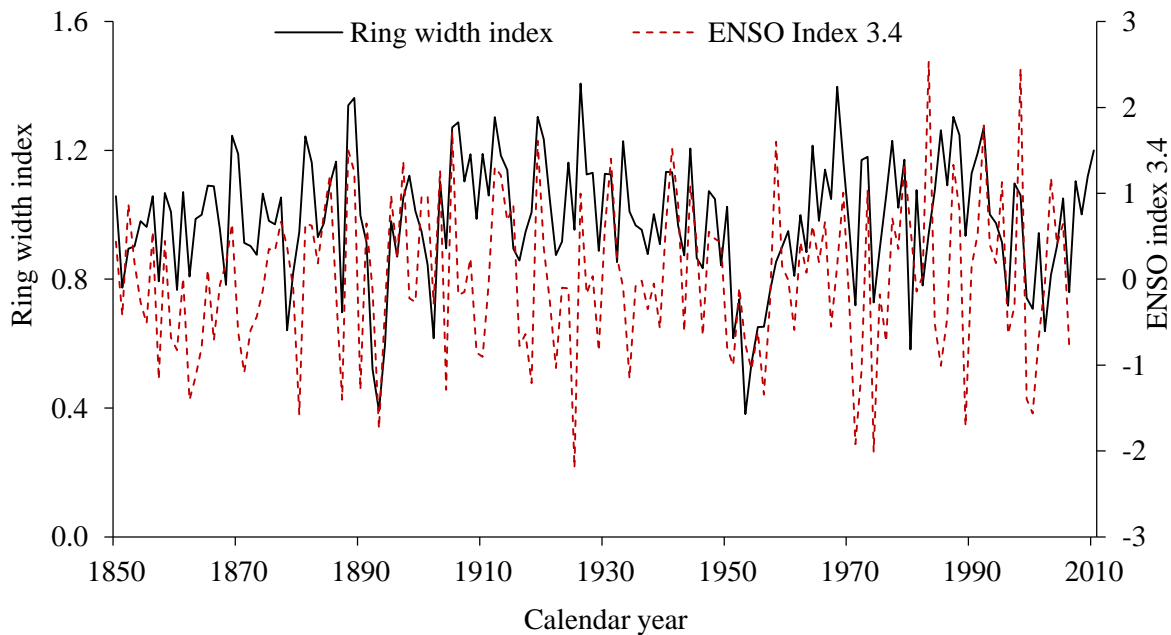
Figure 2.10 Relationship between RWI and ENSO index 3.4 for the period 1850 to 2010.
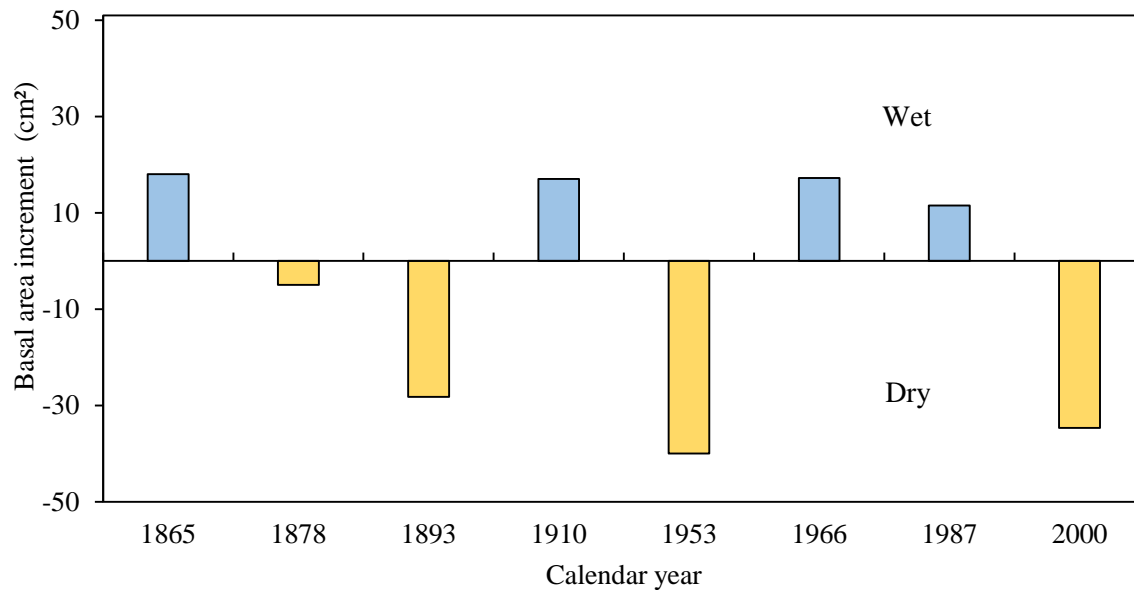
Figure 2.11 Principal BAI fluctuations on dry and wet episodes 1850-2000. The bars in blue
are wet episodes and yellow are dry episodes.

Performing a t-test analysis of BAI between wet and dry years indicated significant differences
($P<0.05$) with reductions in BAI up to 48 cm^2 y^{-1} for dry years and increases of 59 cm^2 y^{-1} in wet
years, with respect to the average BAI. Similar results have been reported for other species, for
example, in central Mexico *Pinus hartwegii* trees showed three distinctive productivity peaks, in
1875, 1910, and 1920 declining substantially thereafter, but remaining relatively stable since 1970
(Gómez-Guerrero *et al.*, 2013).

Abrupt growth fluctuations in BAI have been found for ==Abies religiosa== in central Mexico for
the periods 1845 to 1854, 1940 to 1960 and 2000 to 2010. Tree growth decline has prevailed in
most forest biomes (Silva & Anand, 2013) suggesting that CO_2 stimulation of forests will not
counteract anthropogenic emissions (Silva *et al.*, 2010, Nock *et al.*, 2011, Peñuelas *et al.*, 2011).
However, exceptions to this general trend are expected in cold regions, where temperature limits
productivity.

Some dendrochronological studies indicate recent acceleration of tree growth being attributed
to synergistic effects of elevated CO_2 and rising temperatures (Salzer *et al.*, 2009, Leithead *et al.*,
2010, Silva & Anand, 2013). Contrasting results in this matter suggest the need for new analytical

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approaches to better understand past responses and predict future consequences of forest–atmosphere interactions. (Innes, 1991), (Briffa *et al.*, 1998), and (Voelker *et al.*, 2006) found that older trees are growing faster than predicted by the sigmoidal model over the last century due to anthropogenic global changes. This result in some cases has been attributed to increased CO_2 levels, warming temperatures, higher precipitation, and increased N deposition (Aber *et al.*, 1989). Globally, not only increases in atmospheric CO_2 are affecting forests ecosystems, nitrogen levels have increased in the world over the last 50 to 100 years and combined effects will stress forest all over the world (Körner, 2000, Solomon *et al.*, 2007) Fenn *et al.,* 2006).

2.7 CONCLUSIONS

The chronologies of tree ring and basal area increment of Douglas-fir were statistical correlated and were complementary to explain climate and tree growth relationships. Tree growth is explained by the accumulated January-July precipitation. The significant correlation between tree ring width and precipitation allowed the reconstruction of the precipitation for the last 150 years in the study area. The identification of dry episodes from 1870 to 1880, 1888 to 1897, 1949 to 1958, 1997 to 2006, and wet episodes from 1882 to 1887, 1910 to 1920, 1962 to 1971, and 1983-1992, was consistent with related studies confirming the reliability of Douglas-fir for studying climate variability. The wavelet spectrum for the reconstructed precipitation shows significant areas corresponding to 4, 7, 11, 24 and 31 years. The ENSO wavelet produced irregular cyclicity at 5, 7, and 27 years for the periods 1891 to1897, 1908 to 1912, 1920 to 1924, 1948 to 1975, 1971 to 1976, 1986 to 1990 and 1988 to 2000. The decrease in BAI on dry episodes in the period 1850-2010 was 3.06% in 1876 to 1880, 28.23% in 1891 to 1895, 40.02% for 1951 to 1955 and 34.65% on 1998 to 2002. In other hand, in wet episodes the gain on BAI was 22.30% in 1863 to 1867, 17% on 1908 to 1912, and 17.22 and 11.49% for 1964 to 1968 and 1984 to 1989, respectively.

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CAPÍTULO III
GROWTH AND WATER USE EFFICIENCY OF *Pseudotsuga menziesii* (Mirb.) Franco DURING THE DRIEST AND WETTEST PERIODS OF THE LAST CENTURY

3.1 RESUMEN

Las relaciones entre cambios en la composición de isótopos de la madera y el crecimiento de los árboles aportan información valiosa sobre cómo los ecosistemas forestales han respondido al cambio climático. En este estudio se empleó un enfoque isotópico dual, estimando $\delta^{13}C$ y $\delta^{18}O$ en anillos de crecimiento de árboles de *Pseudotsuga menziesii* (Mirb.) Franco (Abeto Douglas), para entender cómo esta especie ha enfrentado los eventos climáticos extremos en el último siglo. Se analizaron datos de tres sitios forestales, que geográficamente abarcan ~5° de latitud, en el noroeste de México para determinar el efecto que los períodos anormalmente secos y húmedos han tenido sobre el crecimiento de *P. menziesii* y sobre la eficiencia de uso de agua intrínseca (EUAi). Los resultados muestran que el ancho de los anillos de crecimiento y los incrementos en área basal (IAB) se correlacionan significativamente ($P<0.05$) con la precipitación. A pesar del aumento (22.5%) en EUAi, se observó una disminución (34%) en IAB. En los últimos 50 años, la intensidad de los efectos climáticos ha sido más severa, forzando la salud de los bosques a niveles críticos. El uso dual del análisis de isotópos proporciona conocimiento importante para la validación de los modelos existentes sobre cambio climático, confirmando que el incremento en la EUAi en el último siglo no refleja aumento en la tasa fotosintética (*A*), sino que constituye la evidencia de estrés hídrico y reducción en la conductancia estomática (g_s), lo cual resulta en disminución de crecimiento del Abeto Douglas.

Palabras clave: isótopos, anillos de crecimiento, cambio climático, dendrocronología.

3.2 SUMMARY

Relationships between changes in wood isotopic composition and tree growth bring valuable information about how forests ecosystems have responded to climate change. Here we use a dual isotope approach, measuring $\delta^{13}C$ and $\delta^{18}O$ in tree ring of *Pseudotsuga menziesii* (Mirb.) Franco (Douglas fir), to understand how this dominant species coped with extreme climate events over the past century. We analyze data from three forest sites, spanning ~5º of latitude, in northwestern Mexico to determine the effect of atypically dry and wet periods on radial growth of *P. menziesii* and intrinsic water use efficiency (iWUE). Our results showed that tree ring width (TRW) and basal area increments (BAI) are well correlated ($P<0.05$) to precipitation. There is a decline (34%) in BAI despite higher (22.5%) iWUE in last century. During the last 50 years, the intensity of the climatic effects on tree physiology were more severe overtime, pushing the health of forests to a critic level. Using dual isotopic analyses and BAI provide important insights for the validation of existing models on climate change, confirming that the increases in iWUE over the last century do not reflect increased photosynthetic assimilation rate *(A),* but the evidence of water stress and reduced stomatal conductance *(gs),* which resulted in decreased radial growth of Douglas fir.

Keywords: isotopes, growth rings, climate change, dendrochronology.

3.3 INTRODUCTION

Understanding how forest ecosystems have responded to recent environmental changes is critical to find conservation and management strategies for the near future. Recent changes in atmospheric composition and climate are expected to impact forest growth worldwide; however, species-or site-specific responses may occur indicating the need for further research (Barnard *et al.*, 2012). Most scientists now agree that global warming will continue to occur as predicted, due anthropogenic CO_2 emissions (Allen *et al.*, 2013, Cook *et al.*, 2013). Despite great uncertainties with respect to future changes in precipitation patterns, it has become clear that extreme weather events, marked by atypically dry or wet periods, will be increasingly more common. Two main questions remain to be addressed when predicting responses to such extreme events; one is how resistant are dominant species to environmental stresses posed by extreme fluctuations in climate

patterns, and another is how resilient, or capable of returning to original physiological and productive states, are these species once extreme events cease.

A common physiological response of trees to higher atmospheric CO_2 concentrations is an increase in water use efficiency, or the ratio of CO_2 fixed to unit of water loss during transpiration(Gómez-Guerrero *et al.*, 2013, Peñuelas *et al.*, 2011). This response has various implications from leaf to canopy level gas exchange processes with the atmosphere, as well as for changes in primary productivity, which could potentially counteract CO_2 emissions. Although there are numerous reports on the response of plants to CO_2 enriched environments carried out under controlled chambers and field free-air CO_2 enriched experiments, it is not fully understood how general are the expected responses to CO_2 and plant-atmosphere water exchange under climate change (Ainsworth & Long, 2005, Battipaglia *et al.*, 2013, Keenan *et al.*, 2013)

For a better understanding of the effects of increased atmospheric CO_2 on plant physiology, Scheidegger *et al.* (2000) developed a conceptual model based on the dual relationship of $\delta^{13}C$ and $\delta^{18}O$. This model relies on the fact that $\delta^{13}C$ and $\delta^{18}O$, in both leaves and annual tree-rings, are independently related to stomatal processes. While $\delta^{13}C$ provides information on the carbon assimilation, $\delta^{18}O$ is a surrogate for vapour pressure differences and water exchange controlled by relative humidity; thus, combined information from both isotopic proxies would bring valuable insights on the effects of rising CO_2 and climate change on carbon assimilation (*A*) and stomatal conductance (g_s), allowing the determination of how A or g_s or both change over time.

Barnard *et al.* (2012) used the conceptual model of Scheidegger *et al.* (2000) relating crown classes of a *P. menziesii* stand, and found that $\delta^{13}C$ and $\delta^{18}O$ of cellulose were correlated with year-to-year variation on relative humidity; and the dual isotopic analysis was useful to explain the theory of the conceptual model. Roden and Farquhar (2012) used dual isotopic analyses ($\delta^{13}C$ and $\delta^{18}O$) and the conceptual model of Scheidegger *et al.* (2000) to explain physiological changes in seedlings of *Pinus radiata* D. Don and *Eucalyptus globulus* Labill. The authors concluded that the dual conceptual model has potential for the interpretation of plant physiology changes; however, more research under different scenarios is needed. Offermann *et al.* (2011) found that $\delta^{18}O$ in the phloem and tree-ring whole wood of *Faguss sylvatica* L. was not positively related to leaf water evaporative enrichment and $\delta^{18}O$ of canopy organic matter pools, which indicates a weakness in the dual isotopic analyses; nonetheless, the results seemed to be related to forest species, for example *P. menziesii* has showed high consistency with the dual analysis and physiological

responses (Warren *et al.*, 2003) and the theory of the conceptual model (Barnard *et al.*, 2012). Although the model of Scheidegger *et al.* (2000) has been tested under different scenarios, it has not been analysed with systematic extreme changes of wet and dry periods.

The enrichment in ^{18}O in the leaf water above the source of water ($\Delta^{18}O_e$) is determined by:

$$\Delta^{18}O_e = \varepsilon^* + \varepsilon k + (\Delta v - \varepsilon k)\, h \qquad \text{(eq. 1)}$$

Where ε^* is the proportional depression of vapor pressure by the heavier $H_2^{18}O$, εk the diffusion fractionation trough stomata and leaf boundary layer, Δv the difference between atmospheric water vapor and the source of water, and h stands for the relative humidity of the air at leaf temperature (Yakir *et al.*, 1993). According to equation (1) plants growing in similar hydrological environments, experiencing higher temperatures will show higher $\Delta^{18}O_e$ (Ferrio & Voltas, 2005b). Therefore, we expect that contrasting periods of dryness may be reflected in physiological variables derived from isotopic analysis leading to a better understanding of the processes in forest species.

Here we analyzed $\delta^{13}C$ and $\delta^{18}O$ in *P. menziesii* tree-rings to determine physiological responses to extreme climate events occurred over the past century. The analysis of tree ring series help to evaluate resistance and resilience of this dominant species across a 5° latitudinal range, determining whether rising atmospheric CO_2 has stimulated growth and ability of trees to cope with unusually dry and wet events. Because isotope signatures are affected by moisture regimes and atmospheric CO_2, our hypotheses were: (i) The relationship among physiological variables vary over time and according to extreme dry and wet events; (ii) Physiological variables and wood isotopic signatures of Douglas fir have changed over last century according to changes in atmospheric CO_2. (iii) Independent dual isotopic analyses for wet and dry periods provide information on the response of trees to climate change, as predicted by conceptual models (Scheidegger *et al.*, 2000).

3.4 MATERIALS AND METHODS

3.4.1 Study area

The study stands of Douglas fir are located in northwestern Mexico in the states of Chihuahua and Durango, along the Sierra Madre Occidental (Figure 3.1). The altitude ranged from

2268 to 2749 where temperate and sub-humid climate mean annual temperature and precipitation oscillates from 5 to 12°C and from 375 to 786 mm, respectively. According to the Reference Base for Soil Resource (WRBSR), soils in the study area are Leptosols, Pheozems and Cambisols, which correspond to Entisols, Mollisols and Inceptisols in the Soil Taxonomy Classification (WRBSR, 2006). Douglas-fir rarely forms pure stands and is mixed with conifer species such as *Picea chihuahuana*, *Abies durangensis, Pinus arizonica, Pinus durangensis, and Pinus ayacahuite,* and associated species are *Arbutus xalapensis, Juniperus deppeana, Arctostaphylos pungens, Ceanothus fendleri, Populus tremuloides, Quercus rugosa,* and *Quercus sideroxyla* (Brown, 1994, Cleaveland, 1986, Stahle *et al.*, 1998)
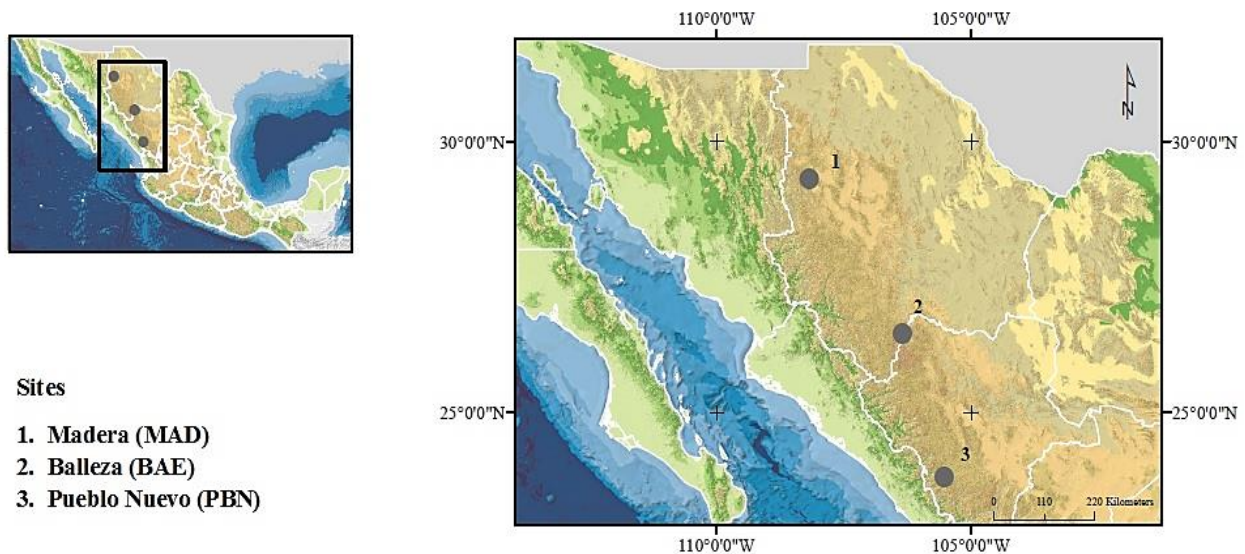
Figure 3.1 Study sites long Chihuahua and Durango Mexico.

3.4.2 Wood core sampling

In June 2011, a total of 50 dominant and healthy trees were selected for wood core sampling. Dominant trees are more suitable for isotopic analysis as they reflect lower variation to determine the potential growth of the forest (Barnard *et al.*, 2012). We obtained two increment cores per tree, taking samples at breast height with a 12-mm Pressler borer (Haglöf, BS009). Tree rings of Douglas fir are well defined with a sharp latewood boundary and their size variability is highly related to limiting environmental conditions such as precipitation, for these reasons it has

been widely used for dendroclimatic studies from Canada to Central México (Griesbauer & Scott Green, 2010, Villanueva-Diaz *et al.*, 2007). Increment cores were air-dried for eight days to reduce moisture, then were mechanically polished with a sequence of sandpaper (grains 120,240, 400, 600, 800 and 1,200) to increase the contrast between early and late wood.

3.4.3 Wood core measurement

Tree ring samples were dated with dendrochronological standard techniques, and measured with a Velmex measuring system to a precision of a 0.01 mm (Fritts, 1976, Stokes & Smiley, 1968). To avoid false or missing rings, all series of tree ring measurements were statistically tested with a master correlation assuring a high and statistically significant correlation (0.64, P<0.05) with COFECHA software (Holmes & Fritts, 1986). A negative exponential model was used to standardize the age series for each tree and to develop our tree-ring width chronology using the ARSTAN software (Cook, 1985). A *"spline"* with a five-year resolution was fitted to the Ring Width Index values (RWI) to determine low frequency events (Cook & Peters, 1981). Basal area increments (BAI) were derived from tree ring with measurements assuming concentric and regular tree rings, using equation (1). There was a significant correlation between BAI and RWI (0.79, P<0.01). BAI is a tree growth parameter that remains constant from young to middle ages providing a forest productivity indicator (Weiner & Thomas, 2001).

$$BAI = \pi \, (R_n{}^2 - R_{n-1}{}^2) \hspace{4cm} \text{(eq. 2)}$$

Where R is the tree radius and n is the year of tree ring formation.

3.4.4 Climatic data

Climatic records of monthly average for precipitation and temperature with the longest period of available information were obtained from the database of the Mexican Institute for Water Technology (IMTA, 2000). Nine meteorological stations were selected based on the distance to the study sites and their correlation to the RWI. To correlate the RWI to precipitation the time period selected was 1968 to 1988 time period where all weather stations matched with comprehensive information. To find the best window of time correlated to precipitation and temperature we used the DENDROCLIM algorithm, proposed by Biondi and Waikul (2004). Additionally we tested the correlation between RWI and ENSO (El Niño Southern Oscillation) indices.

3.4.5 Isotopic analyses

For isotopic analysis we selected nine trees with the highest correlation with the master chronology. This was twice as much the size of an appropriate sample as long as the juvenile effect (rings close to the pith) is avoided (Leavitt, 2010). Dual isotopic analysis ($\delta^{13}C$ and $\delta^{18}O$) were performed in the total ring width and were focused in three significant dry and wet low frequency events as detected in the tree ring series. The six studied periods were: 1891-1895, 1951-1955, 1998-2002 identified as dry periods, and 1908-1912, 1964-1968 and 1985-1989 considered as wet periods. The moisture conditions of the selected periods were statistically supported by a significant correlation of RWI, precipitation, and ENSO indices. Each low frequency event (wet/dry) was identified in the ring width series such that wood was collected from a five annual bands formed in the period (Figure 3.2). Combining rings for isotopic analysis is a common practice that allows adequate sample homogenization, yields enough material for analysis and reduces processing cost and time (Mc Carroll & Loader, 2004, Silva *et al.*, 2009).
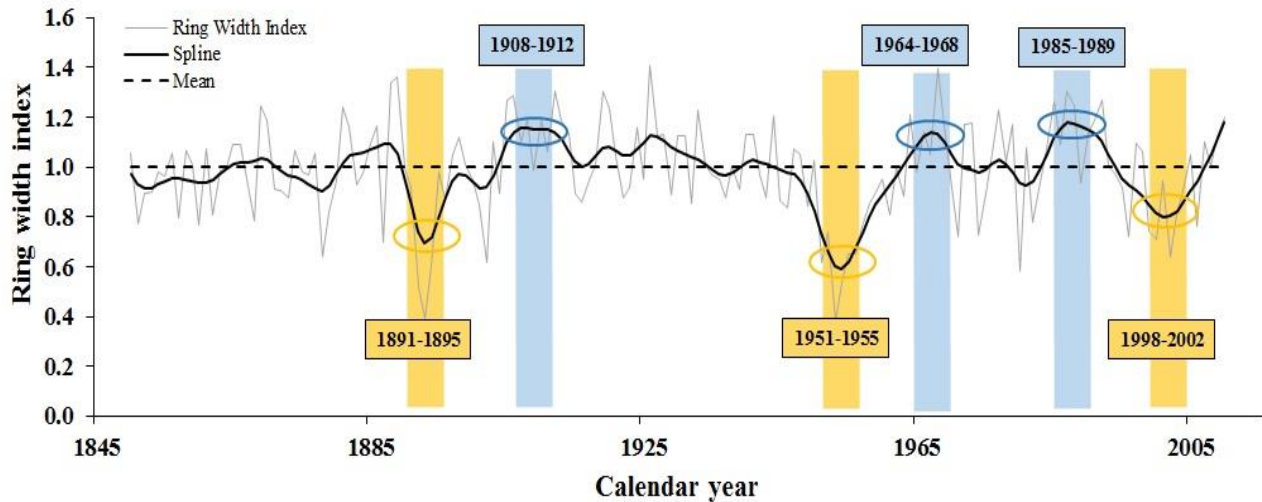
Figure 3.2 Identification of wet and dry periods across the time, blue bands represent wet periods and yellow bands the dry.

Aliquots of grinded wood samples were weighed on a microbalance (Sartorius, 0.01 mg) and placed into tin and silver capsules (Elemental Microanalysis Limited) for $\delta^{13}C$ and $\delta^{18}O$ analyses, respectively. Analyses for $\delta^{13}C$ were done on a PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20-20 isotope ratio mass spectrometer (Sercon, Cheshire, UK). The

$\delta^{18}O$ analysis was performed on a Hekatech HT Oxygen Analyzer (Wegberg, Germany) interfaced to a PDZ Europa 20-20 isotope ratio mass spectrometer. Isotopic values of $\delta^{13}C$ and oxygen $\delta^{18}O$ were expressed relative to VPDB (Vienna Pee Dee belemnite) and VSMOW (Vienna standard mean ocean water), respectively.

3.4.6 ^{13}C discrimination and intrinsic water use efficiency

We relied on the natural existence of both ^{12}C and ^{13}C stable isotopes in the atmosphere to investigate changes in intrinsic water use efficiency (iWUE). CO_2 molecules contain these isotopes in the proportion of 98.89% for ^{12}C and 1.11% for ^{13}C. However, in plant tissues carbon isotope ratios are variable and ^{13}C abundance relative to ^{12}C is expressed as $\delta^{13}C$ values (Farquhar *et al.*, 1982):

$$\delta^{13}C\ (‰) = (R_{sample}/R_{VPDB} -1) \times 1000 \qquad (eq.\ 3)$$

where R_{sample} and R_{VPDB} are the abundance ratios between ^{13}C and ^{12}C of a given sample and Vienna PeeDee Belemnite international standard, VPDB, respectively. Accounting for atmospheric variability, the ^{13}C abundance in plant's biomass can be expressed in relative terms of source to product carbon discrimination as (Farquhar *et al.*, 1982):

$$\Delta^{13}C = (\delta^{13}C_{air} - \delta^{13}C_{plant})/(1 + \delta^{13}C_{air}/1000) \qquad (eq.\ 4)$$

Where Δ is discrimination against ^{13}C, $\delta^{13}C_{air}$ is the carbon isotope ratio of the air (the source) and $\delta^{13}C$plant is the carbon isotope ratio of the product (plant biomass).

In order to be translated into physiologically relevant information, the discrimination (Δ) of ^{13}C isotopes is expressed as:

$$\Delta^{13}C = a + (b-a)(C_i/C_a) \qquad (eq.\ 5)$$

where a is the discrimination against $^{13}CO_2$ during diffusion through the stomata (4.4‰), b is the net discrimination due to carboxylation (27‰) and, C_i and C_a are the intercellular and ambient CO_2 concentrations, respectively. Following Fick's first law ($A = gCO_2\ (C_i/C_a)$) this equation can be converted into:

$$\Delta^{13}C = a + (b-a)\ [(1-(1.6\ A/C_a\ gH_2O)] \qquad (eq.\ 6)$$

where A is the net photosynthesis, measured as total CO_2 uptake; gCO_2 is the leaf conductance to CO_2 and given that gH_2O, or the leaf conductance to water vapor is known to be 1.6 gCO_2, $\Delta^{13}C$

values can then be related to the ratio A/gH_2O, which represents the intrinsic water use efficiency (iWUE) of the plant during the process of carbon uptake.

3.4.7 Dual isotopic analyses

Using the relationship between $\delta^{13}C$ and $\delta^{18}O$ by wet and dry periods we relate changes of physiological variables over time interpreting the trends according to the conceptual model of Scheidegger *et al.* (2000). The interpretation of results was based on the shifts of $\delta^{13}C$ and $\delta^{18}O$ of the extreme events overtime as they occurred (Figure. 2).

2.4.6 Statistical analyses

We used correlation analysis for the isotopic signatures and physiological variables ($\delta^{13}C$, $\delta^{18}O$, $\Delta^{13}C$, iWUE, Ci, Ci/Ca, Ca-Ci) considering both and separate moisture regimes (dry and wet). To test the significance of trends for the wet and dry periods overtime, we used random coefficient models which are appropriate for unequally spaced repeated measurements method (Fitzmaurice *et al.*, 2004, Littell *et al.*, 1998). Using SAS PROC MIXED, (SAS, 2004) the intercept and first degree coefficient for individual trees were considered as mixed effects and the effects of time, regime (wet/dry) and interaction were tested at 0.05 level of significance. In mixed models common parameters of the population are set as fixed effects and the subject specific effect unique for individuals which are the random effects (Fitzmaurice *et al.*, 2004).

3.5 RESULTS

3.5.1 Ring Width Index (RWI), basal area increment (BAI) and precipitation

Our results showed that BAI, RWI and precipitation were highly correlated. The Douglas fir chronology of this study was significantly correlated to the seasonal January-July precipitation (r=0.53; P<0.05). The correlation between the RWI and BAI was 0.84 and statistically significant (0.45, P<0.005) (Figure. 3.3).
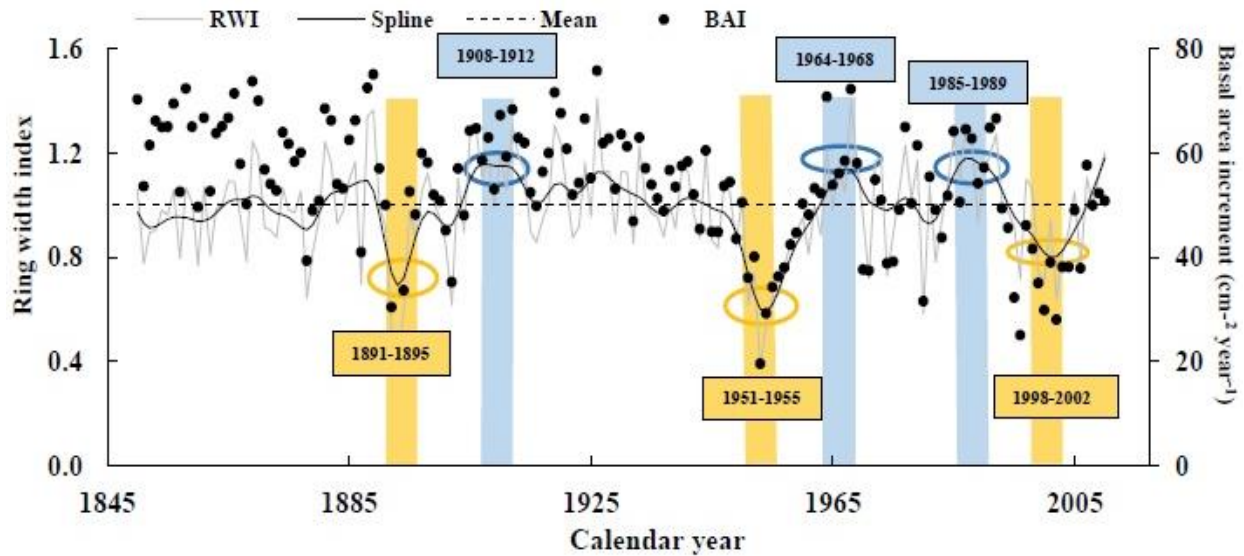
Figure 3.3 Basal area increment for *P. menziesii* in northwest México. Each point is the average value of 4 to 20 trees. Wet and dry period are in blue and yellow bands, respectively.

3.5.2 Correlation of physiological variables

Tables 3.1 to 3.3 show the correlation among physiological variables considering both, wet and dry periods, respectively. The gradient of CO_2 concentration, C_a-C_i, was the variable more frequently correlated to the rest of variables. For dry periods the significant correlations for $\delta^{18}O$ were four of seven as compared to both (dry and wet), and wet periods where the significant correlations were one and two of seven, respectively.

Table 3.1 Correlations of physiological variables in *Pseudotsuga menziesii* during the period 1893-2010.

	$\delta^{13}C$	$\Delta^{13}C$	C_a	C_i	iWUE	C_a-C_i	C_i/C_a	$\delta^{18}O$
$\delta^{13}C$	1	**-0.712**	**-0.524**	**-0.928**	-0.050	-0.051	**-0.712**	0.143
$\Delta^{13}C$		1	-0.224	**0.405**	**-0.665**	**-0.665**	**0.999**	0.115
C_a			1	**0.798**	**0.876**	**0.876**	-0.224	**-0.345**
C_i				1	**0.408**	**0.408**	**0.406**	-0.256
iWUE					1	**0.999**	**-0.665**	-0.323
C_a-C_i						1	-0.664	-0.318
C_i/C_a							1	0.113
$\delta^{18}O$								1

Table 3.2 Correlations of physiological variables in *Pseudotsuga menziesii* wet periods

	$\delta^{13}C$	$\Delta^{13}C$	C_a	C_i	iWUE	C_a-C_i	C_i/C_a	$\delta^{18}O$
$\delta^{13}C$	1	**-0.780**	**-0.509**	**-0.935**	0.052	0.056	**-0.781**	0.378
$\Delta^{13}C$		1	-0.139	**0.513**	**-0.664**	**-0.667**	**0.999**	-0.082
C_a			1	**0.778**	**0.832**	**0.829**	-0.139	**-0.494**
C_i				1	0.298	0.294	**0.513**	**-0.480**
iWUE					1	**0.999**	**-0.664**	-0.326
C_a-C_i						1	**-0.667**	-0.324
C_i/C_a							1	-0.086
$\delta^{18}O$								1

Table 3.3 Correlations of physiological variables in *Pseudotsuga menziesii* in dry periods

	$\delta^{13}C$	$\Delta^{13}C$	C_a	C_i	iWUE	C_a-C_i	C_i/C_a	$\delta^{18}O$
$\delta^{13}C$	1	**-0.650**	**-0.559**	**-0.926**	-0.142	-0.146	**-0.650**	-0.079
$\Delta^{13}C$		1	-0.266	**0.323**	**-0.659**	**-0.656**	**0.999**	**0.346**
C_a			1	**0.825**	**0.899**	**0.901**	-0.265	-0.288
C_i				1	0.494	**0.497**	0.323	-0.080
iWUE					1	**0.999**	**-0.658**	**-0.384**
C_a-C_i						1	**-0.655**	**-0.380**
C_i/C_a							1	**0.346**
$\delta^{18}O$								1

Note. The statistical significant of the physiological variables are in black numbers p<0.001

3.5.3 Relationship among physiological variables over time

Value changes on the physiological variables are shown in Figure 3.4a-h. The significance of the effects of the mixed model is shown in Table 3.4. Carbon composition $\delta^{13}C$, $\Delta^{13}C$, and C_i/C_a decreased overtime with no significant differences between dry and wet periods (Figures, 3.4a, 3.4d and 3.4h). For $\delta^{18}O$, changes overtime showed a negative linear relationship and there were significant differences between wet and dry periods with a higher decrease in the wet periods (Figure 3.4e). The relationship between $\delta^{13}C$ and $\delta^{18}O$ for individual trees was significant and positive (P≤0.05) only for wet periods with a correlation coefficient of 0.38 (Figure 3.4b). iWUE

and C_a-C_i have increased overtime in a quadratic way with significant differences between wet and dry periods. Internal CO_2 concentrations (C_i) have increased overtime according to a second order polynomial equation with no differences between wet and dry periods (Figure 3.4 c and d). The C_i/C_a ratio has decreased linearly over time and no differences between wet and dry periods were seen.

Table 3.4 Significant effects and interactions for the physiological variables that showed to be statistically significant.

Variable	Intercept	Time	Regime	Time X Regime	Time^2
$\delta^{18}O$	<0.0001	<0.0001	0.0408	0.0368	Nt
iWUE	0.0007	<0.0001	0.0438	0.0400	<0.0001
C_a-C_i	0.0005	<0.0001	0.0354	0.0322	<0.0001

Nt= Not tested.
Regime was given for wet and dry periods.
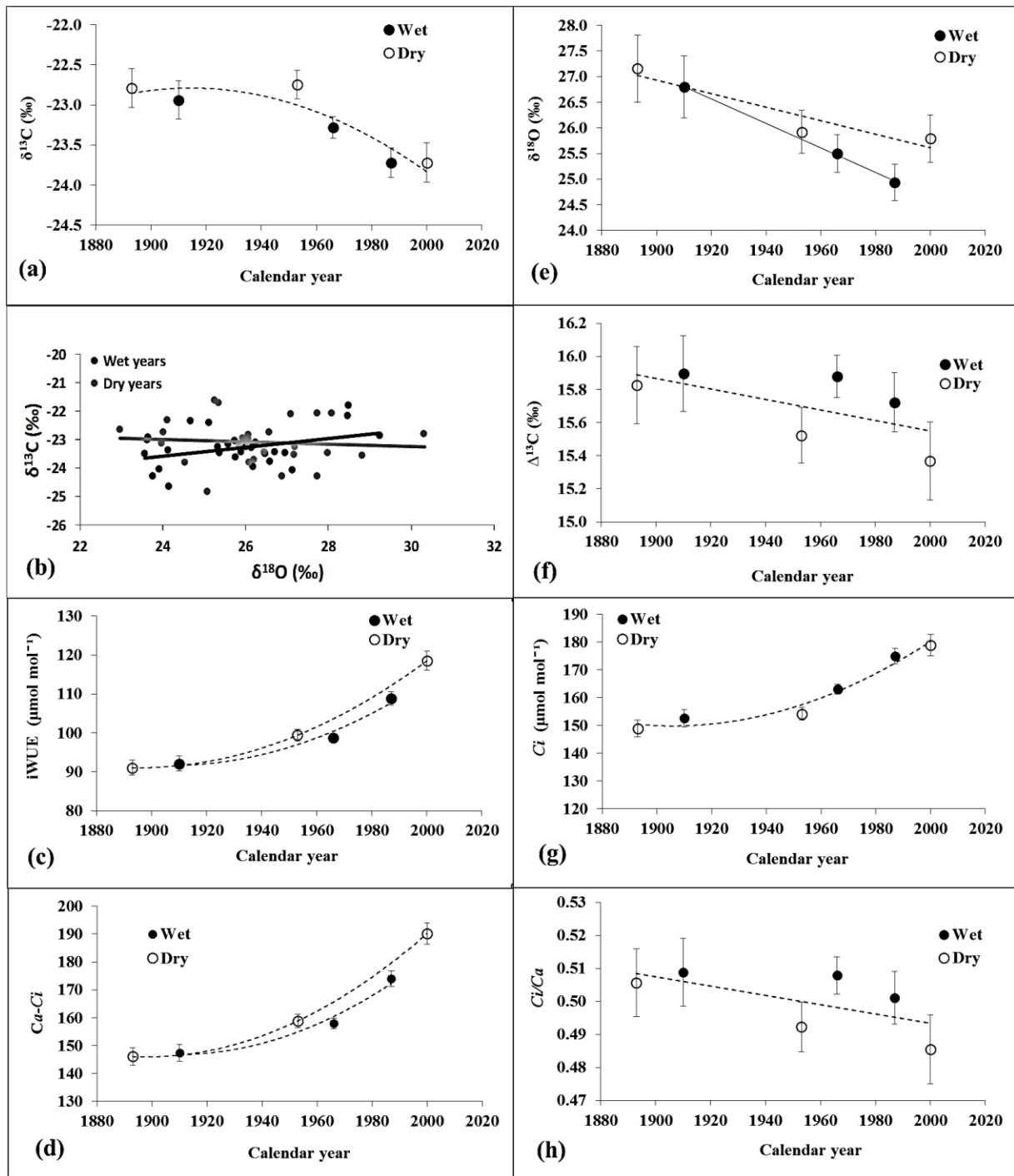
Figure 3.4 Relationship of physiological variables overtime, according to wet and dry periods. Plots with two trend lines represent statistically significant differences between wet and dry periods. Significance of the lineal and quadratic effects are as showed in Table 3.4

3.5.4 Relationships between physiological variables and atmospheric CO_2 increment

Physiological variables ($\delta^{13}C$, $\Delta^{13}C$, iWUE, C_i, and C_i/C_a) were related to changes in atmospheric CO_2. Although physiological variables ($\delta^{13}C$, $\Delta^{13}C$, and C_i/C_a have changed in the last century with the CO_2 increment (Figure 3.5), there were not significant differences between wet and dry periods. $\delta^{13}C$ increased in relation to the increment of CO_2 in the atmosphere in a similar way for the two regimes. Trees have incorporated more ^{13}C into their structural biomass as a consequence of more enriched atmospheric CO_2 in recent times. Although C_i has increased in recent times, the increases in CO_2 have influenced the ratio C_i/C_a resulting in decreased values with increments in atmospheric CO_2. For $\delta^{18}O$, changes showed a negative linear relationship, and iWUE showed a linear increment.
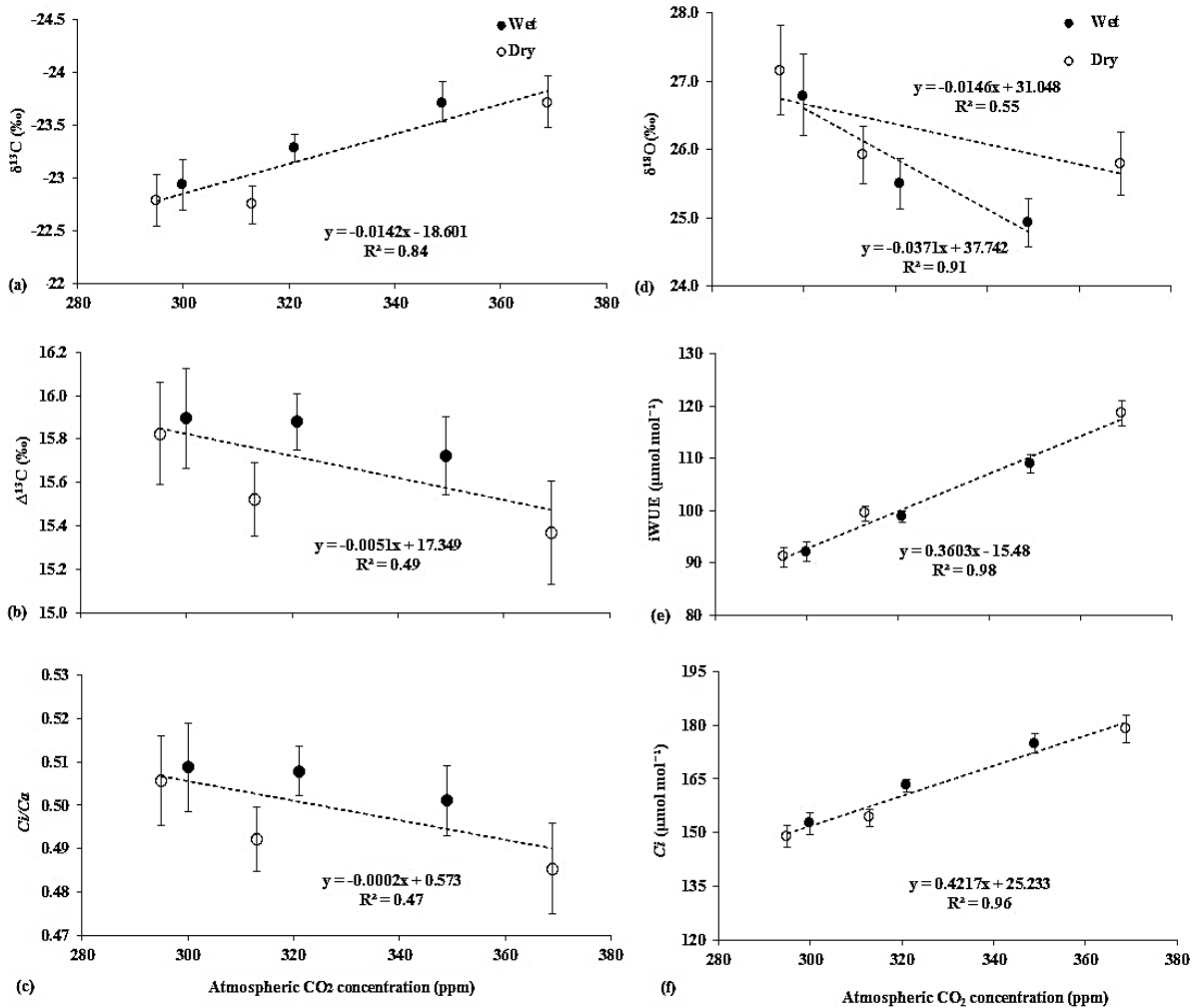
Figure 3.5 Physiological variables overtime in relationship to CO_2 increases, in wet and dry periods.

3.5.5 Dual isotope analysis as related to a conceptual model (Scheidegger *et al*., 2000)

Analyzing the shifts of $\delta^{13}C$ and $\delta^{18}O$ from the oldest to the subsequent studied episode, the changes were from dry to wet (1893-1910), from wet to dry (1910-1953), from dry to wet (1953-1966), and from wet to dry (1987-2000) (Figure 3.6). Assuming that changes were linear between the two dates, the results suggest that the changes in iWUE have been driven mainly for two processes: (i) the proportional adjustment of A and g_s and (ii) by an increase of g_s with similar rates in A. This result was deduced from the parallel distribution of three vectors along the horizontal where deviation in $\delta^{13}C$ were lower than 0.5‰ and one vector (1953-1966) in the third quadrant (clockwise direction). None of the scenarios suggests increment in A.
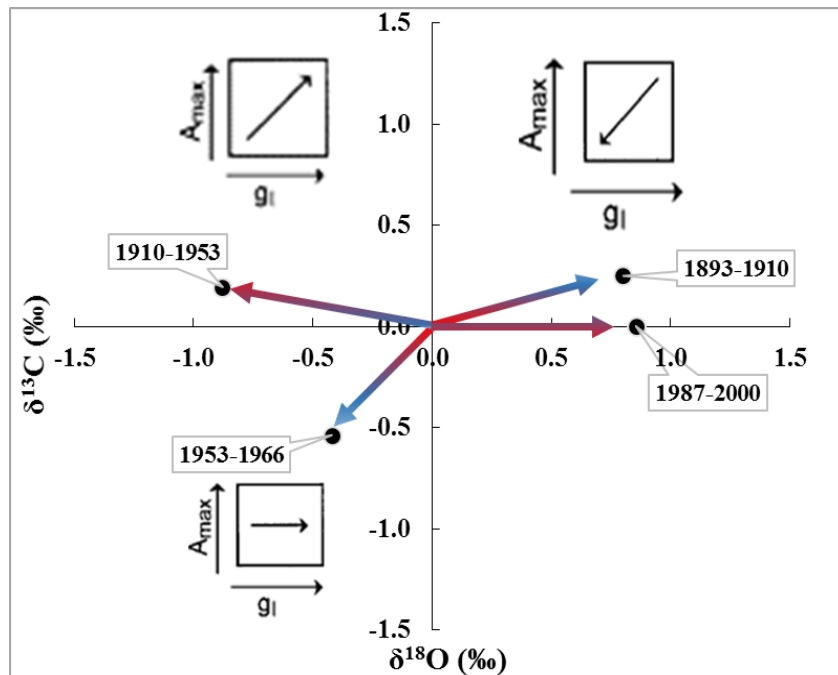
Figure 3.6 Deviations from the mean of $\delta^{13}C$ and $\delta^{18}O$, assuming linear changes over time.

3.6 DISCUSSION

3.6.1 Ring width index (RWI), basal area increments (BAI) and precipitation

The high correlation between RWI and BAI indicates a good agreement of ring width and tree growth. The dominant trees selected in this study provided adequate information to relate forest productivity and precipitation. The high correlation of tree variables to precipitation and isotopic correlation confirmed the suitability of Douglas fir for climate change studies (Barnard *et al.*, 2012, Warren *et al.*, 2003). Isotopic and tree ring measurements of Douglas fir is suitable to derive proxy variables to tree growth, reconstruct past climate and forecast future climate scenarios. The sequence of dry and wet periods was statistically supported by the correlations found.

3.6.2 Correlation of physiological variables

When the information was separated into wet and dry periods, there were improvements on the correlations among physiological variables for dry periods. This finding suggests that the extreme dry events improve the correlations of physiological variables with $\delta^{18}O$. Therefore, the first hypothesis of the study is accepted because the relationship among physiological variables vary over time and according to extreme dry and wet events. Our results are in agreement with other authors who have observed that under drought conditions changes on the water stress variables derived from isotopic analyses ($\delta^{13}C$ and $\delta^{18}O$) are more evident (Linares and Camarero, 2012, Ferrio and Voltas, 2005a, Saurer *et al.*, 1997, Wang *et al.*, 2012).

Probably the higher correlation among variables ($\delta^{13}C$ and C_i , $\Delta^{13}C$ and C_i/C_a, C_a and C_i , iWUE, C_a-C_i, iWUE and C_a-C_i) with dry periods is because during dry events trees will relay on the stored water of the soil surface and the intensity of the physiological variables will increase as the soil water reserves are run out. On the other hand, under wet periods the soil profile reaches its maximum water capacity and the excess of water follow to other compartments as run-off or groundwater without affecting the physiological variables (Sarris *et al.*, 2013). In the last century, iWUE and Ca-Ci are changing at different rates according to the moisture regime. The rate of increase of iWUE in dry periods is higher than in wet periods, indicating that the influence of atmospheric changes on vegetation will be increasing in the next decades, because Ca and iWUE are correlated and its trend is increasing. Some authors have observed that once trees reach an iWUE of 120 mol μmol^{-1}, there are no more increases in this variable (Wang *et al.*, 2012) but our

data suggest higher increases in the next decades according to trends and the increases of CO_2, indicating that this effect is related to species.

3.6.3 Physiological variables over time and in relation to CO₂ increases

A decrease in $\delta^{13}C$ overtime is an expected result found in others studies and is due to the recent dilution in ^{13}C in the atmosphere by the use of hydrocarbons; a signal showed in temperate and tropical forests (Fichtler *et al.*, 2010, McCarroll and Loader, 2004). Changes in wood $\delta^{13}C$ were not different for wet and dry periods, but data reflects a negative quadratic trend resembling the increased rated of CO_2 emissions (Figure 3.4a). The decrease in $\delta^{18}O$ overtime showed higher rates in wet periods. This result is difficult to explain but it may indicate that the source of water in the studied ecosystem has changed overtime, resulting in different wood signatures.

One possible explanation for changes in $\delta^{18}O$ overtime may be the differences in the signature of water source due to changes in the rain pattern, but this possibility is unlikely as the $\delta^{18}O$ of precipitation reported by the Global Network of Isotopes in Precipitation, from the Chihuahua station near the study sites do not show any decade trend. Although circulatory models suggest changes in the rain pattern due to climate change, the study of $\delta^{18}O$ signature by a combination of evaporations process and orographic effects in forests requires the support of further research. On the other hand, it is known that in most of the temperate ecosystems, trees use water from the soil surface for their physiological process (Dawson TE *et al.*, 2002); thus, results indicates that overtime trees have been exploring deeper soil water with different $\delta^{18}O$ signature (Sarris *et al.*, 2013).

At the tree level the $\delta^{13}C$ and $\delta^{18}O$ relationships were weak and only in wet events a positive correlation was seen (Figure 5c). However, using tree average measurements, there was a positive correlation between these variables indicating that iWUE increases have been adjusted by reducing g_s. Because BAI decreases overtime (P< 0.05) and iWUE increases, no evidences of beneficial effects of increased CO_2 were seen (Gómez-Guerrero *et al.*, 2013). Over time, dry periods are conducting to higher iWUE and *Ca-Ci* gradient compared to wet periods. This suggests that, from a physiological perspective, the intensity of the stress is increasing at higher rates in dry periods. Thus, recent atmospheric changes are pushing the physiological stress of the ecosystems to their limit and the health of forest is determined by frequency and intensity of droughts (Peñuelas *et al.*, 2011). This result support the second hypothesis (Physiological variables and wood isotopic

signatures of Douglas fir have changed over last century according to changes in atmospheric CO_2) showing changes in physiological variables according to moistures regimes of the past.

3.6.4 Results according to a conceptual model (Scheidegger et al. 2000)

The third hypothesis of the study was supported by the fact that separating the events into wet and dry periods there is an improvement on the interpretation of the conceptual model. Analyzing the shifts of $\delta^{13}C$ and $\delta^{18}O$ and assuming linear changes from one episode to another we are simplifying the processes. Nonetheless, the conclusions derived from this analysis are consistent with the correlation of $\delta^{13}C$ and $\delta^{18}O$. This analysis confirms that physiologically trees are adjusting the A and gs processes to increase iWUE, with not improvement in tree growth. According to the third hypothesis, separating the shifts of $\delta^{13}C$ and $\delta^{18}O$ into extreme wet and dry periods confirms the bases of the conceptual model. Thus, the analysis of shifts in $\delta^{13}C$ and $\delta^{18}O$ from low frequency events (wet and dry) may be used as a complementary tool to understand de conceptual model proposed *by* Scheidegger *et al.* (2000).

3.7 CONCLUSIONS

Wood δ13C reflects the dilution effect of atmospheric 13CO2 due to the increased use of hydrocarbons. Douglas fir ring width series are highly correlated to basal increments and precipitation. Dry periods provided stronger information of the physiological variables. The rate of change of iWUE and the gradient Ci-Ca overtime is higher in dry periods. Results indicated that, in the last 50 years, the intensity of the climatic effects on the tree physiology are being more severe overtime pushing the health of forest to a critical level. Using dual isotopic analyses and separating the information into wet and dry periods reinforce the interpretation of conceptual model of Scheidegger et al. (2000). Thus, the analysis of shifts in δ13C and δ18O from low frequency events (wet and dry) may be used as a complementary tool to understand this conceptual model. Studied forests ecosystems have increased iWUE in the last century adjusting proportionally the ratio A/gs, with no evidences of improved tree growth; thus these forests showed evidence of stress and this condition is getting worse overtime with more severe droughts.

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CAPÍTULO IV
INTRINSINC WATER USE EFFICIENCY IN THE LAST CENTURY OF THREE SPECIES OF *ABIES*, ALONG THE MEXICAN PACIFIC: FACING THE RISING OF ATMOSPHERIC CO2

4.1 RESUMEN

Es necesario mejorar la comprensión de las respuestas de árboles en relación con los aumentos de CO_2 en la atmósfera para estimar y predecir las respuestas de los ecosistemas forestales. En este estudio, utilizamos métodos dendrocronológicos y análisis isotópico para examinar la respuesta de *Abies* spp. en diferentes latitudes a los cambios atmosféricos de CO_2 en el siglo pasado. Tres bosques de gran altitud a través de un ~15 ° de un transecto latitudinal en el Pacífico Mexicano se investigaron. Árboles dominantes maduros se tomaron muestras en tres sitios, San Pedro Mártir en Baja California (BC), Pueblo Nuevo Durango (DGO), El Porvenir y Siltepec, en Chiapas (CHIS). Para describir los cambios de las variables fisiológicas, dividimos la serie de anillos de árboles en extremo húmedo y seco 1893-2000. Los resultados muestran que la eficiencia intrínseca del uso del agua (iWUE), durante el siglo pasado ha aumentado en todos los sitios, el 31% a DGO sitio, seguido CHIS (28%) y BC (21%). Este resultado es contrario a la primera hipótesis de mayor cambio en el sitio más seco. El sitio de BC mostró más de enriquecimiento en ^{13}C y menos discriminación, lo cual es consistente con el medio ambiente seco del sitio. La falta de diferencias en $\delta^{18}O$ a través del tiempo dentro de cada sitio, indican que la fuente de agua para los árboles de *Abies* no ha cambiado en los sitios de estudio, pero la firma en el sitio CHIS era 5 ‰ inferiores a los de otros sitios, lo que sugiere una diferente firma de la lluvia y de aguas poco profundas en esa latitud. El régimen (húmedo o seco) o la interacción tiempo x régimen no fueron significativas para explicar las diferencias en las variables fisiológicas de los árboles de *Abies*. Según los resultados, nuestra segunda hipótesis fue rechazada, ya que los resultados no dependen del régimen de humedad

Palabras clave: Isótopos estables, eficiencia de uso de agua, anillos de crecimiento, cambio climático, México.

4.2 SUMMARY

Improved understanding of tree responses in relation to CO_2 increases in the atmosphere is needed to estimate and predict forest ecosystem responses. In this study, we use dendrochronological methods and isotopic analysis to examine the response of *Abies spp.* from different latitudes to atmospheric CO_2 changes in last century. Three high-elevation forests across a ~15º latitudinal transect in the Mexican Pacific were studied. Mature dominant trees were sampled at three sites, San Pedro Mártir in Baja California (BC), Pueblo Nuevo Durango (DGO) and El Porvenir and Siltepec in Chiapas (CHIS). To describe the changes of physiological variables, we divided the tree ring series into extreme wet and dry periods from 1893 to 2000. The results showed that intrinsic water use efficiency (iWUE), during the past century has increased at all sites, 31% at DGO site, followed by CHIS (28%) and BC (21%). This result contrasted with the first hypothesis of higher change in the driest site. The BC site showed more enrichment in ^{13}C and less discrimination, which is consistent with the dry environment of the site. The lack of differences in $\delta^{18}O$ over time within every site, indicated that the source of water for *Abies* trees has not changed in the study sites, but the signature for the CHIS site was 5‰ lower than the other sites, suggesting a different signature for the rain and shallow water at that latitude. The regime (wet or dry) or the interaction time x regime were not significant to explain the differences in physiological variables for *Abies* trees. According to the results, our second hypothesis was rejected, as the results are not dependent on the moisture regime

Keywords: Stable isotopes, water-use efficiency, tree rings, climate change, Mexico.

4.3 INTRODUCTION

Atmospheric CO_2 concentration has increased from 300 to 400 ppm in the last century (NOAA, 2014), and the forest areas have responded in different ways to that change. Today, climate change effects, which start with the changes in the chemistry of the atmosphere, is one of the major concerns for humans because of its potential effects on forest ecosystems, water and food availability (Bonan, 2008, Hansen *et al.*, 2012). Rising atmospheric CO_2 is expected to have positive effects on tree growth due to the increased availability of carbon dioxide, which is referred to as ''CO_2 fertilization effect'' (Keenan *et al.*, 2013) but the findings from field studies have been

variable (Peñuelas *et al.*, 2011a). Tree-ring studies have reported increased radial growth of trees in response to rising atmospheric CO_2 (Soulé & Knapp, 2006), or no response or reduction tree growth (Tognetti *et al.*, 2000, Jump *et al.*, 2006, Nock *et al.*, 2011, Peñuelas *et al.*, 2011b). The contrasting results found about the response of forests indicate that the topic deserves more research (Hyvönen *et al.*, 2007, Levanič *et al.*, 2011).

The *Abies* forest are important ecosystems of the temperate regions that may have a rapid response to climate change due to the high moisture conditions where they are established. In Mexico, a number of Abies species are found in forests at different latitudes, from the Sierra of Chiapas (*Abies guatemalensis* Rehder), Transvolcanic Belt *Abies religiosa* (Kunth Schltdl. *et* Cham.), and Sierra Madre Occidental (*Abies durangensis*) to San Pedro Martir in Baja California *Abies concolor* (Gordon & Glend.) Lindl. There are no studies that investigate the response of the *Abies* genus, at different latitudes to the atmospheric CO_2 changes. Because of the high sensitivity to water regime, the *Abies* forests may register particular signals in their tree rings series showing the dynamics of droughts periods in Mexico.

This work used dendrochronolical and isotope techniques to study how *Abies* forests have responded to CO_2 atmospheric changes in the last century in the latitudinal range of 15 to 30° N. The analysis of the responses was separated into dry and wet periods according to the trend of ring width. Because the precipitation in *Abies* forests decreases from south to north, we hypothesized that (*i*) *Abies* trees of north latitude have been more seriously affected by changes in the atmosphere than trees growing southern Mexico, and (*ii*) Separate analysis by moisture regimes (dry/wet) show differences over time.

4.4 MATERIALS AND METHODS

4.4.1 Study species and field sampling

The study species were *A. concolor, A. durangensis,* and *A. guatemalensis,* which grow in stands located in San Pedro Martir National Park in Baja California (BC), Ejido San Pablo in Pueblo Nuevo Durango (DGO), and El Porvenir and Siltepec municipalities in Chiapas (CHIS) (Figure 4.1). Summarized information related to characterization of the sites, is presented in Table 4.1 (García, 1998). Additionally, others associated species in fir forests are *Juniperus deppeana, Arbutus xalepensis, Arctostaphylos pungens, Alnus firmifolia, Ceanothus fendleri, Populus tremuloides and Quercus spp.* (Rzedowsky, 1978).

Table 4.1 Climatic conditions in the study sites along the Mexican Pacific.

Variable	San Pedro Mártir, Baja California	Pueblo Nuevo, Durango	El Porvenir, Chiapas
Altitude (masl)	2765	2761	2998
T. max. (°C)	18	18	22
T. min. (°C)	-3	-3	-3
Precipitation (mm.)	400-600	407-712	1500-2500
Climate	Semi-cold, sub-humid	Temperate and sub-humid	Temperate sub-humid
Codominat species	*Pinus jeffreyi*	*Pseudotsuga menziesii*	*Pinus ayacahuite*

4.4.2 Wood core sampling

A total of 41 dominant and healthy trees were selected for wood core sampling. Trees of the upper position canopy are the best trees for isotopic analysis purposes (Barnard *et al.*, 2012). We obtained one wood core per living tree at 1.3 m above the ground using a 12-mm Pressler Borer (Haglöf, BS009). Wood cores were air dried for a week and then polished with sand paper for better identification of tree rings.
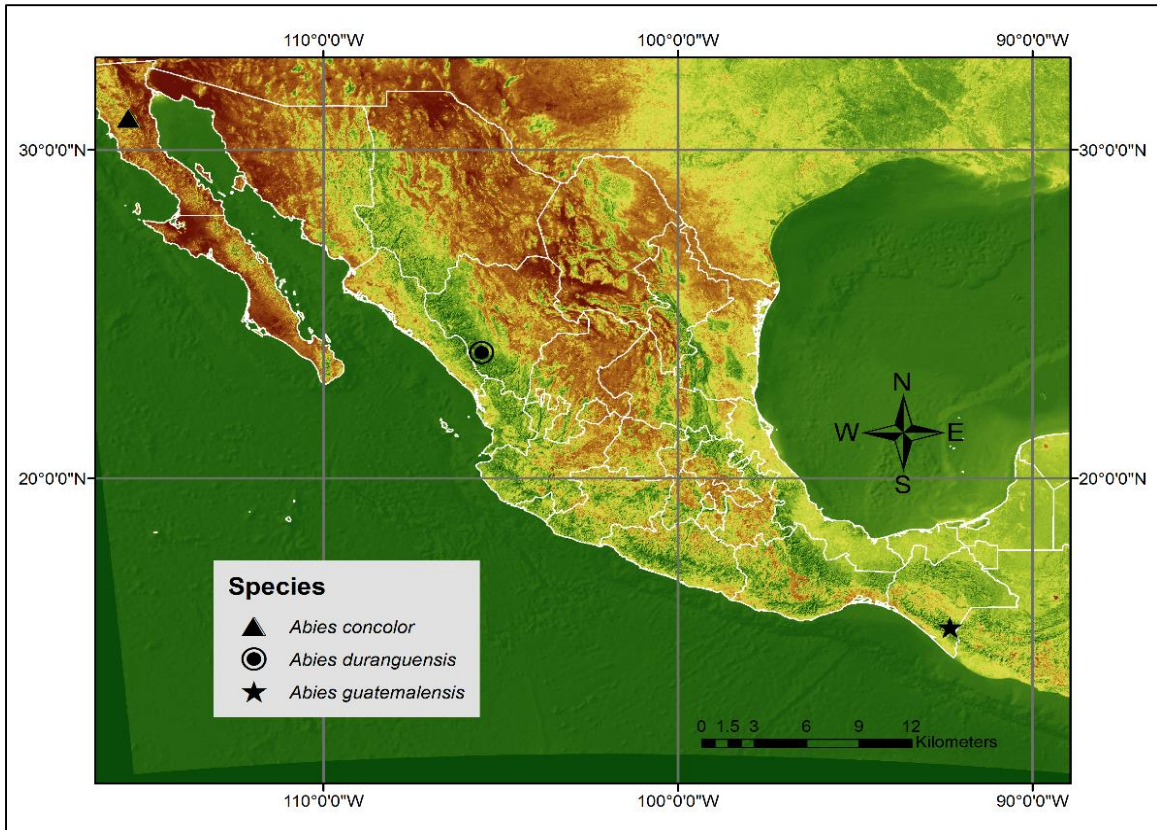
Figure 4.1 Sampling sites of *Abies* species in Mexico.

4.4.3 Wood core measurement

Tree ring samples were dated with dendrochronological standard techniques (Stokes & Smiley., 1968, Fritts, 1976). Tree rings were measured to a precision of 0.01 mm with a VELMEX equipment (Robinson & Evans, 1980). Cross dating of the tree rings was checked using the COFECHA program (Holmes, 1983). A negative exponential model was used to detrend the age series for each tree and developed our tree-ring width chronology using the ARSTAN software (Cook, 1985) and the *"spline"* with a ten-year resolution for tree ring index (TRI) was estimated with the same software (Cook & Peters, 1981).

4.4.4 Isotope analysis (^{13}C and ^{18}O)

Samples of sawdust were collected from five-year periods as described in chapter according to a master chronology of *Pseudostuga menziesii* (Mirb.) Franco of the West Sierra Madre of Mexico that has shown to be consistent with the principal extreme episodes in the past; we used the same

frame of time periods for isotope analysis. The extreme events for *Abies* in general match with the principal extreme events indicating wet (1908-1912, 1964-1968 and 1985-1989) and dry periods (1891-1895, 1951-1955, 1998-2002). The matching of extreme periods is not as good as that for *P. menziesii*, but is still useful for comparison purposes of extreme events (Figure 4.2). For the analysis of $\delta^{13}C$ we weighed 1.1 mg and 0.5 mg $\delta^{18}O$ of sawdust. More details for sample collection and isotope analysis are given in chapter III.
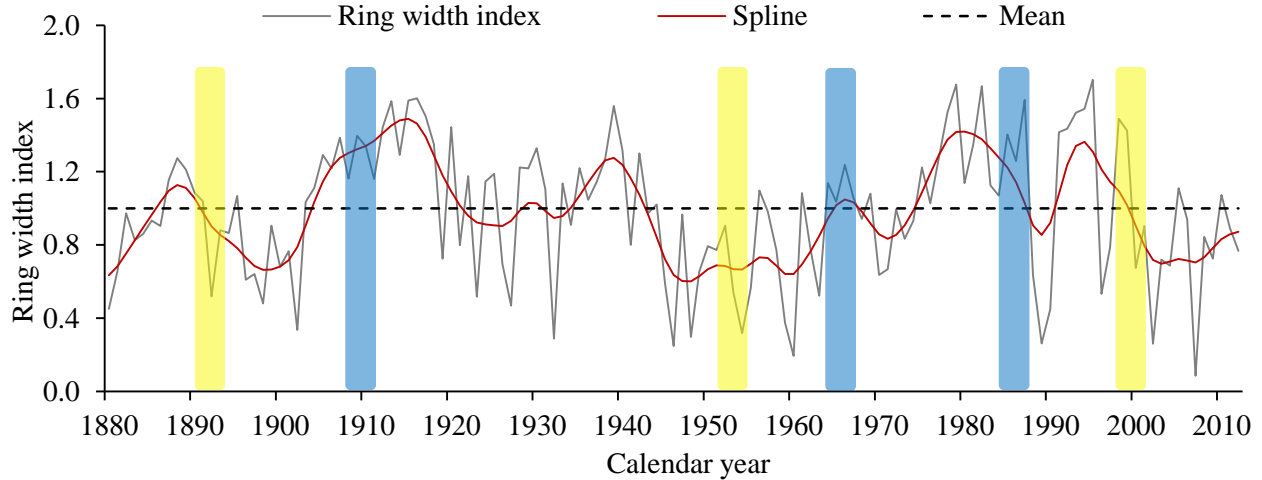
Figure 4.2 Identification of wet and dry episodes across the time, blue bands represent wet periods and yellow bands the dry.

4.4.5 Intrinsic Water Use Efficiency (iWUE)

To calculate iWUE we took into account the atmospheric variation in ^{13}C and its relationship to plant biomass as established by Farquhar *et al.,* (1982) as indicated in eq. 1:

$$\Delta^{13}C = (\delta^{13}C_{air} - \delta^{13}C_{plant})/(1 + \delta^{13}C_{air}/1000) \qquad \text{(eq. 1)}$$

where $\Delta^{13}C$ is discrimination against ^{13}C, $\delta^{13}C_{air}$ is the carbon isotope ratio of the air (the source) and $\delta^{13}C_{plant}$ is the carbon isotope ratio of the product (plant biomass).

The discrimination (Δ) of ^{13}C isotopes can also be expressed as in equation 2:

$$\Delta^{13}C = a + (b-a)(C_i/C_a) \qquad \text{(eq. 2)}$$

where a is the discrimination against $^{13}CO_2$ during diffusion through the stomata (4.4‰), b is the net discrimination due to carboxylation (27‰) and, as previously explained, C_i and C_a are the intercellular and ambient CO_2 concentrations, respectively. Following Fick's first law ($A = gCO_2$ (C_i/C_a)) this equation can be converted to:

$$\Delta^{13}C = a + (b-a)\ [1-(1.6\ A/C_a\ gH_2O)] \hspace{3cm} \text{(eq. 5)}$$

where A is the net photosynthesis, measured as total CO_2 uptake; gCO_2 is the leaf conductance to CO_2 and given that gH_2O, or the leaf conductance to water vapor, is known to be 1.6 gCO_2, the $\Delta^{13}C$ values can be related to the ratio A/gH_2O, which represents the intrinsic water use efficiency (iWUE) of the plant during carbon fixation.

4.4.6 Statistical analyses

To test the significance of trends for the wet and dry episodes over time, we used random coefficient models, which are appropriate for unequally spaced repeated measurements method (Littell *et al.*, 1998, Fitzmaurice *et al.*, 2012). Using SAS PROC MIXED SAS, (2004).

4.5 RESULTS

4.5.1 Carbon isotope composition ($\delta^{13}C$) and oxigen ($\delta^{18}O$)

All sites showed a trend of dilution in carbon isotope composition ($\delta^{13}C$) over time, but the BC site is more ^{13}C enriched compared to DGO and CHIS sites. The DGO and CHIS sites sowed similar values for $\delta^{13}C$ over time (Figure 4.3).
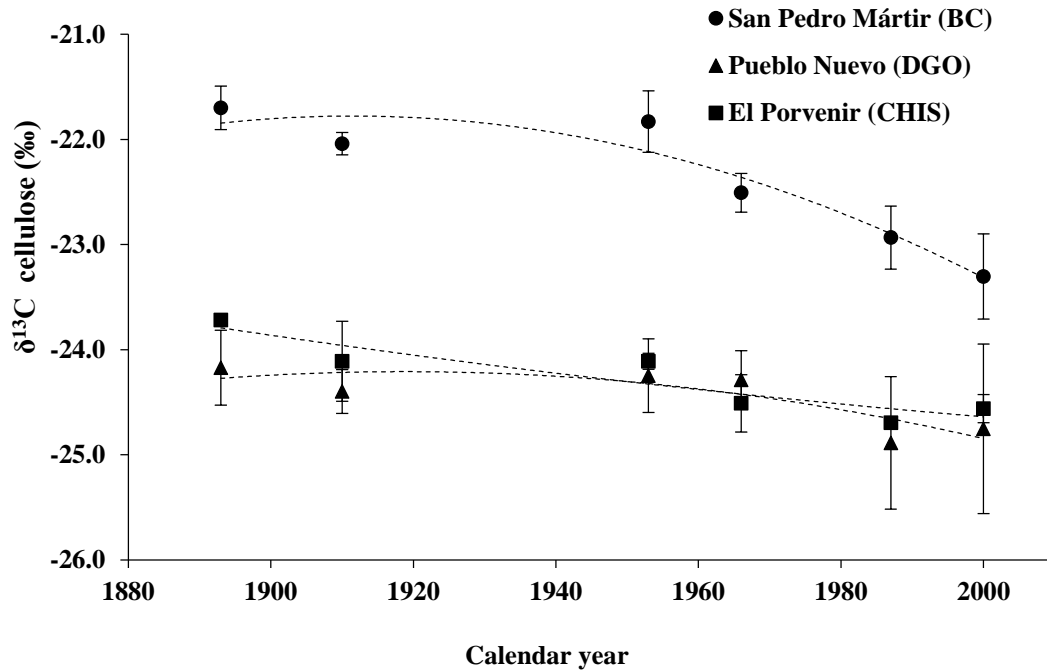
Figure 4.3 Values of $\delta^{13}C$ in the time. The vertical lines are standard errors.

At the BC site, the effect of the time factor was significant; indicating that a difference of 1.6 ‰ in about 100 years is statistically significant for *A. concolor* trees (Table 4.2). The effect of the time factor in the CHIS site was statistically significant ($P<0.001$) with a difference of 0.9 ‰ for the same period. Thus, a difference of 0.9 ‰ is relevant for *A. guatemalensis*. There were no significant effects of the regime (dry or wet periods) or their interaction with time, which indicates that all sites responded similarly over time regardless the moisture regime.

Table 4.2 Statistical effects of the time and water regime for the carbon composition in wood ($\delta^{13}C$).

Site	Effect	GL	F-Value	Pr > F
Baja California "San Pedro Mártir"	Time	12	18.60	**0.0010**
	Regime	12	0.37	0.557
	Time x Regime	12	0.35	0.564
Durango "Pueblo Nuevo"	Time	12	2.88	0.115
	Regime	12	0.01	0.910
	Time x Regime	12	0.01	0.917
Chiapas "El Porvenir"	Time	12	17.57	**0.0013**
	Regime	12	0.02	0.899
	Time x Regime	12	0.01	0.928

Numbers in bold show significant (P<0.05), * marginal significance.

The $\delta^{18}O$ in wood showed similar values around 26 ‰ over time for the north sites, and 21‰ for the south site (CHIS) respectively (Figure 4.4). With respect to $\delta^{18}O$, the interaction Time x Regime was significant ($P = 0.015$) only at the DGO site, indicating that the responses over time in this site were dependent on the moisture regime. There was only a marginal ($P= 0.07$) significance of the interaction Time x Regime in the BC (Table 4.3).
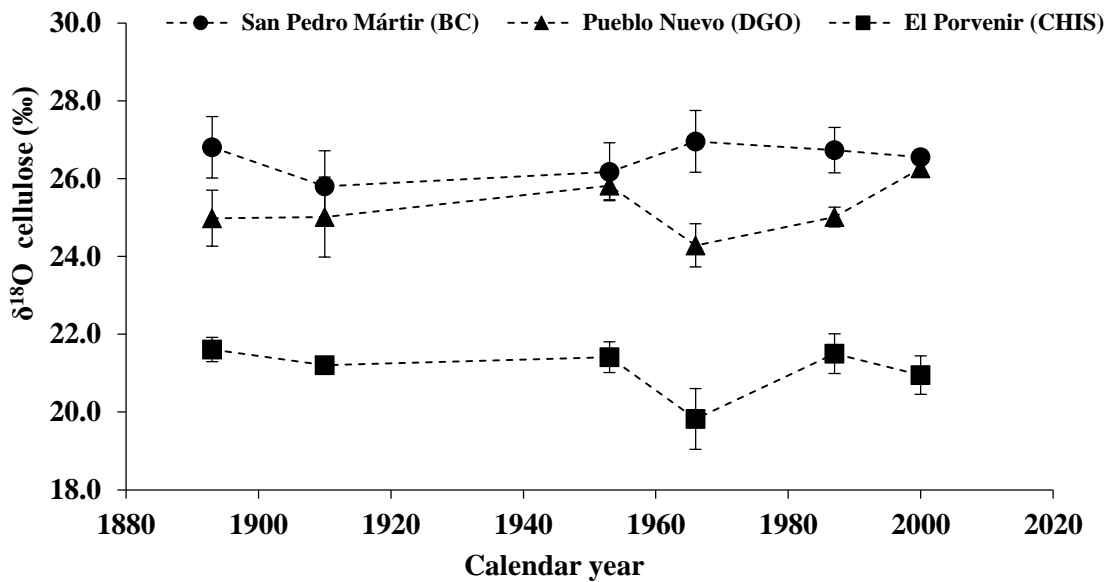
Figure 4.4 Values of $\delta^{18}O$ over time. Vertical lines are standard errors.
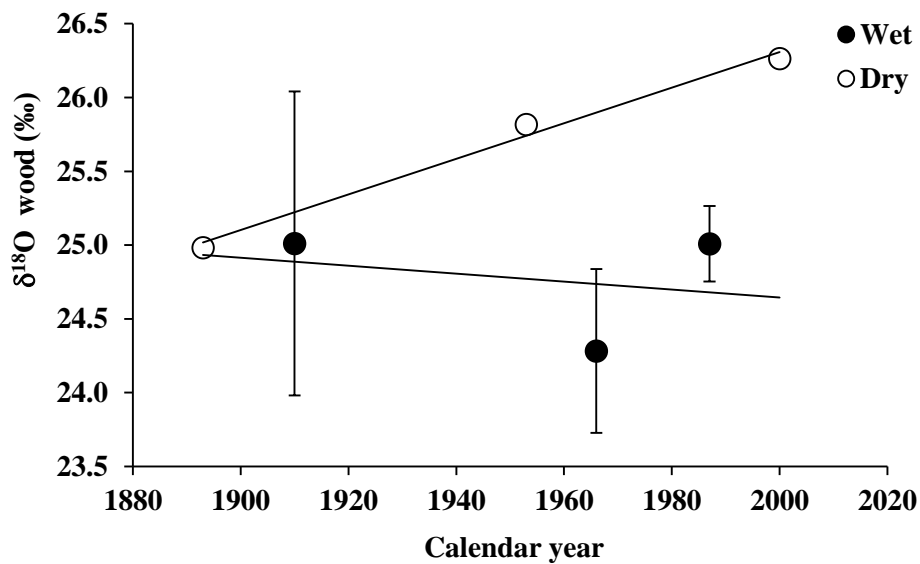
Figure 4.5 Values of wood δ18O by regime in the time. Vertical lines are standard errors.

Table 4.3 Test of fixed effects for the composition of $\delta^{18}O$.

Site	Effect	GL	F-Valor	Pr > F
Baja California "San Pedro Mártir"	Time	12	1.53	0.239
	Regime	12	3.56	0.083
	Time x Regime	12	3.81	0.074
Durango "Pueblo Nuevo"	Time	12	3.56	0.083
	Regime	12	7.96	**0.015**
	Time x Regime	12	7.95	**0.015**
Chiapas "El Porvenir"	Time	12	0.55	0.472
	Regime	12	0.15	0.708
	Time x Regime	12	0.13	0.723

4.5.2 Carbon discrimination ($\Delta^{13}C$)

Carbon discrimination ($\Delta^{13}C$) showed similar values around 16.7‰ over time for the sites of the north (DGO and BC) and 14.7 ‰ for the south site (CHIS) (Figure 4.6). There was a statistical significance for the Regime x Time interaction at the DGO site indicating that the response to the changes of $\Delta^{13}C$ were dependent on the moisture regime (Table 4.4).
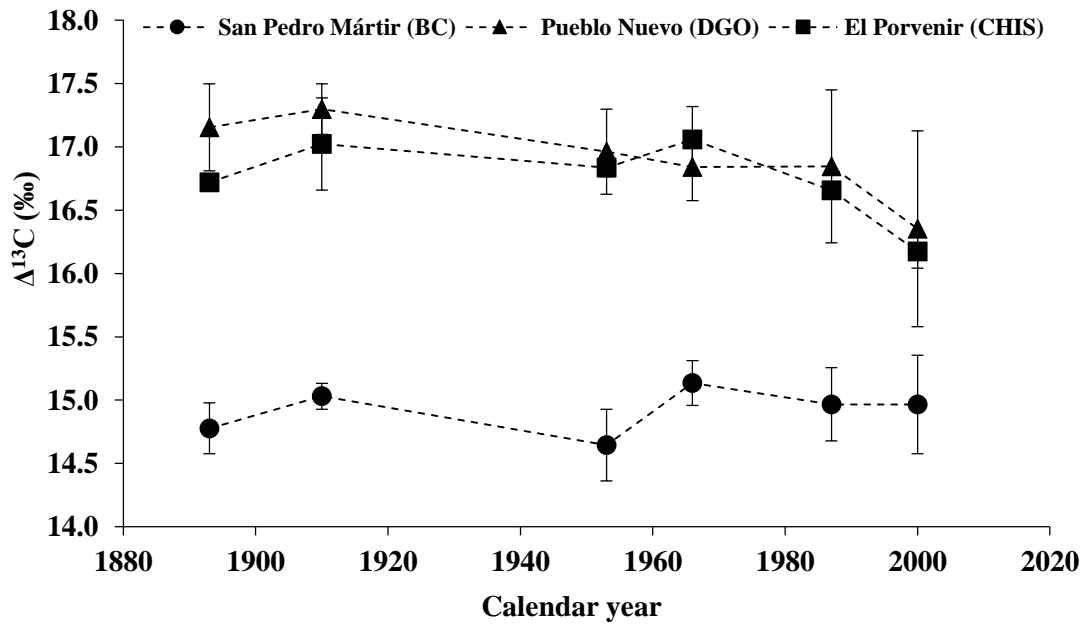
Figure 4.6 Carbon discrimination ($\Delta^{13}C$) in the Sites. Vertical lines are standard errors.

Table 4.4 Test of fixed effects for the composition of $\Delta^{13}C$.

Site	Effect	GL	F-Valor	Pr > F
Baja California "San Pedro Mártir"	Time	12	0.08	0.788
	Regime	12	0.17	0.686
	Time x Regime	12	0.15	0.704
Durango "Pueblo Nuevo"	Time	12	6.67	0.024
	Regime	12	0.02	**0.878**
	Time x Regime	12	0.03	**0.862**
Chiapas "El Porvenir"	Time	12	4.18	0.634
	Regime	12	0.05	0.821
	Time x Regime	12	0.08	0.788

4.5.3 Intrinsic water use efficiency (iWUE)

All sites showed increased iWUE over time (Figure 4.7). None of the sites showed significant responses due to the regime or the interaction Time x Regime indicating similar and parallel responses over time at all of the sites (Table 4.5). However, BC, the site of the north, where *A. concolor* grows shows higher values for iWUE than the other sites.
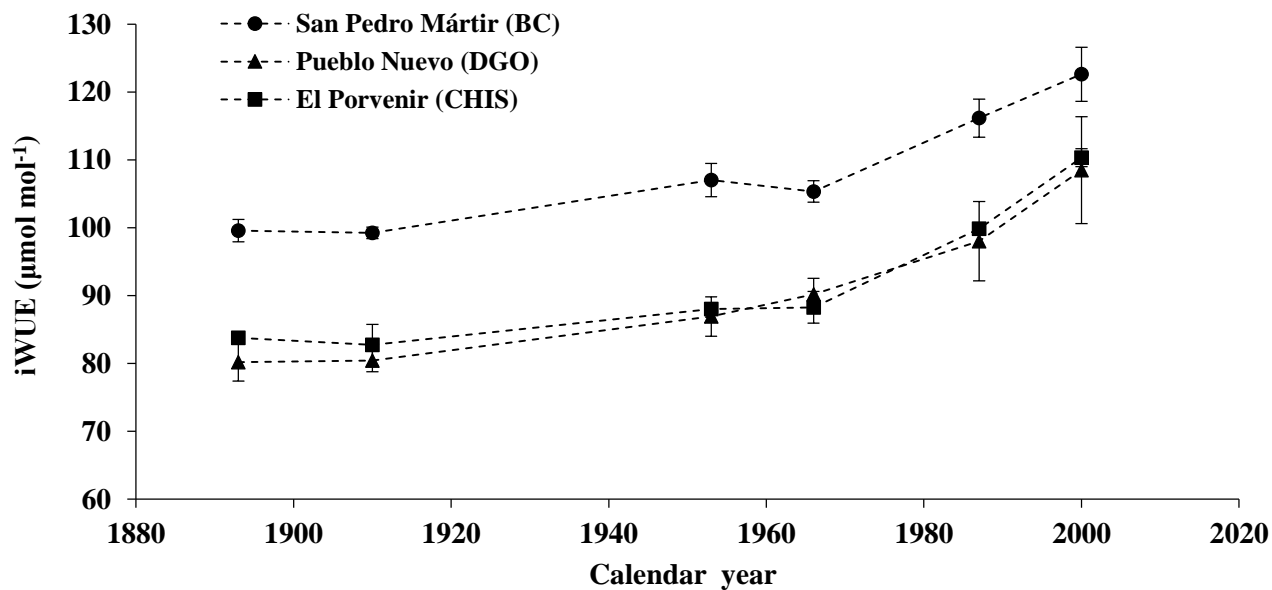
Figure 4.7 Intrinsic water use efficiency (iWUE). Vertical lines are standard errors.

Table 4.5 Test of fixed effects for the composition of iWUE.

Site	Effect	GL	F-Valor	Pr > F
Baja California "San Pedro Mártir"	Time	12	47.52	**0.0001**
	Regime	12	0.31	0.587
	Time x Regime	12	0.34	0.569
Durango "Pueblo Nuevo"	Time	12	53.22	**0.0001**
	Regime	12	0.05	0.828
	Time x Regime	12	0.07	0.800
Chiapas "El Porvenir"	Time	12	50.91	**0.0001**
	Regime	12	0.44	0.517
	Time x Regime	12	0.50	0.492

Numbers in bold show significant (P<0.05).

4.6 DISCUSSION

The decrease in wood $\delta^{13}C$ for all sites is an expected result because in recent time the atmosphere has been diluted with respect to ^{13}C. This response has been reported in other studies and is linked to the use of fossil fuels in the last century (McCarroll & Loader, 2004). Several studies show this trend with approximated changes from 0.9 to 2‰ (Andreu-Hayles *et al.*, 2011, Gómez-Guerrero A *et al.*, 2013). The differences for the last century fall in the range for these studies, BC site showed 1.6‰, DGO 0.5‰ and CHIS 0.9‰ respectively.

The result for the BC site with more enrichment in ^{13}C is consistent with its environment. This is the driest site and *A. concolor* changed its signature from -21 to -23‰. Which is result is also consistent with other reports with estimated values from 0.17 to 1.0‰ (Barber *et al.*, 2000, García-G *et al.*, 2004, Kirdyanov *et al.*, 2008, Penũelas *et al.*, 2008).
The $\delta^{18}O$ is strongly related to summer moisture conditions, especially in temperate regions (Treydte *et al.*, 2007), due to its variation through time it is possible to infer the origin of the moisture utilized in tree growth, however, the lack of differences in $\delta^{18}O$ over time within every site indicate that the source of water for the *Abies* trees has not changed (Saurer *et al.*, 1997, Sarris *et al.*, 2013). However, compared to the northern sites (BC and DGO) the CHIS site showed lower values with a difference of almost 5‰, which denotes an environment with lower changes in atmospheric moisture which leading to different rain signatures (Shu *et al.*, 2005). This may be expected because the rain signatures ($\delta^{18}O$), are the main source of water at high altitudes, change with latitude (Saurer *et al.*, 2002).

In terms of discrimination ($\Delta^{13}C$) the most important changes were observed in the DGO and CHIS sites, which showed a decrease in the two last decades. BC is the driest site and *A. concolor* discriminated about 2‰ less compared to the other species. The discrimination at the BC site has not changed over time, which contradicts our first hypothesis of higher changes in the driest site. The increase in iWUE on the different forest biomes in the last century was in the range reported by other authors 29%, 20%, 23% and 28%, (Andreu-Hayles *et al.*, 2011, Gagen *et al.*, 2011, Wang *et al.*, 2012, Battipaglia *et al.*, 2013). Accordingly, in this study for the same period, the sites showed similar increases in iWUE, 28%, 21 % and 31% for CHIS, BC and DGO, respectively. Again, these results contradicted our first hypothesis of higher change in the driest sites, as found in other studies (Ferrio & Voltas, 2005). The most important factor for the physiological variables

was time. The regime or the interaction time x regime (P>0.05) could not explain the differences for Abies trees. Hence, our second hypothesis was rejected.

These results may have two possible explanations, firstly, the differences of the physiological variables are significant over time but they are not dependent of the water regime, and secondly our method to separate wet and dry periods was not suitable for all of the tree sites. This second explanation is the more likely as the only site that showed significant effects of the interaction time x regime was DGO, the site closest to the *Pseudotsuga* forests, where the master chronology was built. The results for this study indicate a need for further research with a more intensive sampling to examine the effects of moisture regime over time. For future research, it would be convenient to develop local master chronologies to separate wet and dry periods.

4.7 CONCLUSIONS

Tree ring of *Abies* forest showed a δ^{13}C decrease over time, which is consistent with the dilution in the atmosphere in last century. The result for the BC site with more enrichment in ^{13}C and less discrimination is consistent with the environment as this is the driest site. The lack of differences in δ^{18}O over time within every site, indicate that the source of water for *Abies* trees has not changed in the study sites, but the signature for the CHIS site was 5‰ lower than the other sites. This result was expected because the signatures of the rain (δ^{18}O) by evapotranspiration and the CHIS site is more humid. Last century, the increases in iWUE were 31%, 28% and 21% for DGO, CHIS and BC, respectively. This result was contrary to the first hypothesis of higher change in the driest site. The most important factor for the physiological variables was time. The regime or the interaction time x regime (P>0.05) could not explain the differences for Abies trees. Hence, our second hypothesis was rejected. The results for this study indicate a need for further research with a more intensive sampling to examine the effects of moisture regime over time. For future research, it would be convenient to develop local master chronologies to separate wet and dry periods.

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CAPÍTULO V
BASAL AREA INCREASE FORECAST OF *Picea chihuahuana* Martínez AND *Pseudotsuga menziesii* (Mirb.) Franco THROUGH TIME SERIES ANALYSIS

5.1 RESUMEN

El ancho de series de anillos de árboles se puede transformar en incrementos de área basal (IAB) para el analizar las tendencias de crecimiento en el pasado sobre los árboles y para la construcción de modelos para proyectar el crecimiento futuro. En este trabajo utilizamos series de tiempo de IAB para identificar la periodicidad y pronosticar el crecimiento de *Picea chihuahuana* Martínez y *Pseudotsuga menziesii* (Mirb.) Franco, en la Sierra Madre Occidental de México. Los resultados mostraron periodicidad de 7 y 27 años en el abeto Chihuahua y 7, 21 y 60 en el abeto de Douglas, los cuales concuerdan con estudios relacionados. El modelo ARIMA en el abeto Chihuahua fue (1,1,0), la periodicidad aproximada de 60 años en el abeto de Douglas, que también se observa en los eventos de El Niño Oscilación del Sur (ENOS), fue determinante para construir un modelo ARIMA (0,1,1) y describir los cambios en crecimiento. El pronóstico de IAB en este modelo indica que el crecimiento disminuirá el corto plazo (cinco años), y presentará recuperación de valores medios en el año 2025 en ambas especies. El reducido crecimiento en los arboles jóvenes del abeto Chihuahua a edades de 141, y 124 años en el abeto Douglas concuerda con la disminución general de la productividad forestal en otros bosques del mundo. El crecimiento proyectado en los árboles prevé que no será superior a la media histórica (21 cm^2 año^{-1} en el abeto Chihuahua y 54 cm^2 año^{-1} en el abeto de Douglas), lo cual sugiere que los recientes cambios climáticos pueden empeorar la condición de los bosques en el Norte de México. El análisis de series de tiempo de IAB como se muestra aquí es una poderosa herramienta de predicción para proyectar los futuros cambios en crecimiento, y avance en las prácticas de manejo forestal.

Palabras clave: dendrocronología, anillos de crecimiento, productividad forestal, bosque templado

5.2 SUMMARY

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 of BAI to identify periodicity and forecast tree growth of *Picea chihuahuana* Martínez and *Pseudotsuga menziesii* (Mirb.) Franco growing in the West Sierra Madre of Mexico. Results showed periodicity in tree growth of 7 and 27 years in Chihuahua spruce and 7, 21, 27 and 60 in Douglas-fir, which are in agreement to related studies. The type of ARIMA models for Chihuahua spruce and Douglas-fir were (1,1,0) and (0,1,1), respectively. A periodicity of 60 years, which was seen in the ring series of Douglas-fir and in the El Nino Southern Oscillation (ENSO) was used to describe the changes in tree growth. The forecast of BAI by these models indicates decreased tree growth in the short period (five years) and a recovery phase by the year 2025 in both species. Reduced tree growth forecast in young trees of Chihuahua spruce and Douglas-fir (120-240-year-old) is in agreement with a general decrement in forest productivity in other forests of the world. According to the model, future tree growth will not reach average growth rates (21 cm^2 year^{-1} on Chihuahua spruce and 54 cm^2 year^{-1} in Douglas-fir) in the next decades, which suggest that recent climate changes may worsen the condition of forest in North México. Time series analysis of BAI as illustrated here is a powerful prediction tool to project future changes in tree growth, and advancement of forest management practices.

Keywords: Dendrochronology, tree ring, forest productivity, temperate forest

5.3 INTRODUCTION

Due to the increased variability of the climate in the last three decades (Hansen *et al.*, 2012), more understanding on the relationship of tree growth and climatic variables is needed. Forest growth depends on tree species composition, stand age, stand density, soil quality and climate , and the combined effect of these factors is reflected in the ring width of forest species . 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 purposes. The standard procedures for time series analyses were developed by Box and Jenkins (1970) 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 no only to describe the metrics of tree rings but also to describe past tree physiological processes trough 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, planning the use of water resources, determine the frequency of hydroclimatic 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*) and Douglas-fir (*P. menziesii)* which are long-lived climate sensitive species present in specific habitats along the Western Sierra Madre. Currently, these species were considered in danger of extinction, and are included under protection of Mexican norm NOM-059-2010 . This paper aims to analyze basal area increment (BAI) of Chihuahua spruce and Douglas-fir derivated from tree ring measurements at the breast height. Hypothesis were (i) BAI of *P. chihuahuana and P. menziesii* in the Western Sierra Madre of Mexico show a periodic or quasi-periodic component, and (ii) the periodicity found for *P. chihuahuana and P. menziesii* can be described and forecasted with a time series model.

5.4 MATERIALS AND METHODS

5.4.1 Study sites

The study site is located in the Western Sierra Madre of Mexico (WSM) in the municipalities of Bocoyna (BOC) and Balleza (BAE) in the state of Chihuahua (Figure 5.1), in coordinates 27° 57' 19.64"N, 107° 45' 9.38"W and 26° 27' 59.14" N and 106° 21' 14.95" W. The altitude ranges from 2,400 to 2,730 m, the climate is temperate sub-humid with mean annual temperature and precipitation of 12°C and 780 mm, respectively. In the study sites Douglas-fir, does not form pure stands but it is mixed in associations with *P. chihuahuana*, *Pinus arizonica*, *Pinus durangensis*, and *Pinus ayacahuite*, which have been also reported in other studies.
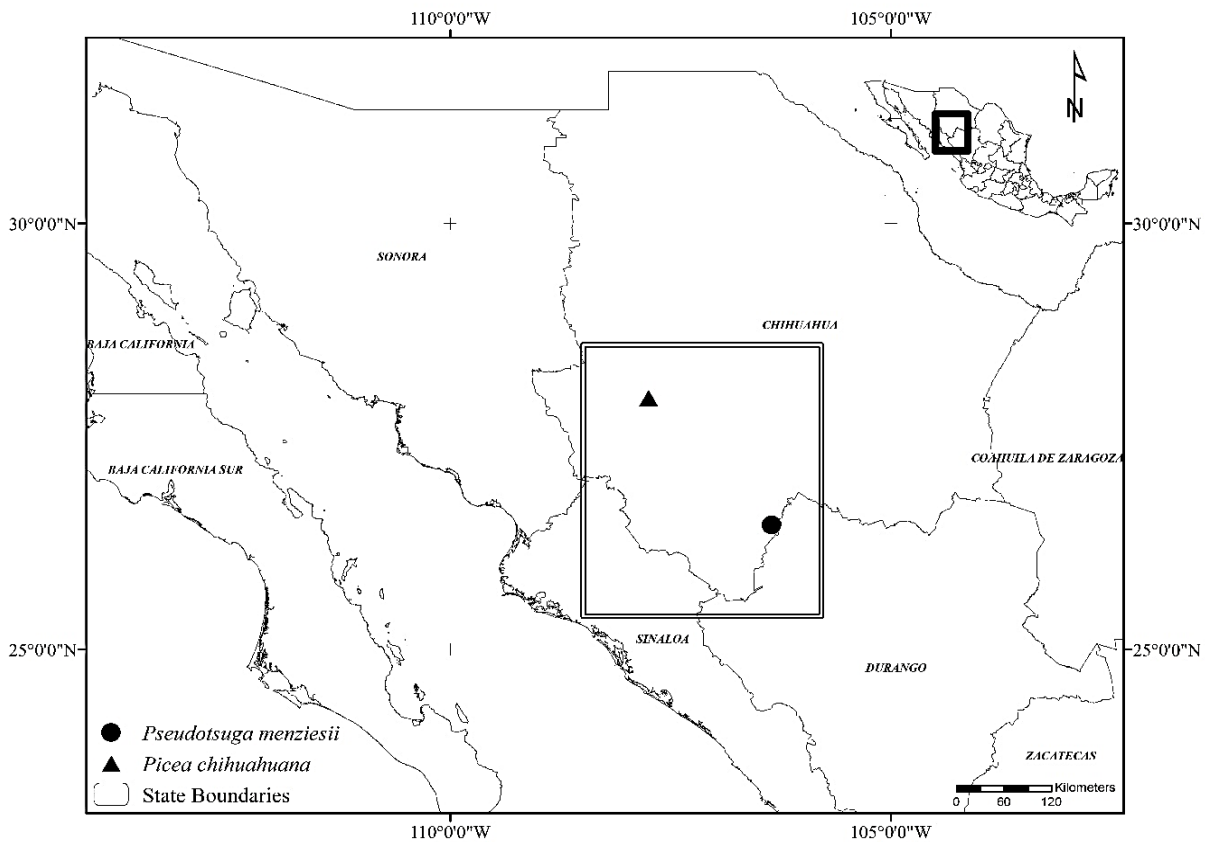
Figure 5.1 Geographical location of the sampled site in the state of Chihuahua, Mexico.

5.4.2 Wood core sampling

In summer of 2012, eight-increment cores of Chihuahua spruce and twenty three Douglas-fir were 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 12 mm Haglöf borer, BS009 model. The samples were taken in transversal direction to the slope at 1.3 m above the ground. Two wood cores were taken in opposite direction of the circular section of the stems. The average age of the sampled trees was 141 years in Chihuahua spruce and 124 years in Douglas-fir. At this age, basal increments of Douglas-fir plateau and remain constant up to the age of 300 years .

5.4.3 Sample core measurement

Increment core samples were processed at the Laboratory of Dendrochronology from 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 Velmex measuring system with a 0.001mm precision . Increment cores samples were processed following standard dendrochronology techniques .

5.4.4 Basal Area Increment (BAI)

Basal area increments (BAI) for each tree was computed according to the following equation:

$$\text{BAI} = \pi(R_n^2 - R_{n-1}^2) \tag{1}$$

where: BAI is basal area increment, π 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.

5.4.5 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 (Eq. 2) .

$$x_t = \frac{a_0}{2} + \sum_{k=1}^{m}(a_k \cos(\omega_k t) + b_k \sin(\omega_k t)) \tag{2}$$

where: x_t are the data, a_0 is the mean term: $a_0 = 2\bar{x}$, m is the number of frequencies in the Fourier decomposition, a_k are the cosine coefficients, ω_k are the Fourier frequencies: $\omega_k = \frac{2\pi k}{n}$, 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.

5.4.6 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 . The model is presented in equation 3.

$$\phi_p(B)Z_t = \theta_q(B)u_t \tag{3.1}$$

$$Z_t = \phi_i Z_{t-1} + \cdots + \phi_p Z_{t-p} + u_t + \theta_j u_{t-1} + \cdots + \theta_q u_{t-q} \tag{3.2}$$

where: Z_t is the mean deviation in time t of an equally spaced stationary series; ϕ_i and ϕ_p are autorregresive terms $[\phi_p(B) = (1 - \phi_i B^i - \cdots - \phi_p B^p)]$; B is a backshift operator; θ_j and θ_q are moving average terms $[\theta_q(B) = (1 - \theta_j B^j - \cdots - \theta_q B^q)]$; and u_t represents randomly independent variables with zero mean and variance σ^2 (white noise).

Second-order stationary models are mean ($E(Z_t) = \mu$), variance ($Var(Z_t) = \sigma^2$) and covariance ($Cov(Z_t, Z_s) = \gamma_k$) 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 dth 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 (∇^d):

$$X_t = \nabla^d Z_t \ ; \text{where } \nabla^d = (1 - B)^d \tag{4}$$

Where: X_t is the d times differenced series to be transformed into stationary and Z_t is the original series. 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 $ln\ Z_t$ (Pankrats, 1983). 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.

ARIMA models can describe cycles for annual data. To achieve cycle stationarity, it is convenient to use a cycle difference operator (∇_C^D):

$$W_t = \nabla_C^D X_t \ \ ; \text{where } \nabla_C^D = (1 - B^C)^D \tag{6}$$

where: W_t is the D times differenced series (length of the cycle C).

Cyclical effects ARIMA models can be proposed under the following general model ARIMA (p, d, q) x (P, D, Q)$_C$ (equation 7).

$$\phi_p(B)\Phi_P(B^C)\nabla^d\nabla_C^D(Z_t) = \theta_q(B)\Theta_Q(B^C)u_t \tag{7}$$

where $\phi_p(B)$ is the noncyclic AR operator, $\theta_q(B)$ is the noncyclic MA operator, $\Phi_P(B^C)$ is the cyclic AR operator of length C, $\Theta_Q(B^C)$ is the cyclic MA operator of length C, and $\nabla^d\nabla_C^D = (1 - B)^d(1 - B^C)^D$ are the differencing operators for non and cyclical compounds.

In this work, we analyzed BAI chronology by autoregressive integrated moving average models (ARIMA Box-Jenkins Models).

5.4.7 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 herocedasticity and suggested when the mean of series changes overtime as was seen in this study.

5.4.8 Estimation of ARIMA model components

The ARIMA modeling involves the comparison of estimated autocorrelation function graphs (ACF) and partial autocorrelation (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 (SCAN) 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 $Y_{m,t} = (Z_t, Z_{t-1}, \ldots, Z_{t-m})'$ where Z_t is time series, such that $m = p_{min}, \ldots, p_{max}$ and $j = q_{min}, \ldots, q_{max}$. 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 under the assumption that the past unobserved errors are equal to zero (SAS 9.3).

5.4.9 Strategy for diagnosing, checking and forecasting

The results of spectral analysis were considered to test the different cyclicities in the seasonal component (*C*) of the ARIMA process and generate an appropriate model for understanding the behavior of forest productivity. The statistical reliability of the model was verified through a chi-squared test (Ljung-Box test) by assuring that random shocks and u_t were statistically independent (not autocorrelated) and "white noise". The forecast was calculated with the infinite memory forecast, also called conditional forecast. The term conditional is used because forecasts are computed by assuming that the unknown values of the response series before the start of the data are equal to the mean of the series. A forecast of BAI was performed for the next 15-year period and up to the year 2090 at the of 95% of confidence level.

5.5 RESULTS AND DISCUSSION

5.5.1 Tree ring series and BAI

Thirty-one samples were obtained in the study sites, eight for Chihuahua spruce and twenty-three for Douglas-fir; sample size in this species was reliable for dendrochronological purposes, but not for Chihuahua spruce. The inter-correlation series computed with COFECHA for Chihuahua spruce was 0.18 and 0.67 for Douglas-fir, the average mean sensitivity was 0.23 and 0.27, respectively. The sample of trees captured a common trend for radial growth as indicated by the signal strength of 0.14 in Chihuahua spruce and 0.90 in Douglas-fir in ARSTAN. Mean BAI of Chihuahua spruce was 21 cm^2 year^{-1} and for Douglas fir 54 cm^2 year^{-1} (Std ± 4 and 12), respectively. The result in Chihuahua spruce is similar to that reported for stands of Norway spruce

of 22-year-old, which was 24 cm^2 year^{-1} . In western Oregon where trees with ages from 100 to 300 years Douglas-fir plateaued at 50 cm^2 year^{-1} . In general, there was a trend to reduce BAI over time, which is not an expected result because healthy and dominant young trees with average diameters of 75 centimeters and average age of 141 and 124 years composed the sample. 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 for Chihuahua spruce. In contrast, in Douglas-fir showed a reduction of BAI of 24 and 28% for the periods of 1890-1899 and 1950-1959. Favorable periods resulted in an increased BAI of about 15% in Chihuahua spruce and 16% on Douglas fir above the mean value respectively (Figure 5.2). A generalized reduction in BAI has also been reported for other forests suggesting that water and nutrient are the main stress factors.

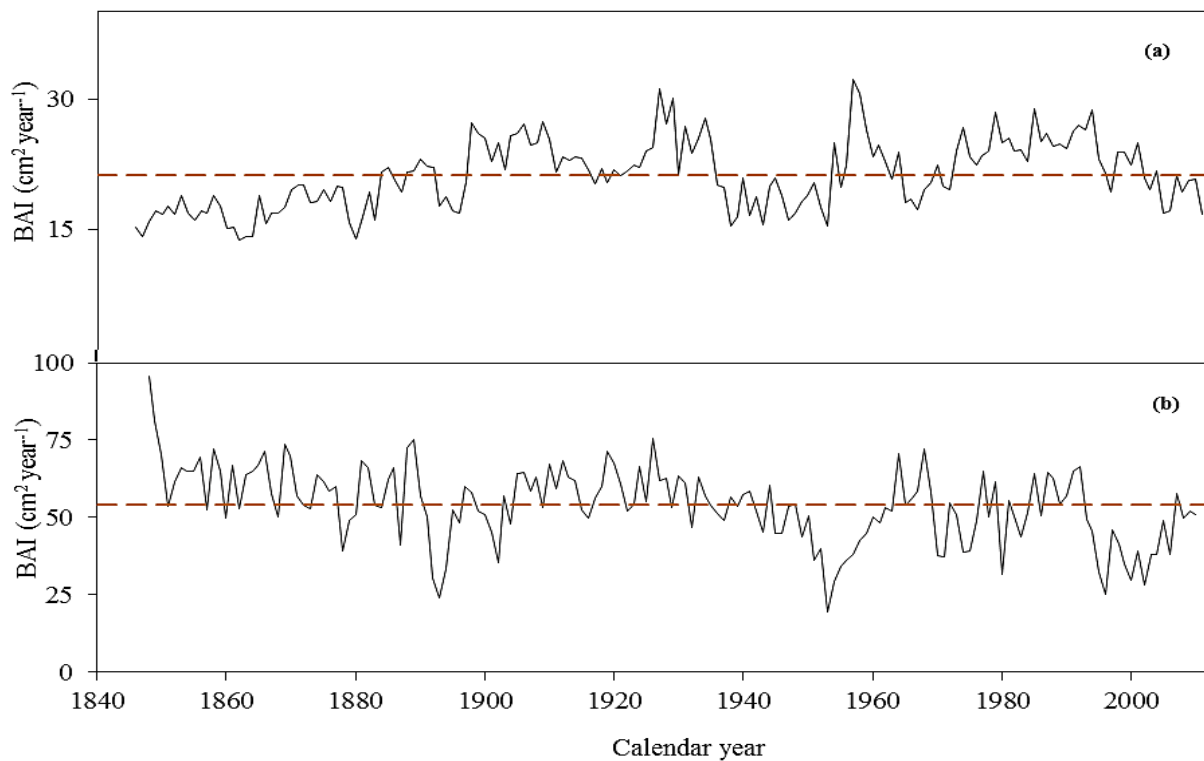Figure 5.2 Time series of basal area increment for two conifer species in Chihuahua. The
dotted line represents the mean value for each series (a) *P. chihuahuana* and
(b) *P. menziesii*.

5.5.2 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 and 27 years in Chihuahua spruce (Figure 5.3a) and 7, 21, 27 and 60 years in Douglas-fir (Figure 5.3b). The last cycle is in agreement with droughts recurrence of 60 years reported for northern Mexico . Also, this *quasi* periodicity is present in the Aztec codices, and was named as "The Rabbit Year" related to predict natural events in their calendar; each event is associated with calamitous periods such as famine and death, with a 52-year cycle . Although it is difficult to establish a direct relationship with global circulatory events, the fact that deserves special attention is that the cycles found here have showed to be compatible with ENSO and PDO cycles. One explanation for these results might be the high sensitivity of the study species to climate variations due to global events (Griesbauer and Scott Green, 2010). The correlation to BAI and precipitation from January to July was high (0.70, *P*<0.01) in both species.
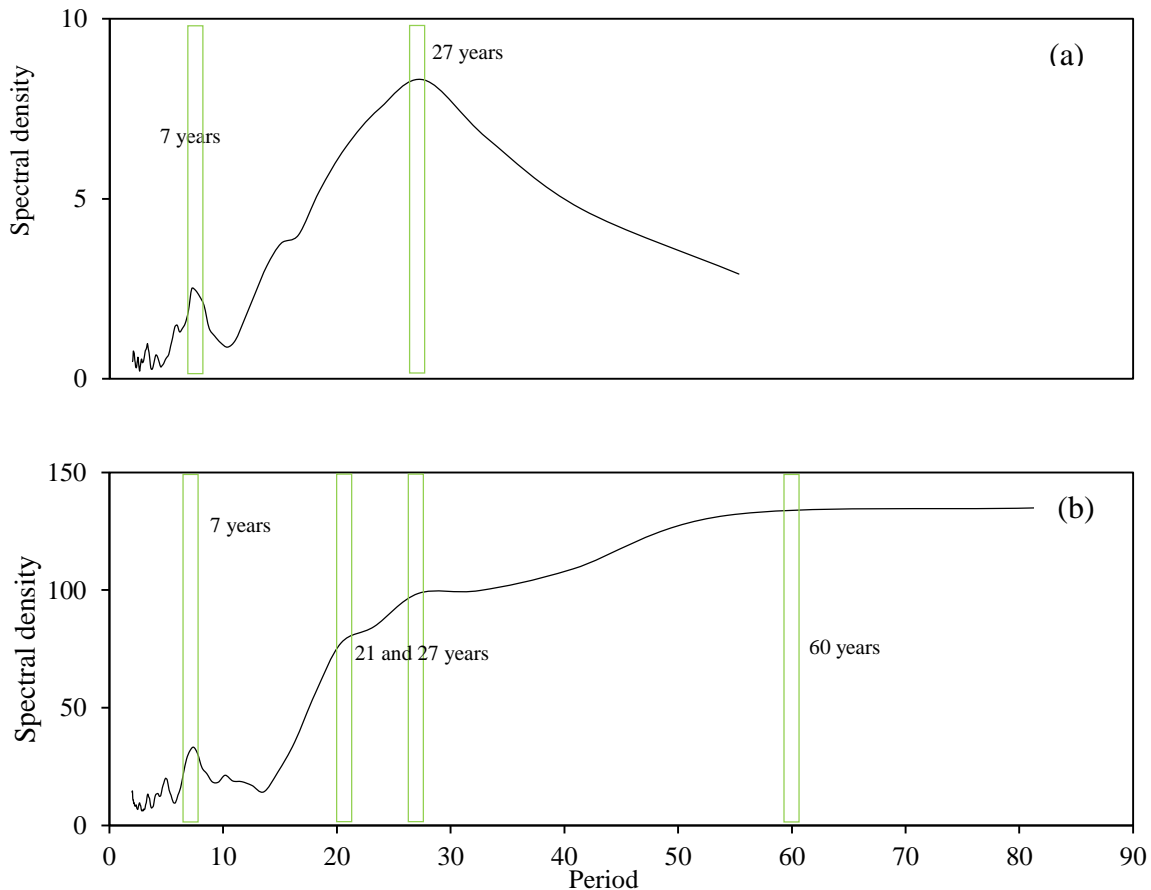

Figure 5.3 Spectral density in basal area increment series of Chihuahua spruce (a) and Douglas-fir (b). Green bars represent statistical significant cycles (*P*<0.05)

5.5.3 BAI transformation and stationarity

Dickey-Fuller Unit Root Tests and the autocorrelation function (ACF) of the original series showing nonstationarity (Table 5.1). 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 is convenient to decrease heterocedasticity and the *d*th 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, in Douglas-fir three years (Figure 5.4 and 5.5 top); 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 (Figures 5.4 and 5.5 bottom).

Table 5.1 Augmented Dickey-Fuller Unit Root Tests of the BAI chronology in Chihuahua spruce and Douglas-fir

| Type	Lags	Rho	Pr<Rho	Tau	Pr<Tau	F	Pr>F
Single Mean	0	-43.238	0.0013	-4.99	0.0001	12.46	0.001
	1	-29.162	0.0013	-3.89	0.0027	7.57	0.001
	2	-27.069	0.0016	-3.58	0.0072	6.43	0.003
Trend	0	-51.363	0.0005	-5.35	0.0001	14.45	0.001
	1	-34.992	0.0018	-4.04	0.0093	8.42	0.001
	2	-33.526	0.0026	-3.73	0.0234	7.19	0.026
Tests of the BAI chronology in Douglas-fir							
Single Mean	0	73.4046	0.0013	-7.24	<0.0001	26.25	0.001
	1	-53.2311	0.0013	-5.46	<0.0001	14.97	0.001
	2	-49.2134	0.0013	-4.8	0.0002	11.58	0.001
Trend	0	-89.0382	0.0005	-8.04	<0.0001	32.51	0.001
	1	-70.7552	0.0005	-6.09	<0.0001	18.70	0.001
	2	-73.0600	0.0005	-5.49	<0.0001	15.16	0.001
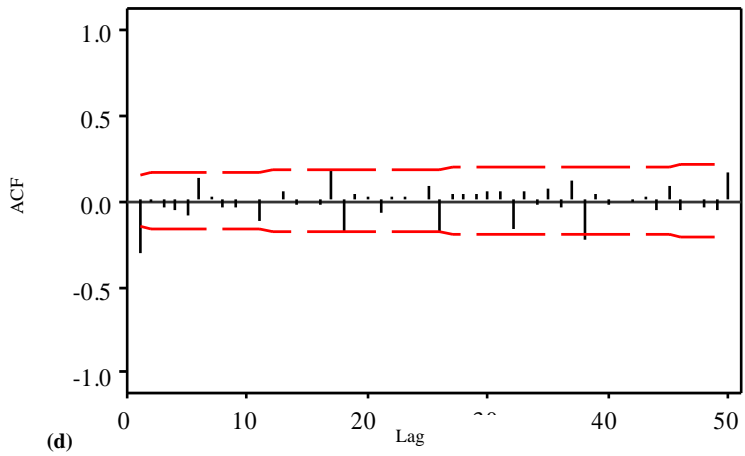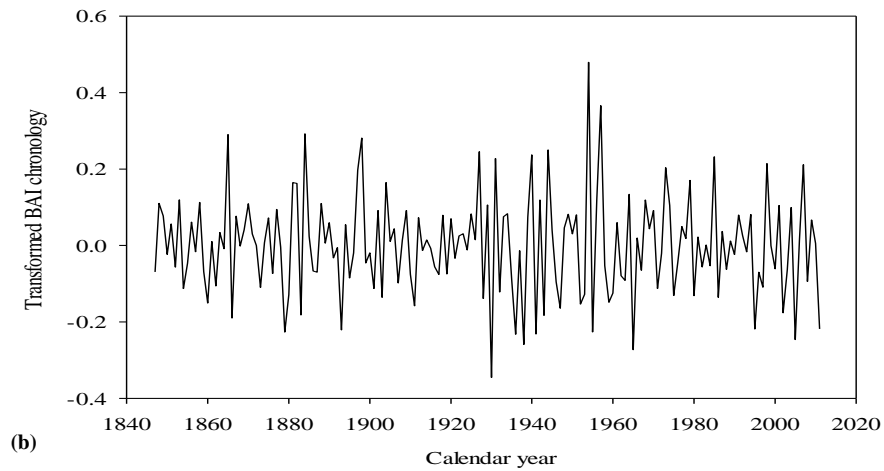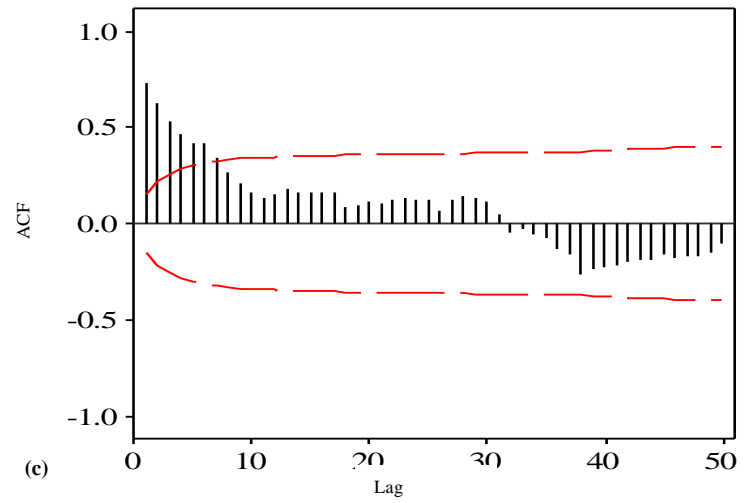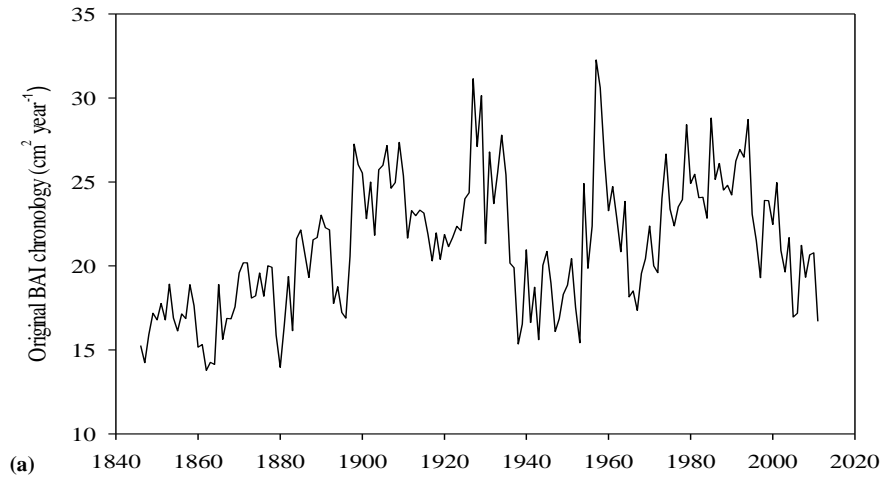
Figure 5.4 Original (top) and transformed (bottom) basal area increment chronology of *P. chihuahuana*, with autocorrelation functions (ACF). The dotted line represents 95% of confidence intervals.
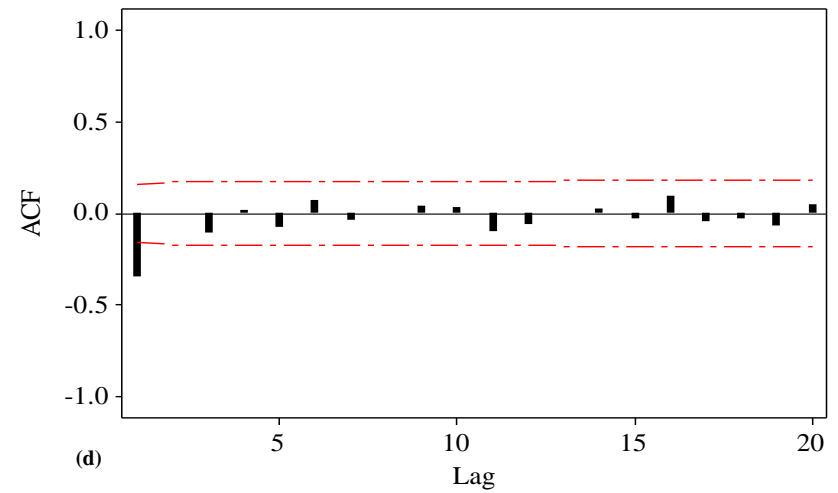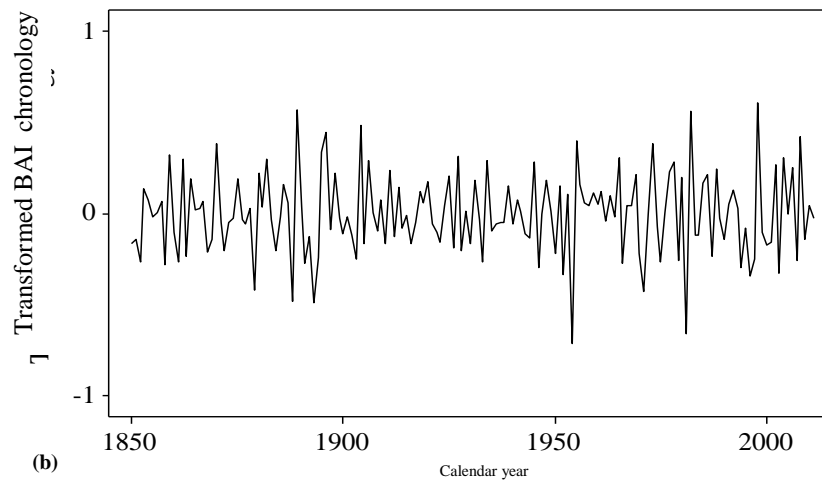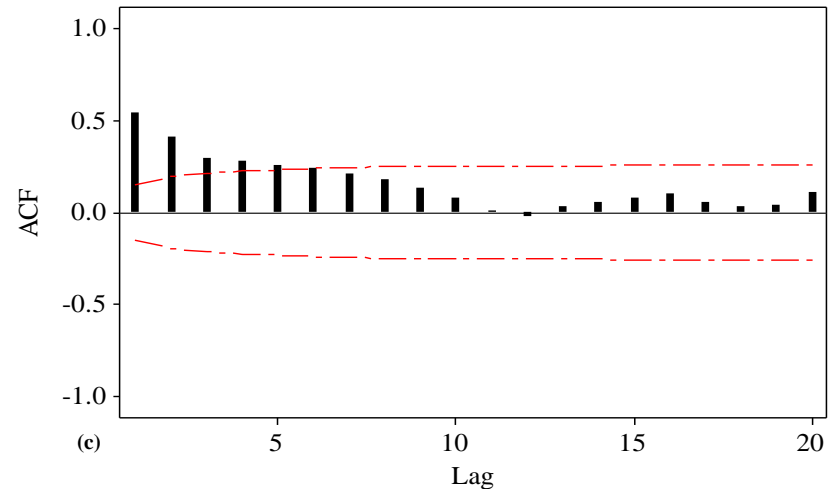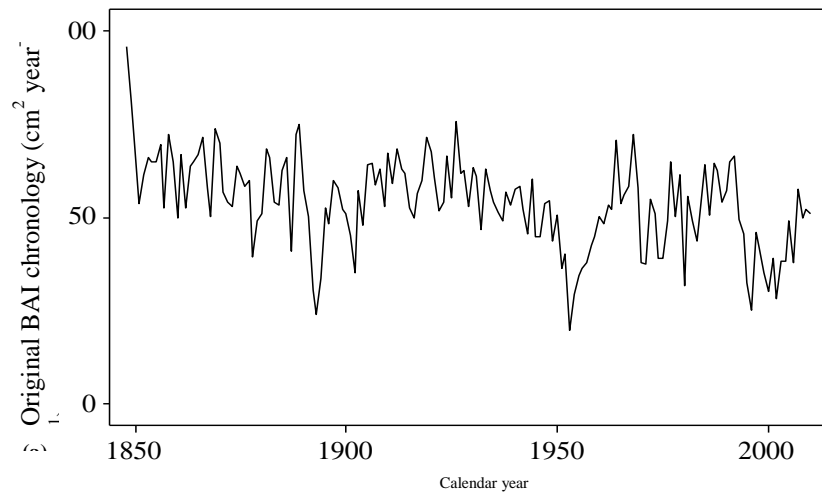
Figure 5.5 Original (top) and transformed (bottom) basal area increment chronology of *P. menziesii*, with autocorrelation functions (ACF). The dotted lines represents 95% of confidence intervals.

5.5.4 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 and MA (1) processes in Douglas-fir (Figure 5.6 and 5.7). The features of the process were defined by the spike at lag 1, then cuts off to zero, and if the spike is negative then $\theta > 0$ (ACF) and by the exponentially negative side (ACFp) . This result was consistent with the smallest canonical (SCAN) correlation method and the proposed ARIMA models were (1,1,1) for Chihuahua spruce and (0,1,1) in Douglas-fir (1,1,0).

Figure 5.6 Autocorrelation function (ACF) and partial autocorrelation function (ACFp) of the transformed basal area increment chronology of *P. chihuahuana*. The dotted lines represents 95% confidence intervals.

Figure 5.7 Autocorrelation function (ACF) and partial Autocorrelation Function (ACFp) of the transformed basal area increment chronology of *P. menziesii*. The dotted lines represents 95% confidence intervals.

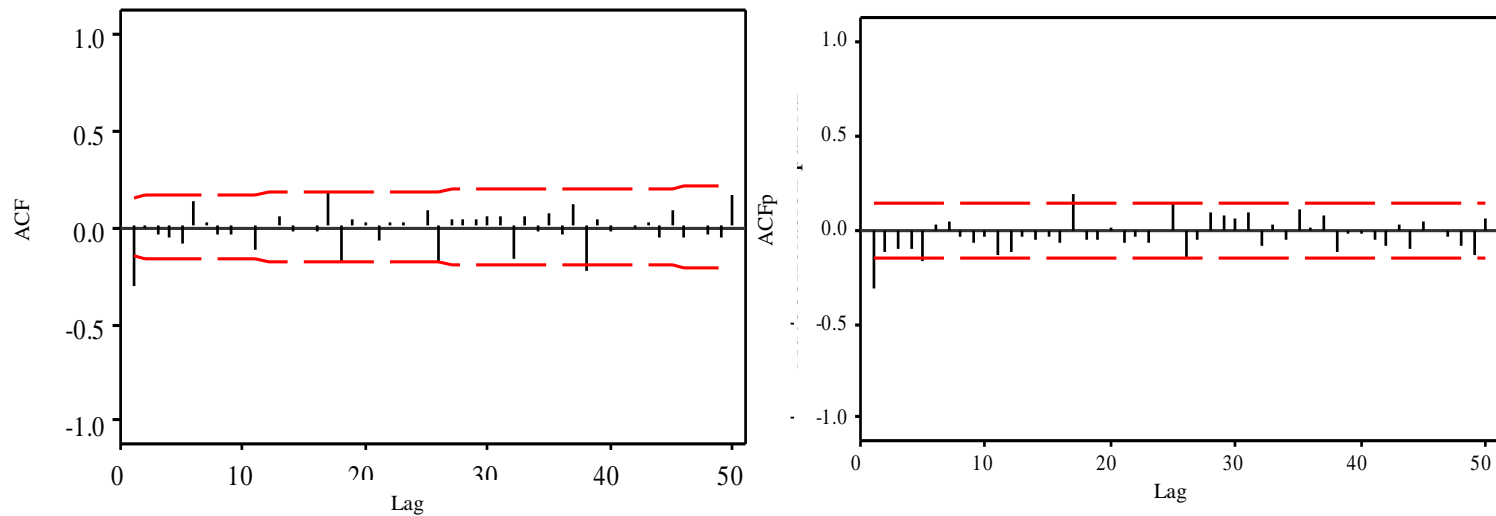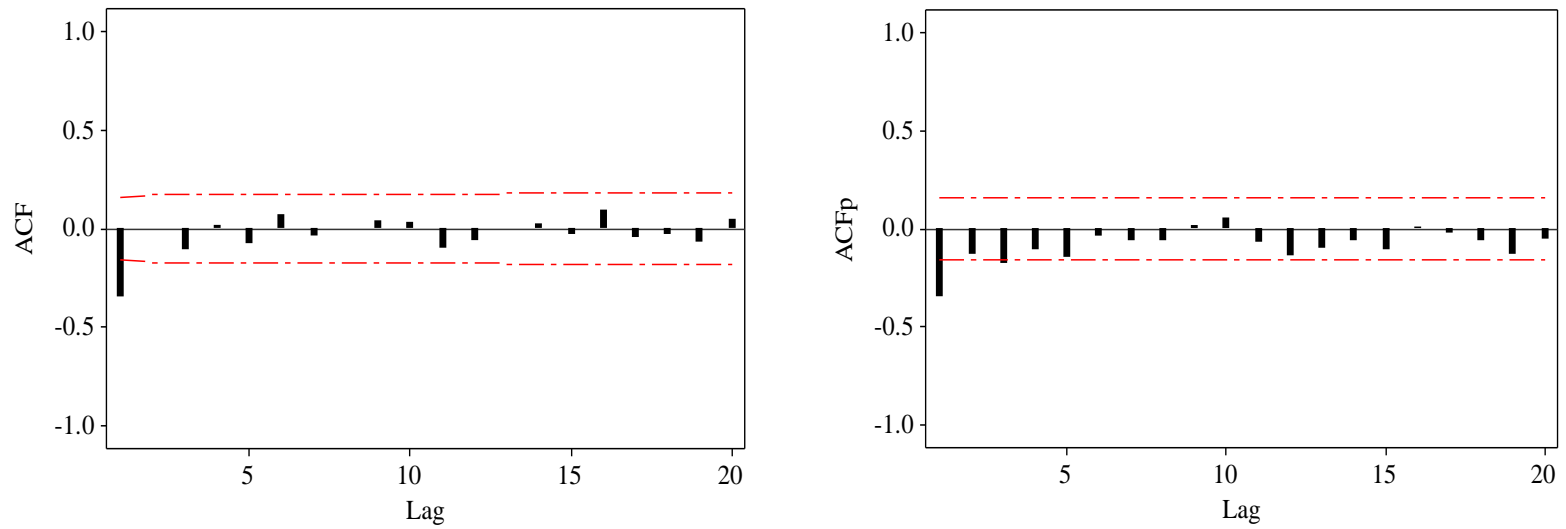After considering the ACF, ACFp the selected ARIMA (1,1,1) model in Chihuahua spruce and (0,1,1) in Douglas-fir, models had a moving mean parameter (q) involving random shocks (Monserud, 1986), which is different from the AR(1) or ARMA (1,1) models that are frequently proposed to the ring-width series

The selected models were evaluated with all the periodicities found (7 and 27) in Chihuahua spruce and (7, 21, 27 and 60) in Douglas-fir, 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. In contrast, all models in Douglas-fir were significant (C = 7, 21, 27 and 60). The estimation of the moving average term in Chihuahua spruce (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. In Douglas-fir the moving average term (θ) was positive with values from 0.46 to 0.76, while the cyclic moving average term (Θ) varied from 0.45 to 0.83 (Table 5.2).

For forecasting purposes the selected model was ARIMA(1,1,1) x $(1,1,0)_{27}$ in Chihuahua spruce and ARIMA (0,1,1) x $(0,1,1)_{60}$ in Douglas-fir. Two reasons support this selection:

i) First, 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.

ii) Second, the periodicity of 27 years and the *quasi* periodicity of 60 years may be related to global circulatory patterns as it has been reported by other authors .

Table 5.2 Adjustment of models for *P. chihuahuana* and *P. menziesii*.

Model	θ_1	φ_1	Φ_p/Θ_q	Standar error	T value	Pr > |t|	Variance estimation	Standard error of the estimation	AIC	SBC
		Parameter								
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) (1,1,0)$_7$	0.445	--	--	0.176	2.55	0.0116	0.023	0.152	-143.27	-134.09
	--	0.048	--	0.197	0.25	0.8059	--	--	--	--
	--	--	-0.490	0.074	-6.63	<0.0001	--	--	--	--
ARIMA(1,1,1) (1,1,0)$_{27}$	**0.873**	**--**	**--**	**0.071**	**12.23**	**<0.0001**	**0.024**	**0.156**	**-116.46**	**-107.68**
	--	**0.506**	**--**	**0.120**	**4.21**	**<0.0001**	**--**	**--**	**--**	**--**
	--	**--**	**-0.450**	**0.088**	**-5.10**	**<0.0001**	**--**	**--**	**--**	**--**
P. menziesii										
ARIMA (0,1,1)	0.503	--	--	0.068	7.38	<0.0001	0.043	0.207	-49.23	-46.14
ARIMA (0,1,1) (0,1,1)$_7$	0.458	--	--	0.071	6.38	<0.0001	0.050	0.225	-20.01	-13.92
	--		0.832	0.047	17.54	<0.0001	--	--	--	--
ARIMA (0,1,1) (0,1,1)$_{21}$	0.647	--	--	0.065	9.97	<0.0001	0.054	0.232	-8.81	-2.91
	--		0.645	0.075	8.53	<0.0001	--	--	--	--
ARIMA (0,1,1) (0,1,1)$_{27}$	0.492	--	--	0.076	6.49	<0.0001	0.063	0.251	11.75	17.56
	--		0.780	0.074	10.46	<0.0001	--	--	--	--
ARIMA (0,1,1) (0,1,1)$_{60}$	**0.764**	**--**	**--**	**0.065**	**11.59**	**<0.0001**	**0.060**	**0.246**	**5.72**	**10.97**
	--		**0.448**	**0.166**	**2.70**	**<0.0001**	**--**	**--**	**--**	**--**

* Conditional Least Squares Estimation

5.5.5 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. In the case of Chihuahua spruce with the following equations.

The model selected was ARIMA $(1,1,1)x(1,1,0)_{27}$; with the following equations:

$$\phi_p(B)\Phi_P(B^C)\nabla^d\nabla^D_C(Z_t) = \theta_q(B)\Theta_Q(B^C)u_t \tag{8}$$

$$0.506(B) - 0.45(B^{27})\,\nabla^1\nabla^1_{27}(Z_t) = 0.873(B)u_t \tag{9}$$

where:

$$\ln(x_t) = Y_t \tag{10}$$

$$\nabla^{d=1}Y_t = Y_t - Y_{t-1} = W_t \tag{11}$$

$$\nabla^{D=27}W_t = W_t - W_{t-27} = Z_t \tag{12}$$

$$Z_t - \Phi_{27}Z_{t-27} - \phi_1 Z_{t-1} + \phi_1\Phi_{27}Z_{t-28} = -\theta_1 u_{t-1} + u_t \tag{12.1}$$

$$Z_t = \phi_1 Z_{t-1} + \Phi_{27}Z_{t-27} - \phi_1\Phi_{27}Z_{t-28} - \theta_1 u_{t-1} + u_t \tag{12.2}$$

Substituting the estimated coefficients

$$Z_t = 0.506Z_{t-1} - 0.450Z_{t-27} - (0.506 \text{ x} - 0.450)Z_{t-28} - 0.873u_{t-1} + u_t \tag{12.3}$$

$$Z_t = 0.506Z_{t-1} - 0.450Z_{t-27} + 0.2277Z_{t-28} - 0.873\,u_{t-1} + u_t \tag{12.4}$$

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 (87%). The reduction forecasted for BAI in the period 2011 to 2025 was about 97% with average of 42 cm^2 year^{-1}, and significant recovery for the period 2025 to 2028 (Figure 5.8 and 5.10). For this period, the projected growth will be below the historical mean (21 cm^2 year^{-1}) proposing a reduction in growth for 2090 (Figure 10).

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

$$\phi_p(B)\Phi_P(B^C)\nabla^d\nabla^D_C(Z_t) = \theta_q(B)\Theta_Q(B^C)u_t \rightarrow \nabla^1\nabla^1_{60}(Z_t) = 0.764(B)0.448(B^{60})u_t \tag{13}$$

Where:

$$\nabla^{d=1}Z_t = Z_t - Z_{t-1} = X_t \qquad \nabla^{C=60}X_t = X_t - X_{t-60} = W_t \tag{13.1}$$

$$\hat{Z}_t = (1 - \theta_1 B)(1 - \Theta_{60} B^{60}) u_t \qquad (13.2)$$

$$\hat{Z}_t = u_t - \Theta_{60} u_{t-60} - \theta_1 u_{t-1} + \theta_1 \Theta_{60} u_{t-61} \qquad (13.3)$$

Using coefficients from Table 2.

$$\hat{Z}_t = u_t - 0.764 u_{t-1} - 0.448 u_{t-60} + 0.342 u_{t-61} \qquad (13.4)$$

This 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. The forecast indicates reductions of 72% in BAI with average of 15 cm^2 year^{-1}, and a recovery about the year 2025 (Figure 5.9). However the projected growth in 2025 for this specie is below the historical mean (54 cm^2 year^{-1}) suggesting a net reduction in growth for the next 75 years (Figure 5.11). 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 (Silva *et al.*, 2010). Biologically, the forecast indicates that if mean annual temperature increase and precipitation decreases in the Wet Sierra Madre as predicted by some authors (Villers-Ruiz and Trejo-Vazquez, 1997), 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.

Figure 5.8 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%.
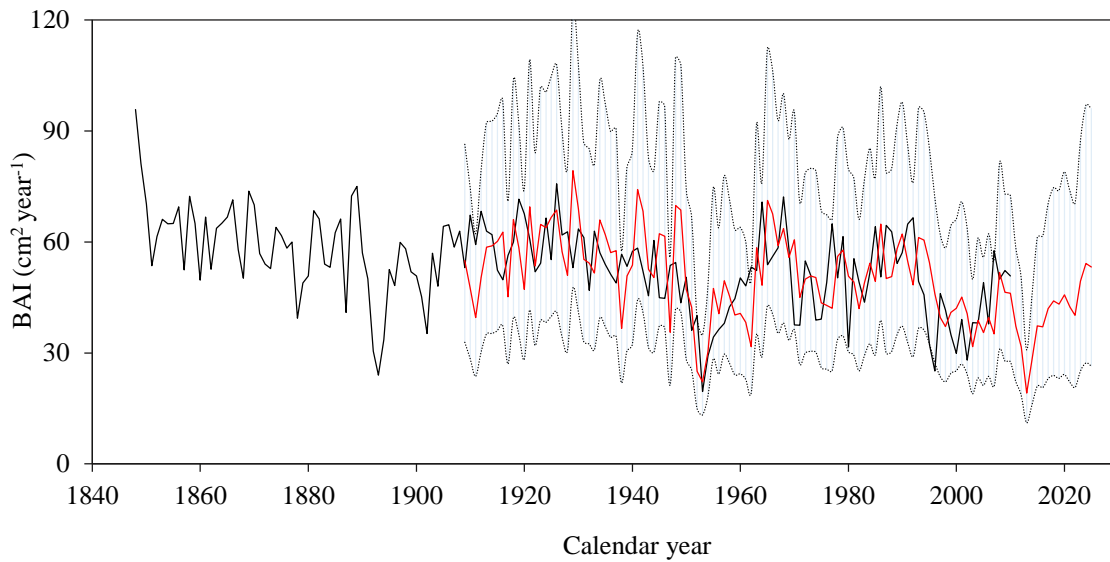
Figure 5.9 Forecast of BAI *P. menziesii* of from the ARIMA model. The black line is for real measurements and red line for estimation. The blue area defines the confidence interval at 95%.

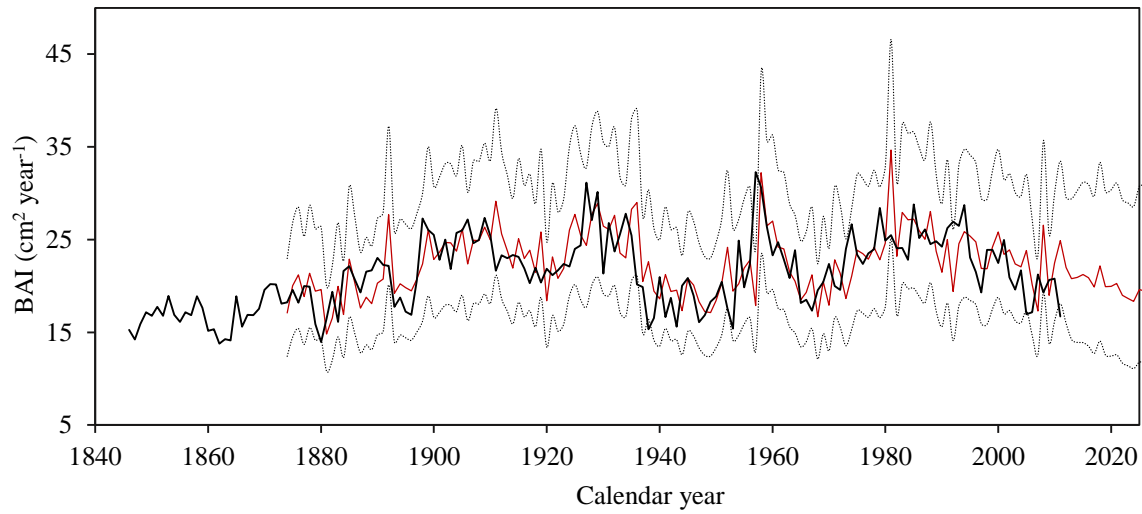Figure 5.10 Extended forecast of BAI *P. chihuahuana* from the ARIMA model. The black line is for real measurements and red line for estimation. The white area defines the confidence interval at 95%.

Figure 5.11 Extended forecast of BAI *P. menziesii* from the ARIMA model. The black line is for real measurements and red line for estimation. The blue area defines the confidence interval at 95%.
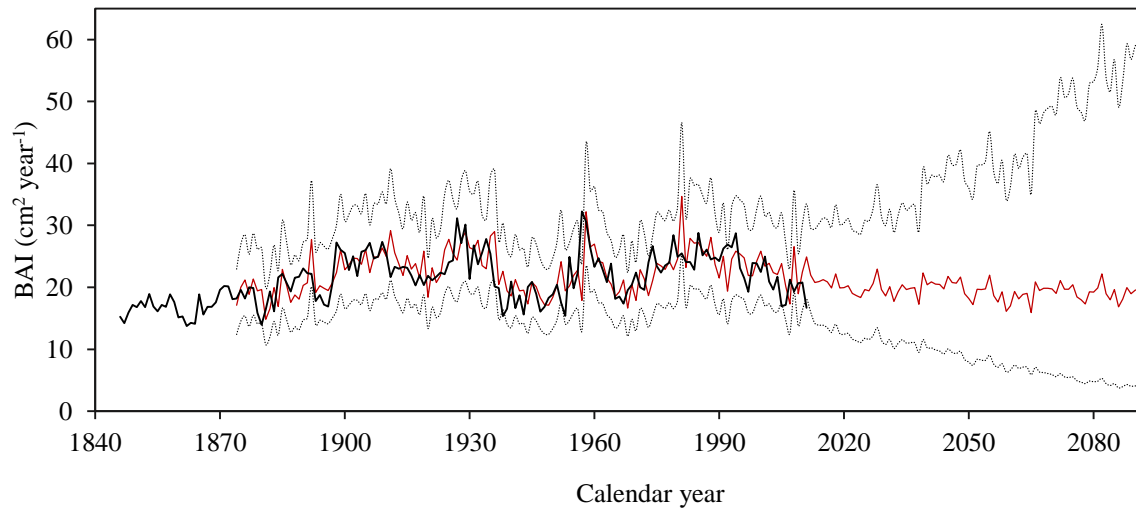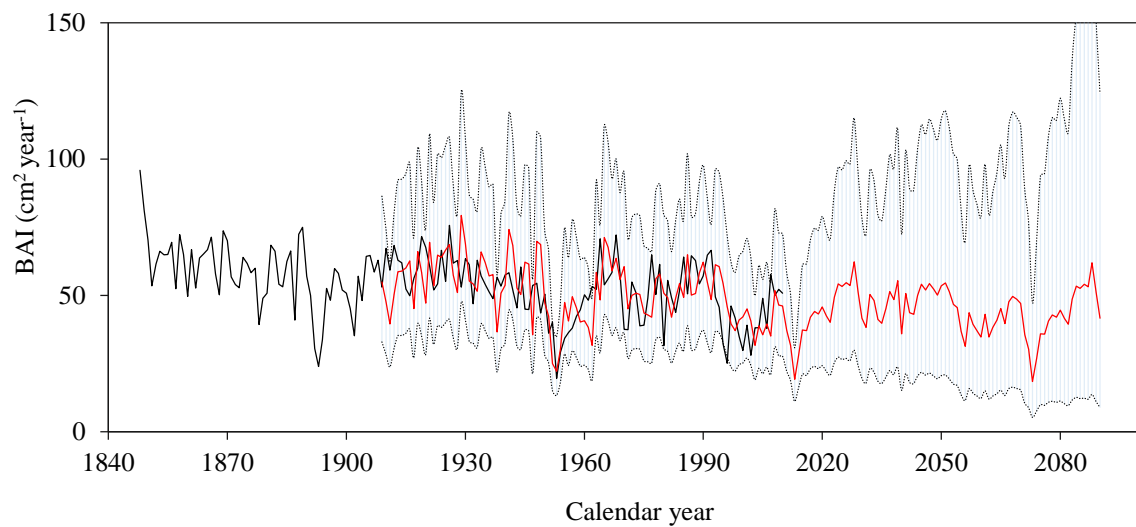
5.6 CONCLUSIONS

The length analyses of the BAI in both chronologies was 163 years (1848 to 2010).Time series analysis of BAI of Chihuahua spruce and Douglas-fir in the Western Sierra Madre of Mexico allowed to identifying periodicity in tree growth of 7, 27 in Chihuahua spruce and 7, 21, 27 and 60 years on Douglas-fir. The forecast for BAI indicates decrease in tree growth in the short term (five years) and a recover by the year 2025 in both species. However, the projected growth will not be higher than the historical mean (21 and 54 cm^2 $year^{-1}$). The forecast show significant periods in the reduction of BAI on 2024 and 2059 for Chihuahua spruce, in Douglas-fir for 2015 and 2073. These results have implications if we take into account recent changes in climate variability. Biologically, the forecast indicates that if mean annual temperature increase and precipitation decreases in the West Sierra Madre as predicted by some authors, these forests will be under risk in the next decades. The use of time series analysis for BAI can be helpful to predict future changes in tree growth and to propose management practices. In the future, this has implications for timber supply forecasting of other commercial species in the mixed forest in Western Sierra Madre of Mexico. However, the presence of global climate change at global and regional scale and the increasing climatic variability can lead to experiencing more recurring extreme periods of drought.

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CAPÍTULO VI
CONCLUSIONES GENERALES

La series de anillos de crecimiento y variabilidad climática

- La cronología de 150 años realizada para *Pseudotsuga menziesii* (Mirb) Franco) en la Sierra Madre Occidental fue útil para confirmar que él crecimiento de esta especie tiene una fuerte relación con la variabilidad del clima.

- En la Sierra Madre Occidental la precipitación acumulada de enero a julio es muy importante para explicar el crecimiento de *Pseudotsuga menziesii*, lo que sugiere que se pueden construir modelos de predicción para crear escenarios futuros del crecimiento de coníferas de la Sierra Madre Occidental.

- Existe una correlación significativa entre los índices de anillo y el incremento en área basal, lo que indica que mediante estudios dendrocronológicos hay un alto potencial para reconstruir el ritmo de crecimiento de algunas especies forestales cuya sección transversal se acerque a la forma circular.

- Se encontró una correlación significativa entre los índices del (ENSO) y el crecimiento en área basal de *Pseudotsuga menziesii*, lo que ayuda a comprender cómo el cambio climático podría afectar a los bosques templados.

Análisis de series de tiempo y variabilidad climática

- Las cronologías de las especies forestales se pueden expresar en términos del incremento en área basal para estudiar sus tendencias con análisis de series de tiempo.

- Se realizó un análisis de series de tiempo para *Pseudotsuga menziesii* y *Picea chihuahuana* con la finalidad de conocer las tendencias de crecimiento en área basal y detectar la si existía periodicidad o ciclicidad en el crecimiento.

- Los resultados del análisis de series de tiempo fueron más satisfactorios para *Pseudotsuga menziesii* que para *Picea chihuahuana*, debido a una menor inter-correlación entre la serie de los árboles que componían la muestra.

- Para *Pseudotsuga menziesii* se encontraron periodicidades cercanas (quasi-periodicidad) a los 7, 21 y 60 años. De estos periodos, el de mayor consistencia con la variación de los índices ENSO fue el de 60 años, el cual también ha sido reportado por otros autores.

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- La periodicidad de 60 años detectada y la serie incremento en área basal permitieron la construcción de un modelo de predicción de tipo ARIMA (0,1,1) para la predicción del incremento en área basal.

- El modelo de predicción de área basal indica una reducción paulatina de crecimiento en los bosques de la Sierra madre Occidental. A pesar de que se prevén algunas fases de recuperación en crecimiento, no se lograrán incrementos mayores a 60 cm^2 $year^{-1}$, que el crecimiento bajo condiciones favorables de clima. Este resultado lleva a pregunta de si esta tendencia es un efecto del cambio climático y del futuro de los bosques de la Sierra Madre Occidental en caso de aumentar la frecuencia de sequias y plagas, como se ha visto en las últimas décadas.

- La tendencia de reducción de crecimiento también lleva a la pregunta sobre el cambio de estrategia en la silvicultura de los bosques templados. Ante el probable incremento en sequias la nueva estrategia de la silvicultura sería un mejor control sobre las densidades y acorde a la disponibilidad de agua de tal forma de tener masa vigorosas que resistan los efectos de clima y plagas.

Las series de anillos y las variables fisiológicas de Pseudotsuga menziesii

- Los rodales de *Pseudotsuga menziesii*, como otras especies forestales indican que están respondiendo ante los incremento en CO_2 atmosférico. Una respuesta común es la disminución en discriminación ($\delta^{13}C$) e incremento en la eficiencia de agua intrínseca (iWUE).

- La series de anillos de *Pseudotsuga menziesii* que mostró alta correlación con la precipitación de enero a julio, permitió identificar satisfactoriamente periodos húmedos y periodos secos, los cuales también mostraron correlación significativa con el crecimiento en área basal.

- La tendencia de crecimiento en área basal de *Pseudotsuga menziesii* que en los últimos 150 años esta especie ha soportado, es de reducciones hasta del 50% de crecimiento (resistencia), y requiere de 6 a 10 años (resiliencia) para recuperar sus crecimiento a niveles previos al disturbio.

- Cuando las condiciones de precipitación son arriba del promedio histórico, *Pseudotsuga menziesii*, muestra una "memoria" de efecto favorable de crecimiento por los siguientes tres años.

- Como resultado del incremento de CO_2 atmosférico, *Pseudotsuga menziesii*, muestra incrementos significativos en iWUE, sin embargo estos no van asociados con mayor crecimiento, en consecuencia ha habido un ajuste en la relación de fotosíntesis y conductancia estomática. Esto implica que este estudio no muestra evidencias de efecto de fertilización por CO_2 atmosférico.

La respuesta de tres especies de Abies a los incrementos en CO_2 atmosférico

- Como otras especies forestales *Abies concolor, Abies durangensis,* y *Abies guatemalensis*, muestran evidencias de dilución de ^{13}C en la atmósfera.

- El enriquecimiento en ^{13}C fue mayor en *Abies concolor* lo que es consistente con el ambiente más seco donde crece.

- La composición de isotopos de oxigeno ($\delta^{18}O$) en rodales de *Abies* no ha cambiado en los últimos cien años, lo que sugiere que la fuente de agua no se ha modificado en los lugares de estudio.

- *Abies guatemalensis* muestra una firma de $\delta^{18}O$ menor en 5‰ con relación a las otras especies. Esto se explica por la mayor condición de humedad y menor enriquecimiento por evapotranspiración a nivel de la hoja.

- En el último siglo, el incremento en iWUE fue en el siguiente orden, *Abies durangensis* (31%), seguida de *Abies guatemalensis* (28%) y *Abies concolor* (21 %). Estos incrementos caen dentro los valores observados por otros autores.

- Los cambios en discriminación de CO_2 y de iWUE no fueron mayores en el sitio más seco como se había planteado en la hipótesis. El género *Abies* respondió de manera diferente a la reportada para pinos en otros estudios.

- Para el caso del estudio de género *Abies*, se sugiere realizar trabajos más intensivos y el uso de cronologías locales que den más certeza sobre los periodos húmedos y secos de cada lugar.