Dendrochronologia 45 (2017) 145–155

Contents lists available at ScienceDirect

Dendrochronologia

journal homepage: www.elsevier.com/locate/dendro

Original Article

Observed and projected impacts of climate on radial growth of three endangered conifers in northern Mexico indicate high vulnerability of drought-sensitive species from mesic habitats

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ARTICLE INFO

Keywords:
Climate warming
Dendroecology
Emission scenarios
VS-lite growth model
Mexican forests
Threatened conifers

ABSTRACT

A decline in productivity and radial growth in conifer forests from mesic areas has been associated with increased drought stress induced by climate warming. Nevertheless, studies showing how vulnerable tree species will be in response to forecasted warming conditions are scarce in such mesic habitats. Here we address this issue by analyzing how growth responds to drought and to observed and projected climate conditions in a conifer forest from northern Mexico, which is a hotspot of conifer diversity. We quantify the trends in radial growth (quantified as basal area increment, BAI) of three species (*Abies durangensis, Picea chihuahuana, Cupressus lusitanica*) using dendrochronology and a process-based model of tree growth. Growth decreased in *A. durangensis* and *P. chihuahuana* from the late 1980s onwards in response to warmer and drier conditions, whereas *C. lusitanica* growth showed very low sensitivity to precipitation and increased as temperature did. Winter-spring dry conditions adversely affected the growth of *A. durangensis* and *P. chihuahuana*. Our modeling approach anticipates growth reductions and an increase in the vulnerability of *A. durangensis* and the endangered *P. chihuahuana* against the warmer and more arid conditions predicted after the 2050s. Future warmer and drier climatic conditions could reduce the productivity and lead to growth decline of these mesic conifer forests triggering dieback episodes in highly drought-sensitive species as *A. durangensis* and *P. chihuahuana*.

1. Introduction

If global warming continues and drought episodes become more severe, there will be a strong negative impact on forest productivity in xeric but also in mesic areas (Vicente-Serrano et al., 2015; Yi et al., 2015). In forest ecosystems subjected to seasonal drought this stress impact could be manifested in a decrease of radial growth that could result on dieback and increased mortality (Steinkamp and Hickler 2015). Most worrisome is that these phenomena will not only occur in xeric habitats with negative water balances where dry spells are common, but also in those mesic habitats where tree species are adapted to humid conditions (Singer et al., 2013). Several findings from mesic habitats subjected to sporadic droughts suggest that their vulnerability to warmer and drier conditions has been underestimated (Pasho et al., 2011; Vicente-Serrano et al., 2012). In the future, projected warmer temperatures and more severe droughts (reduced soil water availability, increased vapor pressure deficit) could become major forest stressors (Allen et al., 2015). Such linked climate alterations would negatively impact forest productivity by increasing respiration rates and leading to growth decline and dieback (Williams et al., 2013). Therefore, it is important to investigate how growth variability will respond to projected warmer and drier conditions.

Diverse mountain conifer forests from northern Mexico face this climate-related vulnerability because some of them are located in mesic habitats but endure seasonal drought (Seager et al., 2009). These forests hold significant biodiversity values, due to the presence of tree species under different conservation status (endemism, endangered species), and represent one of the most diverse areas of coniferous (Pinophyta) tree species in the world (Farjon 2010; Gernandt and Pérez-de la Rosa, 2014). The Santa Bárbara forest is a typical example of this diverse and protected areas situated in northern Mexico mountains, and its ecological and management peculiarities make it very interesting for addressing ecological questions (Aguirre et al., 2003). Since it is not subject to recent human uses (e.g., logging, grazing), the ecological processes that occur there are exempt from local anthropogenic influences. Recently, this forest is also showing evidences of dieback

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http://dx.doi.org/10.1016/j.dendro.2017.08.006
Received 17 March 2017; Received in revised form 3 August 2017; Accepted 31 August 2017
Available online 01 September 2017

symptoms (Fig. S1, Supporting Information), suggesting declines in growth and productivity. Therefore, these forests are an example of well-preserved but potentially threatened conifers ecosystems that provide multiple environmental services to local communities (Aguirre et al., 2003; Lujan-Soto et al., 2015).

Some of the protected conifer species growing on mesic habitats from northern Mexico mountains include: *Picea chihuahuana* Martinez (Chihuahua spruce), *Abies durangensis* Martinez (Durango fir) and *Cupressus lusitanica* Mill. (Mexican cypress) (Farjon 2010; NOM 2010). Their coexistence provides a unique opportunity to understand the forest growth responses to climatic conditions in order to evaluate how future warming could affect the persistence of these endangered tree species in similar mesic habitats (see for instance González-Casares et al., 2016). Although, some dendroecological studies have been carried out in northern Mexico (e.g., Bickford et al., 2011; Pompa-García and Camarero 2015), there exists a lack of investigations regarding the growth responses of these forests to climate warming, particularly in mesic habitats. So far it is unknown in what way the dynamics of radial growth of these conifer species are linked to climate variability.

This lack of information could be solved in part by calculating the relationships between past climate and radial growth, considering tree secondary growth as a fundamental part of the forest productivity (Rocha et al., 2006; Zweifel et al., 2010). Such climate-growth relationships can also projected as a function of forecasted climate scenarios by using process-based models of tree growth which allow assessing future forest vulnerability (Sánchez-Salguero et al., 2016). This assessment would improve our knowledge on the vulnerability of these threatened conifer species in response to climate warming (Diffenbaugh and Scherer 2011; IPCC 2013), and help develop new management and conservation strategies for warmer and drier climate scenarios as has been done in other less diverse regions as Europe (Lindner et al., 2014).

Here we study the relationships between climate, drought and radial growth to better understand how endangered conifers inhabiting mesic forests in northern Mexico respond to recent climate variability and how projected rising temperatures would affect their vulnerability. We hypothesize that the tree species most sensitive to drought will be the most vulnerable to the projected rise in temperatures due to increased evapotranspiration rates and drier conditions. Lastly, management strategies to preserve these threatened and vulnerable tree species under the forecasted warmer and drier conditions are discussed.

2. Materials and methods

2.1. Study area and field sampling

The study area (Santa Bárbara forest) corresponds to a hotspot of diversity and ecologically valuable mountain forests located in the Sierra Madre Occidental, Durango, northern Mexico (Aguirre et al., 2003). These forests include rare or endemic species of various conifer genera (e.g., *Pinus, Picea, Abies* and *Pseudotsuga*), which are dominant in mesic sites or humid habitats (Fig. S1, Supporting Information). This area is protected by the Mexican Federal Government and it is located at coordinates 23° 50′ 54″ N, 105° 49′ 30″ W, and at an elevation range of about 2500–2800 m a.s.l. The ecological niche of most of these conifer species is characterized by wet conditions (~1200 mm of annual precipitation), under mean annual temperatures of 11–13 °C (García-Arévalo, 2008).

The studied area has permanent drainage and is located in a valley surrounded by plateaus dominated by pine species in dry sites. At the bottom of valleys and canyons we found stands of the three protected species we studied: *Picea chihuahuana* Martinez, *Abies durangensis* Martinez and *Cupressus lusitanica* Mill., the latter always located close to streams (García-Arévalo 2008). Special protection of this area required a strict permission for sampling trees and such protection has allowed the study area to be relatively undisturbed for the last 50 years (García-Arévalo 2008). The study site includes a marked climatic gradient which allowed considering several tree species. However, the site conditions are not necessarily representative of the environmental and climatic conditions where the study species appear across the Sierra Madre Occidental.

The nearest town to the study area is "El Salto", situated about 20 km apart, where climate data were obtained from its climatic station (23° 47′ 00″ N, 105° 22′ 00″ W, 2560 ma.s.l; data for the period 1965–2014; CNA 2016).

To quantify the duration and severity of drought at different time scales, the SPEI (Standardized Precipitation-Evapotranspiration Index) was used because it considers the effects of temperature on evapotranspiration rates (Vicente-Serrano et al., 2010). According to these authors, the SPEI is based on cumulative climate water balances calculated at different time scales by subtracting potential evapotranspiration from precipitation. The SPEI was calculated locally from instrumental climatological data of the "El Salto" station using the SPEI library of the R statistical package (R Core Team, 2017). Since each tree species can show different temporal responses to the accumulated water deficit (e.g., Pasho et al., 2011), monthly SPEI values were calculated at different scales (1–20 months).

2.2. Dendrochronological analyses

In the field, dominant and apparently healthy trees of the three study species were selected, their diameter at 1.3 m or diameter at breast height (DBH) and height were measured using metric tapes and clinometer. Since species are protected in the study area, only 15 trees per species (Table 1) were allowed to be sampled. Trees were bored at 1.3 m using Pressler increment borers. The wood samples were air dried, glued onto wooden supports and polished with progressively finer sandpaper to visualize and cross-date them using characteristic narrow and wide rings. The ring widths were measured at 0.01 mm resolution using the LINTAB device (Rinntech, Heidelberg, Germany). The dating was checked using the program COFECHA, which compares the ring-width series of each tree with a master chronology built for

Table 1
Characteristics of the trees studied. Values correspond to means ± standard errors. Dendrochronological data correspond to the common 1965–2014 period.

Variable	Tree species		
	Picea chihuahuana	*Abies durangensis*	*Cupressus lusitanica*
Altitude (m a.s.l.)	2688 ± 5	2747 ± 36	2651 ± 8
DBH (cm)	53.4 ± 3.5	36.3 ± 2.1	31.5 ± 1.9
Height (m)	21.9 ± 0.8	18.1 ± 0.9	16.4 ± 0.7
Age at 1.3 m (years)	137 ± 11	89 ± 3	96 ± 10
Number of trees (Number of radii)	15 (25)	15 (28)	15 (22)
Tree-ring width (mm)[a]	2.28 ± 0.26	2.05 ± 0.21	1.35 ± 0.12
AC, first-order autocorrelation[a]	0.81	0.72	0.68
Correlation among trees[b]	0.29	0.49	0.22
MS [b]	0.27	0.29	0.23
Rbar[b]	0.24	0.47	0.19
EPS[b]	0.87	0.96	0.71
PC1 (%)[b]	36.3	53.2	31.0

Variables: MS, mean sensitivity, a variable quantifying the mean relative change in width between consecutive rings calculated as the absolute difference between consecutive ring-width indices divided by their mean value; Rbar, a measure of the common variance between the single series in a chronology; EPS, Expressed Population Signal, a measure of the common variability in a chronology which depends on sample depth; PC1, percentage of variance accounted for by the first principal component of a Principal Component Analysis estimated on the matrix of ring-width indices. See Fritts (1976, 2001) and Briffa and Jones (1990) for details on the calculations of these variables.

[a] Variables calculated on tree-ring width data.

[b] Variables calculated on ring-width indices.