

## RECONSTRUCTING EVAPORATION FROM PINE TREE RINGS IN NORTHERN MEXICO

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### ABSTRACT

Here we reconstructed evaporation using tree-ring width variability. Drought variability and its effects on forest growth have been mainly characterized by changes in precipitation and temperatures, whereas atmospheric drought and evaporation rates have been little investigated. The area of study corresponds to northern Mexico, a region where water resources are increasingly limited. We used correlation analyses to identify the months in which evaporation is most strongly related to tree-ring width series. Then, we built a linear regression model to predict seasonal winter-to-spring evaporation as a function of ring-width indices. Correlation analyses showed that the radial growth of *P. cooperi* decreased in response to reduced water availability and increased evaporation during the winter prior to the growing season, and also during spring and the early summer of the year of tree-ring formation. Pine growth mainly benefitted from wet and cool conditions from winter to early spring. Linear regression models used in reconstruction were statistically robust and allowed reconstructing January-to-April evaporation for the period 1900–2010. Our study contributes to a better understanding of historical changes in evaporation in northern Mexico and, most importantly, it also emphasizes how atmospheric moisture demand is linked to tree growth.

*Keywords:* atmospheric moisture demand, tree rings, *Pinus cooperi*, dendrochronology, growth–climate relationships, evaporation, SPEI.

### INTRODUCTION

Sustainable management of water resources requires quantifying the duration and intensity of critical hydrological events such as droughts (Meko *et al.* 1991; Touchan *et al.* 2008; Stahle *et al.* 2011). Reconstructing water availability on annual to decadal time scales through an adequate assessment of ecological proxies is a prerequisite for that long-term quantification (*e.g.* Meko and Graybill 1995). However, an adequate characterization of the proxy response to aridity is also essential to infer how hydrological and ecological systems are coupled (Fritts 2001).

Various mega-droughts have recently occurred in North America according to dendrochronological reconstructions (Cook and Krusic 2004). These reconstructions were made possible

through the use of the Palmer Drought Severity Index (PDSI), although the main limitation of PDSI is an inherent time scale making PDSI more suitable for agricultural impacts and less so for hydrologic droughts (Mishra and Singh 2010). A large number of PDSI reconstructions implicitly include potential evaporation through the calculation of water balance using for instance the Thornthwaite equation (*e.g.* Cook and Krusic 2004). However, the algorithms used for estimating potential evaporation are mainly based on temperature alone, and therefore will not accurately estimate the actual amount of water that escapes to the atmosphere from the Earth's surface. Consequently, those estimates provide only a partial picture of actual drought stress experienced by vegetation relative to direct measures of evaporation.

Several factors apart from rising temperature and decreased precipitation affect drought development (Sheffield and Wood 2008; Seneviratne

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2012). For example, wind speed, relative humidity and solar radiation should all be taken into account for assessing hydroclimate conditions and drought severity (Palamuleni *et al.* 2011). In addition, some ecologists argue that climate warming is increasing evaporative demand (rising vapor pressure deficit) and causing growth decline in many forest types (Kempes *et al.* 2008; Williams *et al.* 2013). In fact, warming-related drought stress is becoming a major triggering driver of forest dieback not only in semiarid but also in temperate ecosystems (Sarris *et al.* 2007; Camarero *et al.* 2011; Candel-Pérez *et al.* 2012). However, other climatologists claim that in dry conditions, maximum temperature anomalies are likely to be a response to drought, rather than a forcing factor *per se* (Sheffield *et al.* 2012).

Consequently, it is necessary to quantify how forest growth responds to hydroclimate conditions, including related variables such as drought and evaporation (hereafter abbreviated as *E* and according to Shuttleworth (1993), which is defined as the rate of liquid water transformation to vapor from open water, bare soil, or vegetation with soil beneath). Although many efforts have been carried out to reconstruct climatic variables such as precipitation and water deficit (Meko and Graybill 1995; Touchan *et al.* 2008; Burnette and Stahle 2013), to our knowledge *E* has received much less attention. Understanding how water availability and *E* vary through time and affect tree growth is essential to forecast the impacts of ongoing climate warming on forests, particularly in dry and semiarid areas. However, instrumental weather records are rarely available before the 1950s in many of those areas, restricting analysis to climate variability compared to what could be done at sites with long climatic records such as cities. This is the case of northern Mexico where hydroclimatic proxies have been little investigated despite water availability being continuously reduced by increasing demand and recent drought spells (Seager *et al.* 2009).

Dendrochronology (the study of tree rings) could improve understanding of how *E* affects tree growth. Tree-ring width chronologies are increasingly being applied to reconstruct hydroclimate variability in Mexico (Diaz *et al.* 2002; Therrell

*et al.* 2004; Stahle *et al.* 2011). These dendroclimatic reconstructions have been based on *Pinus cooperi* C.E. Blanco (or *Pinus arizonica* var. *cooperi* (C.E. Blanco) Farjon; henceforth *Pinus cooperi*). This is a conifer endemic to Mexico and dominant tree species in the Sierra Madre Occidental, one of the main Mexican ranges, where it is used for wood production (Cruz *et al.* 2008). Further, the wide ecological amplitude of this species provides a good opportunity to evaluate how drought, measured at different time scales, and *E* constrain tree growth (Pompa-García *et al.* 2013). Here, it must be emphasized that Mexico has more native pine species than any other country in the world (Farjon 2010). Consequently, Mexican pine forests represent a valuable ecological monitor of drought and *E* changes through time in Mesoamerica. Here we aim to quantify the main climatic drivers of *P. cooperi* radial growth as a previous step to reconstruct the historic variability of seasonal *E* associated with changes in tree-ring width. Such historical reconstruction of past hydroclimatic variability should aid sustainable water management under different climatic and ecological scenarios.

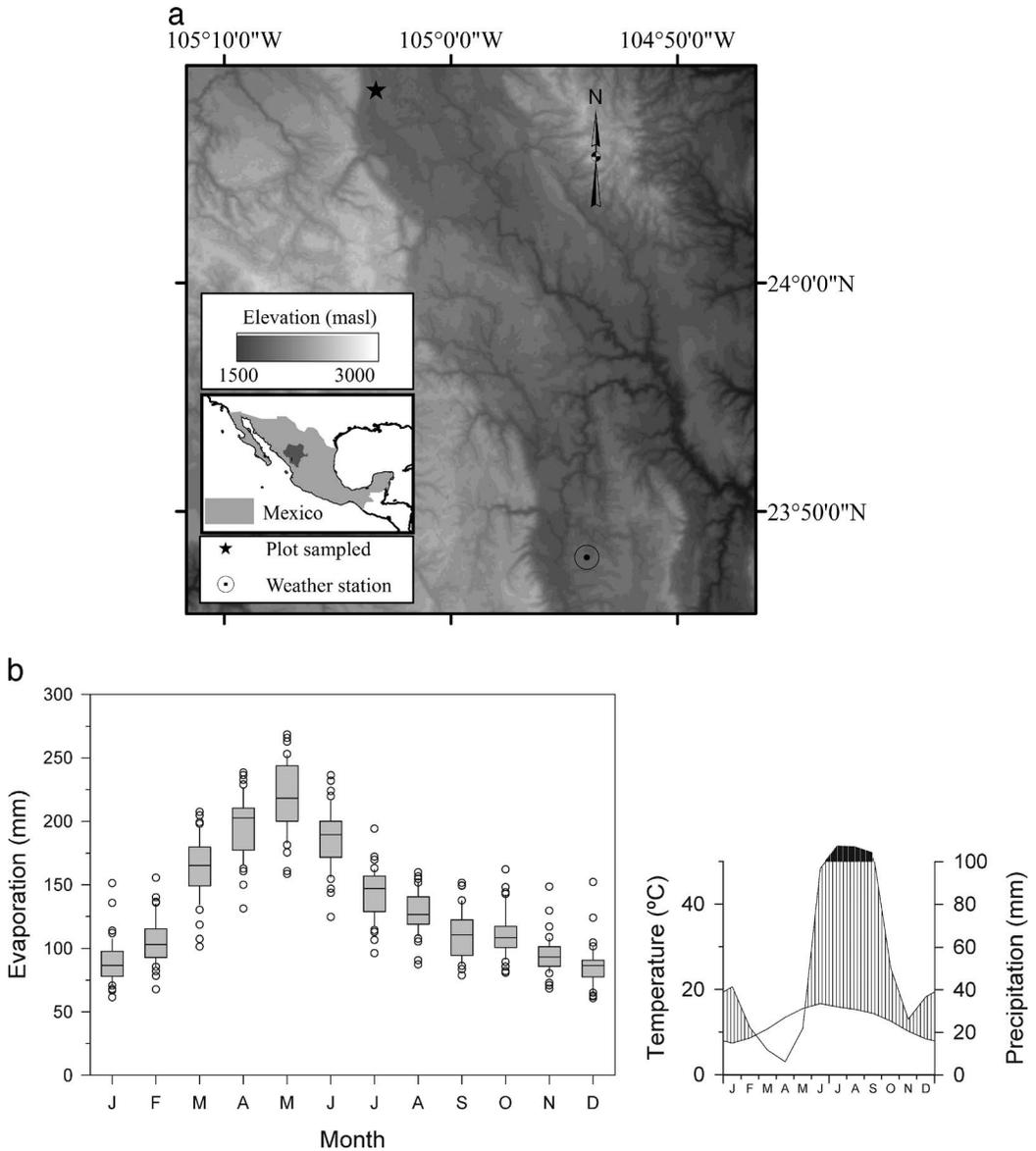
## MATERIAL AND METHODS

### Study Area

Two *Pinus cooperi* stands located in Sierra Madre Occidental in the state of Durango, northern Mexico (24°8' 27" N, 105°3' 18" W, and 24°4' 43" N, 105°1'15" W) were chosen for sampling (Figure 1). Trees were growing under marginal environmental conditions characterized by thin and rocky soils, moderate slopes (5–10%) and southeastern exposure. This region experiences a temperate sub-humid climate with a wet and cool summer period caused by the monsoon influence, and also characteristic dry seasons (spring, winter) (Figure 1). The maximum monthly *E* values are observed in April and May (Figure 1). Soils in the study area are cambisols, lithosols, regosols and feozems (Pompa-García *et al.* 2013).

### Field Sampling

Ten dominant trees separated by at least 10 m from each other were randomly selected



**Figure 1.** The study site (a) is located in northern Mexico, where the period from late fall up to early summer is moderately dry according to the climatic diagram (b) of the nearest weather station (Santa Barbara) and mean evaporation data for the period 1965–2010.

in the stand, sampled, and used in further analyses. We avoided injured, declining, dead or deformed trees, as well as those whose growth may have been influenced by competition. The mean diameter of trees measured at 1.3 m height was 47.1 cm. We extracted at least three increment cores from each tree at 1.3 m height using a Pressler increment borer. Cores were air

dried, mounted, and sanded before being visually cross-dated using the procedures described by Stokes and Smiley (1996). Cores were then measured to 0.001 mm precision using a Velmex measuring stage. The quality of the dating was statistically checked using the computer program COFECHA (Holmes 1983; Grissino-Mayer 2001).

## Chronology Building

The biological and geometric trends not related to climate were removed to emphasize the climatic signal and to maximize the relationship between climatic variables and radial growth (Fritts 2001). Each ring-width series was double-detrended and then standardized using the ARSTAN software (Cook 1985; Cook and Holmes 1996). The series were first fitted to a negative exponential function, and then to a cubic smoothing spline with a 50% frequency response of 64 years, which was flexible enough to reduce the non-climatic variance while preserving high-frequency (yearly to sub-decadal) climatic information. Detrending was followed by transforming tree-ring widths to dimensionless growth indexes by dividing observed ring width values by fitted values. The resulting series were pre-whitened by autoregressive models to remove temporal autocorrelation. Finally, a biweight robust mean was computed on a year-by-year basis to obtain a regional chronology that was used in all subsequent analyses.

The statistical quality of the chronology was assessed by means of the following parameters calculated over the common interval (1900–2010): mean tree-ring width (TRW) and standard deviation (SD), mean sensitivity ( $ms_x$ ; a measure of the year-to-year variability in width of consecutive tree rings), mean between-trees correlation ( $r_{bt}$ ; a measure of the similarity in growth among trees), Expressed Population Signal (EPS; a measure of the statistical quality of the mean site chronology as compared with a perfect infinitely replicated chronology), first-order autocorrelation (AC; a measure of the year-to-year growth similarity), percent of variance accounted for by the first principal component (PC1, an estimate of the common variability in growth among all trees at each site), and Signal-to-Noise Ratio (SNR; a measure of the strength of the common high-frequency signal in the ring-width indices of trees from the same site; Cook and Kairiukstis 1990). The chronology segment with  $EPS > 0.85$  was considered as the common interval that was statistically reliable (Wigley *et al.* 1984).

## Climate Data

We used local monthly climatic variables (mean maximum and minimum temperatures,

precipitation,  $E$ ) available for the years 1965 to 2010 and taken from the Santa Barbara meteorological station (CNA 2012), which is located about 5 km from the sampling sites (Figure 1). The evaporation term includes all processes in which liquid water is transferred as water vapor to the atmosphere (Eagleman 1967). Throughout this paper,  $E$  refers to pan evaporation which represents evaporation from a free water surface, and might approximate evaporation from a lake, but under dry conditions could depart greatly from actual evapotranspiration from a forest, *i.e.*  $E$  plus transpiration from the leaves through stomata (Eagleman 1967; McMahon *et al.* 2013). Here pan evaporation is measured using a class-A evaporation circular pan with a standard screen located 30 to 50 mm above the ground, which is a widely used method throughout meteorological stations around the world (WMO 2006). We correlated the *P. cooperi* residual chronology and climatic variables for the period 1965–2010 by calculating Pearson correlation coefficients using the program DendroClim2002 (Biondi and Waikul 2004). Correlations were obtained from October of the previous year, the one before tree-ring growth, up to September of the year of tree-ring formation based on recent analyses performed by Pompa-García *et al.* (2013).

To study the impact of drought severity on *P. cooperi* growth, we employed a multiscalar (time-dependent) drought index, the Standardized Precipitation–Evapotranspiration Index (SPEI), which is calculated using precipitation and explicitly includes the effect of temperature on  $E$  and water availability (Vicente-Serrano *et al.* 2010). Positive and negative SPEI values correspond to wet and xeric conditions, respectively. The SPEI was used to analyze the influence of drought on tree growth by calculating Pearson correlations at time scales ranging from 1 to 24 months (see Pasho *et al.* 2012).

Finally, to detect the geographical patterns of climate-growth associations, we compared the chronology to regional climatic data (mean temperature, total precipitation, SPEI calculated at 4- and 8-months long scales) derived from the 0.5°-gridded CRU TS 3.1 dataset produced by the Climate Research Unit (Mitchell and Jones 2005). The geographical patterns were expressed in maps

**Table 1.** Dendrochronological statistics of the *Pinus cooperi* chronology calculated for the period 1900–2010.

Standard Chronology				Residual Chronology				
No. Trees/No. Radii	TRW (mm)	SD (mm)	AC	ms <sub>x</sub>	r <sub>tb</sub>	EPS	PCI (%)	SNR
20/25	2.02	1.42	0.67	0.37	0.49	0.87	56.8	6.75

See text for explanation of abbreviations used.

showing the main field correlations and produced using the web-based KNMI Climate Explorer (<http://climexp.knmi.nl>).

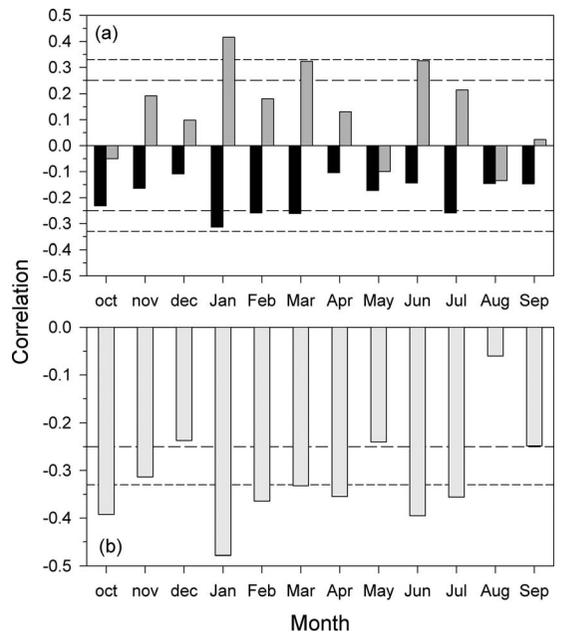
### Evaporation Reconstruction

Correlation analyses identified those monthly climatic factors most strongly and significantly ( $P < 0.05$ ) related to tree growth. Then, we proceeded to build a regression model based on seasonal climatic variables, which showed strong and temporally stable associations with the regional chronology such as cumulative winter-spring evaporation, specifically from previous January to April up to current April. Such transfer-function analysis is a linear regression model in which the tree-ring indices are the predictors and the seasonal  $E$  are the predictands. This model was evaluated using regression statistics such as  $R^2$  (Meko 1997). Then, a split-sample procedure was also used to verify model stability (Meko and Graybill 1995; Touchan *et al.* 2008). This divides the full period into two subsets (1965–1985 and 1986–2010), which were used as calibration and verification periods, respectively. The reduction of error statistic (RE) was calculated to test for skill beyond that possible simply by using the calibration period mean of observed precipitation as the reconstruction. The value of RE theoretically ranges from minus infinity to +1.0, and an RE value greater than 0 is considered positive skill of the model (Fritts 2001). The calculated transfer function was then applied to the regional chronology to obtain the time series of reconstructed seasonal  $E$ . All regression analyses were performed with the SAS statistical software (SAS 2004).

## RESULTS

The tree-ring chronology was well replicated and trees presented common growth patterns and

a high year-to-year variability, probably in response to climate (Table 1). Climate-growth correlations indicated that *P. cooperi* growth responded positively to water availability in January, March and June, but negatively to maximum temperatures in January, March and July (Figure 2a). This finding confirms that radial growth greatly depends on winter climatic conditions previous to the growing season. Increased  $E$  values during particular months (previous October, January, February to April, June to July) were strongly associated with narrow tree rings (Figure 2a). Consequently, the



**Figure 2.** Correlation functions calculated between *P. cooperi* indexed tree-ring widths and monthly climatic variables: (a) mean maximum temperature (black bars) and precipitation (grey bars); (b) evaporation. Correlation coefficients were calculated considering months previous to (abbreviated by lowercase letters) or during the year of tree-ring formation (abbreviated by upper-case letters). Inner dashed lines =  $P < 0.05$ , outer lines =  $P < 0.01$ .

chronology showed the main responses to drought, quantified using the SPEI, in January and June–July for short (1–2 months) and intermediate (8–11 months) time scales (Figure 3a and 3b). Both responses to drought were spatially focused in northern Mexico, suggesting the geographical consistency of growth responses to water deficit (Figure 3c).

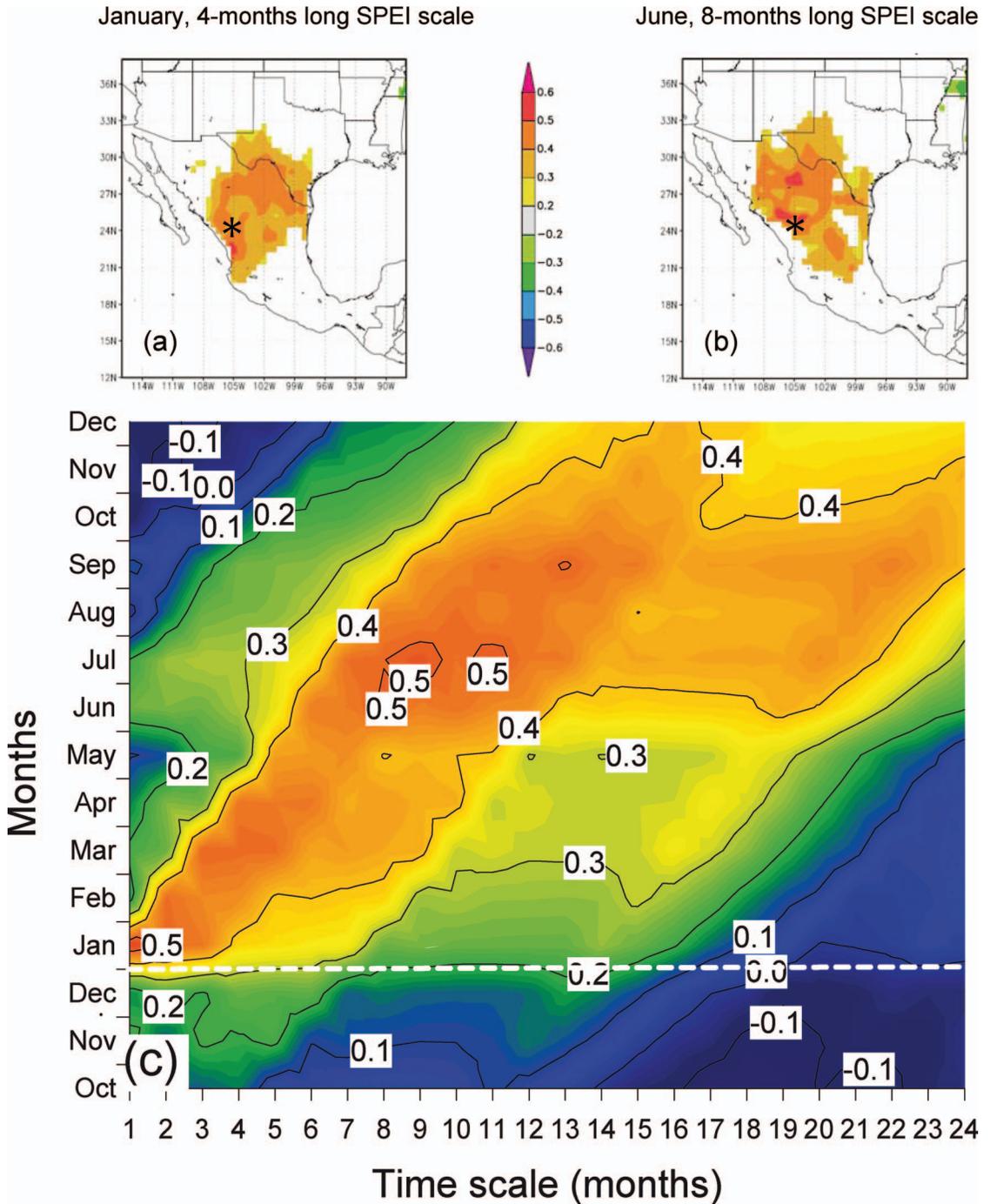
The strongest responses of the tree growth to any climatic variable were observed in response to monthly, seasonal or annual cumulative  $E$  (Figure 4). The regional tree-ring chronology showed a much stronger association with annual  $E$  ( $r = -0.63$ ,  $P < 0.001$ ), accumulated from the previous October up to the current September, than with total precipitation ( $r = 0.25$ ,  $P = 0.09$ ) or mean maximum temperature ( $r = -0.29$ ,  $P = 0.06$ ) during the period 1965–2010. Observed  $E$  showed prominent high (e.g. 1978, 1989 and 2000) and low (e.g. 1968, 1985 and 2002) values corresponding to low and high ring-width indices, respectively. The seasonal (January–April)  $E$  reconstruction and related statistics indicate satisfactory predictive capability (Figure 5). The RE was 0.76, indicating there is reconstructive capacity in the model. Observed and modeled seasonal  $E$  values for the same periods also showed significant correlations ( $r = 0.75$ , period 1965–1985;  $r = 0.82$ , period 1986–2010;  $P < 0.01$  in both cases). The corresponding transfer models explained 56% and 68% of evaporation for the calibration and verification periods, respectively. The reconstruction explained 42% of the seasonal  $E$  variability during the period 1965–2010, reflecting well its temporal variability except during years with extreme  $E$  values, for example those higher than the 95% confidence intervals (e.g. 1999 and 2000).

## DISCUSSION

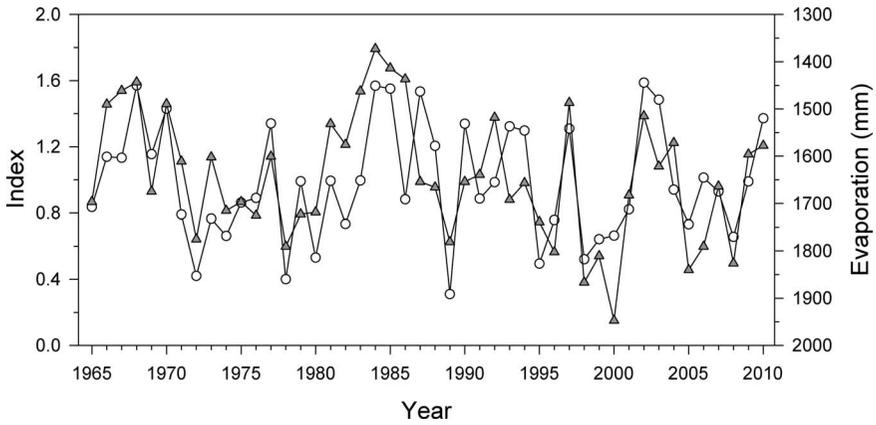
Northern Mexico *P. cooperi* trees responded to water availability, drought and evaporation. The pines benefitted from wet and cool conditions from winter to early spring (January to March), suggesting that cooler temperatures would ensure more water remained available for tree growth, *i.e.* less evapotranspiration. In fact, tree growth responded most strongly to January evaporation,

confirming the importance of climatic conditions that precede the start of the growing season. Tree-ring width chronologies of *P. cooperi* represent a valuable and robust proxy of evaporation in scarcely explored areas such as the Sierra Madre Occidental, where water, biodiversity and forest resources represent valuable ecosystem services to local populations (Pompa-Garcia *et al.* 2013). Our results provide the first reliable dendrochronological reconstruction of seasonal evaporation in northern Mexico. We noted that reduced growth coincided with regional droughts (e.g. 1970s, late 1990s) reported in nearby areas (Díaz *et al.* 2002). Furthermore, the values of dendrochronological statistics reflecting common growth coherency among and within trees and high year-to-year variability in growth were similar to those reported for chronologies of other conifers growing in northern Mexico (Cleaveland *et al.* 2003; Therrell *et al.* 2004; Bickford *et al.* 2011).

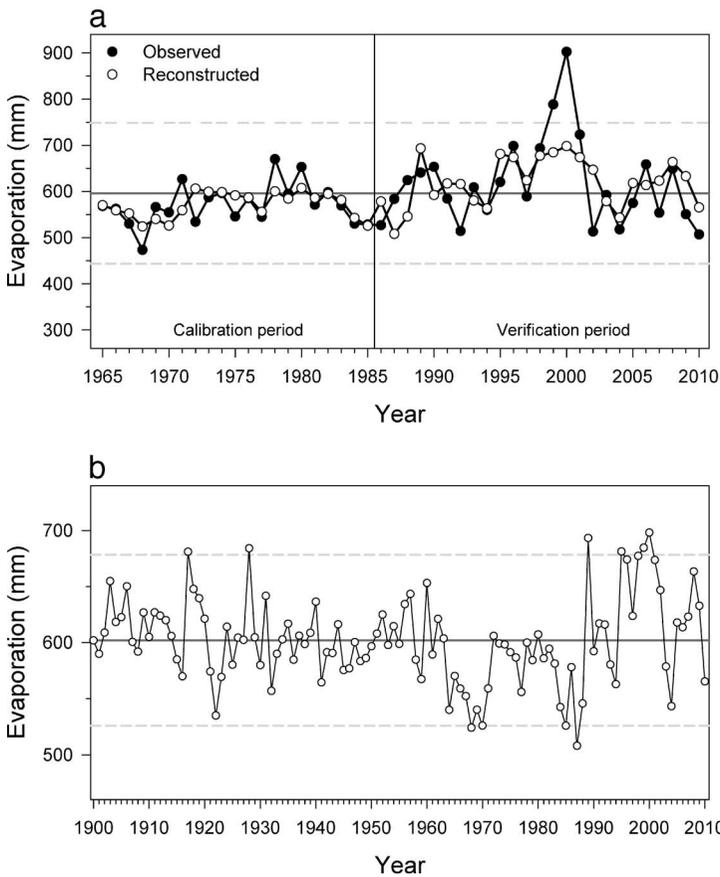
Higher water availability during previous-fall to winter and current spring and early-summer is associated with enhanced growth of *P. cooperi* in the study area. Such wet conditions correspond to low mean maximum temperatures and reduced evaporation rates, but also to high mean minimum temperatures and precipitation amounts (see this study and also Pompa-Garcia *et al.* 2013). The negative responses of tree growth to monthly, seasonal or annual evaporation rates indicate drought stress (Adams and Kolb 2005). Such stress may be the response of enhanced stomatal transpiration to higher temperatures and radiation levels and increased vapor pressure deficit (Guehl and Aussenac 1987). *Pinus cooperi* seems to present a rapid “avoidance strategy” in response to water deficit and rising evaporation rates by reducing growth probably caused by previous stomatal closure and diminishing photosynthetic assimilation rates. High evaporation rates could also enhance tree respiration and stand evapotranspiration, thereby resulting in increased water deficits (Huang *et al.* 2010). Drought stress may reduce the assimilation of carbohydrates during fall and winter, which would be used later for building earlywood during the following spring (Camarero *et al.* 2010; Linares and Tíscar 2010). This could explain the contrasting growth responses to drought before



**Figure 3.** Growth responses to drought stress (estimated using SPEI) of *P. cooperi* indexed tree-ring widths are strongest in January (a) and June-July (b) for short (4 months) and mid (8 months) time scales. The lower plot (c) shows the correlation of SPEI and width indices for several time scales (x-axis) and from the previous October up to the current December (y-axis). In the lowermost graph the white dashed line separates the year of tree-ring formation (above the line) from the previous year (below the line). The upper maps (a, b) show the most important field correlations between *P. cooperi* indexed growth indices and SPEI  $0.5^\circ$  gridded data for 4-month and 8-month time scales (the asterisk indicates the study site).



**Figure 4.** Evaporation is related to *Pinus cooperi* growth as shown by the significant and inverse relationship obtained between tree-ring indices (circles) and cumulative evaporation (triangles) from previous October to current September. Note that the secondary y-axis on the right goes from low to high evaporation values to accentuate the inverse relationship of evaporation with tree growth.



**Figure 5.** Observed and reconstructed winter-spring evaporation based on indexed *P. cooperi* tree-ring widths for the periods 1965–2010 (a) and for 1900–2010 (b). Continuous and dashed lines indicate the average and 95% confidence intervals ( $\pm 1.96$  SD) of the observed and reconstructed evaporation data in the upper and lower figures, respectively.

(e.g. January) or during (e.g. June) the growing season (compare Figures 2 and 3). The growth response to water deficit was stronger and occurred at shorter time scales during the previous winter months. Such rapid reaction to water scarcity may translate into reduced stored carbohydrates to form wood once cambial activity reactivates in spring. On the other hand, spring growth responses to drought were lower than in the previous winter and happened at longer time scales suggesting lagged reactions to cumulative water deficit during the growing season. These different responses highlight the importance of climatic conditions controlling drought severity and evaporative demand before the growing season starts for pine radial growth (Pasho *et al.* 2012; Camarero *et al.* 2013).

Previous dendroclimatological studies in Mexico usually related changes in tree-ring width to rainfall or temperature data (Cleaveland *et al.* 2003; Villanueva-Díaz *et al.* 2007; Stahle *et al.* 2011). Those studies assumed that drought is induced by a deficit in the water balance being caused by lower precipitation and/or warmer temperatures. Using these climatic variables as drivers of drought stress may actually be a misinterpretation of feedbacks between the land and the atmosphere because in dry conditions, maximum temperatures anomalies are likely to be a response to drought (Sheffield *et al.* 2012). Consequently, such formulations neglect the role of evaporation as a consequence of several other climate drivers such as wind or radiation, which vary on time scales shorter than long-term temperature trends (Shuanghe and Qiong 2009). Here we show that seasonal evaporation may be directly reconstructed using changes in radial growth. Our pilot study indicates that additional effort should be invested to search for dendrochronological proxies (density, wood-anatomical features, isotope composition) as a source of climatic information related to “atmospheric drought”, *i.e.* evaporative demand.

Our findings have notable implications to interpret the role played by evaporation on how trees react to drought stress. According to Muller *et al.* (2011), drought affects primary growth much earlier than photosynthesis activity constrains tissue formation. Here we show that secondary growth is also very sensitive to water deficit and high

evaporation rates, which suggests that evaporation by itself may be a likely direct driver of growth decline and forest dieback rather than warmer temperatures or low rainfall (Liang *et al.* 2008). Under moderately or severely dry conditions, warmer air temperatures may raise the evapotranspiration rates leading to negative growth responses as has been observed in Mediterranean conifers (Martínez-Vilalta *et al.* 2008; Lebourgeois *et al.* 2012). Observational and experimental research should go further on this issue to disentangle how evaporative demand (vapour pressure deficit) controls tree growth and survival (McDowell and Allen 2015). Indeed, increasing atmospheric demand for moisture has been revealed as a major driver of global tree mortality in large forest die-off events (Breshears *et al.* 2013; Williams *et al.* 2013).

Recently, dendrochronologists have targeted earlywood and latewood width (Griffin *et al.* 2011, 2013; Pasho *et al.* 2012). They reported that seasonally-resolved width variability contains strong climate signals. These proxies provide novel prospective paleoclimatology and could reveal valuable seasonal evaporation variations. Additional *P. cooperi* ring-, earlywood and latewood width chronologies from more sites should be made available for further research on World Data Center for Paleoclimatology ([www.ngdc.noaa.gov/paleo/contrib.html](http://www.ngdc.noaa.gov/paleo/contrib.html)).

We demonstrate that radial growth of *P. cooperi* was constrained by drought stress related to high evaporation rates during the previous winter and the current spring. Tree-ring widths of this species constitute a potential proxy to reconstruct evaporation in northern Mexico pine forests and in other areas where those meteorological records do not exist. Dry and hot winters in northern Mexico negatively affect forest productivity. This negative impact indicates that rising evaporation rates constitute a major driver of drought stress and could lead to growth decline.

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