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Key Points:
- We developed a new drought reconstruction for the NE Iberian Peninsula on an total of 774 latewood width series from 387 trees
- The reconstruction extended back 279 years from 1734 to 2013 A.D., the first drought reconstruction using the novel SPEI index
- This is the first drought reconstruction in Europe based on latewood width proxies which elicits new possibilities for paleoclimatic studies

Supporting Information:
- Supporting Information S1

Correspondence to:
E. Tejedor,
etejedor@unizar.es

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Summer drought reconstruction in northeastern Spain inferred from a tree ring latewood network since 1734

E. Tejedor[1,2], **M. A. Saz**[1,2], **J. Esper**[3], **J. M. Cuadrat**[1,2], **and M. de Luis**[1,2]

[1]Department of Geography and Spatial Planning, University of Zaragoza, Zaragoza, Spain, [2]Environmental Sciences Institute, University of Zaragoza, Spain, [3]Department of Geography, Johannes Gutenberg University, Mainz, Germany

Abstract Drought recurrence in the Mediterranean is regarded as a fundamental factor for socioeconomic development and the resilience of natural systems in context of global change. However, knowledge of past droughts has been hampered by the absence of high-resolution proxies. We present a drought reconstruction for the northeast of the Iberian Peninsula based on a new dendrochronology network considering the Standardized Evapotranspiration Precipitation Index (SPEI). A total of 774 latewood width series from 387 trees of *P. sylvestris* and *P. uncinata* was combined in an interregional chronology. The new chronology, calibrated against gridded climate data, reveals a robust relationship with the SPEI representing drought conditions of July and August. We developed a summer drought reconstruction for the period 1734–2013 representative for the northeastern and central Iberian Peninsula. We identified 16 extremely dry and 17 extremely wet summers and four decadal scale dry and wet periods, including 2003–2013 as the driest episode of the reconstruction.

Plain Language Summary We developed a new drought reconstruction for the NE Iberian Peninsula based on a total of 774 latewood width series from 387 pine trees. The reconstruction extended back 279 years from 1734 to 2013 AD. This is the first drought reconstruction using a novel drought index which allows the identification of different drought types and impacts in the context of global warming. We identify 16 extremely dry and 17 extremely wet summers since 1734 AD. Besides, some of these years coincide with other drought reconstruction in Europe suggesting large-scale synoptic drivers. In addition, this is the first reconstruction in Europe based on latewood width proxies which elicits new possibilities for paleoclimatic studies.

1. Introduction

Rising temperatures and ecosystem changes are explicit evidences of a warming climate since the beginning of the instrumental period [*Rohde et al.*, 2013]. According to the *Intergovernmental Panel on Climate Change (IPCC)* [2013], mean global surface temperature will continue rising in the 21st century, with a greater risk of hydroclimatological extremes [*Wetherald and Manabe*, 2002]. Several studies identified Spain as a highly vulnerable region [*IPCC*, 2013] suggesting that drought intensity and recurrence has increased during the second half of the twentieth century [*Vicente-Serrano et al.*, 2011, 2014]. Yet the extent to which the severity of drought recurrence can be determined is limited by the short duration of instrumental measurements [*Redmond*, 2002].

Trees are excellent proxies for high-resolution climate reconstruction [*Fritts*, 1976; *Schweingruber*, 1988]. In fact, several paleoclimatic studies have led to a deeper understanding of temperature and precipitation dynamics in central and northern Europe over past millennia [*Büntgen et al.*, 2005, 2011; *Esper et al.*, 2012]. In southern Europe, temperature reconstructions have also contributed to increase our knowledge on climate dynamics [*Büntgen et al.*, 2008; *Dorado-Liñán et al.*, 2014; *Luterbacher et al.*, 2016; *Tejedor et al.*, 2017].

In addition to tree ring width, maximum latewood density demonstrated to be a particularly useful proxy for reconstructing warm season temperatures in boreal regions [see, e.g., *Briffa et al.*, 1992; *D'Arrigo et al.*, 2004; *Esper et al.*, 2010]. Latewood measurements have also been used in the United States as proxies to infer summer precipitation [*Meko and Baisan*, 2001; *Griffin et al.*, 2011] and to reconstruct North American monsoon precipitation [*Griffin et al.*, 2013]. Nevertheless, despite recent advances, drought reconstructions are not very common, and assessments of the frequency, persistence, and magnitude of preinstrumental droughts remain poorly explored (see *Rodrigo et al.* [1999] using historical documents or *Esper et al.* [2015], *Cook et al.* [2015], and *Tejedor et al.* [2016] using tree ring widths as exceptions).

The Standardized Precipitation Evapotranspiration Index (SPEI) is a recently developed index quantifying drought magnitude and persistence and hence identifies the onset and end of drought events [*Vicente-Serrano et al*., 2010]. The SPEI can be calculated over a wide range of climates, allowing comparison of drought severity through time and space. Unlike other indices, the SPEI considers multiscalar characteristics supporting the identification of different drought types and impacts in the context of global warming [*Vicente-Serrano et al*., 2010]. Although recent advances in linking SPEI with tree ring proxies have been achieved [*Seftigen et al*., 2015], a SPEI reconstruction for Mediterranean regions is still missing.

In Mediterranean environments, summer droughts are the main limiting factor of plant growth [*de Luis et al*., 2011, 2013, *Novak et al*., 2016]. In these ecosystems, drought stress reduces cambial activity and morphologically different cells are formed: smaller in diameter but with thicker cell walls (latewood cells) [*Larson*, 1964; *Denne and Dodd*, 1981; *Timell*, 1986; *Schweingruber*, 1988]. Therefore, the width of latewood is expected to be related with the intensity of the summer drought (SPEI). It is thus important to improve our understanding on summer droughts and pluvials, also due to the mitigating effects on reservoirs and aquifers supplying water for various socioeconomic activities including tourism and the irrigation of fields.

In this study, we hypothesize that in middle-to-high elevation Mediterranean forests, latewood width is significantly related with the SPEI and that developing a latewood chronology will enable reconstructing summer SPEI over longer periods. We aim to (i) test the relationship between latewood formation and summer SPEI, (ii) develop for the first time a latewood-based SPEI reconstruction using a new dendrochronological network in northeastern Iberia, (iii) evaluate the spatial extent of SPEI signals, and (iv) identify extremely dry and wet periods over the past three centuries.

2. Materials and Methods

2.1. Study Area

The new tree ring network of 22 sites is distributed across the Iberian Range and the Pyrenees in northeastern Spain (Figure 1 and Table S1 in the supporting information). The area includes the great depression of the Ebro Valley, separating the Pyrenees in the north and the Iberian Range in the south. Due to the dominance of forestry and farming activities in the mountains and the recurrence of forest fires, locations with old trees are limited to high-altitude sites and less accessible areas. Elevation of the sampling sites ranged from 800 to 2100 m above sea level (asl). The higher elevation sites are characterized by cold winters, frequent frosts, and mild summers. Mean annual precipitation is 680 mm, with minimum levels in summer. Maximum precipitation occurs during spring in the western and autumn in the eastern parts of the network. According to their plasticity and adaptation to bioclimatic conditions, *Pinus sylvestris* can be found from 800 to 2000 m asl, whereas *Pinus uncinata* only covers the highest elevations at its southern distribution limits in Europe.

2.2. Tree Ring Network

The tree ring network is composed of 138 *Pinus uncinata* and 249 *Pinus sylvestris* trees. Samples were collected during field campaigns in 2013 and 2014, i.e. the outermost complete ring is from 2013 (Table S1). The network includes dominant and codominant trees of different age and size classes. Maximum, minimum, and average ages are 419, 41, and 232 years, respectively. Two core samples were extracted from each tree at breast height (1.3 m) and processed according to standard procedures [*Stokes and Smiley*, 1968]. Each sample was scanned to identify and date the exact position of the annual rings, and the image software CoRecorder 8.1 [*Larsson*, 2012] was used to objectively define the exact position of the transition between latewood and earlywood. Transitions were thereafter visually cross checked [*Stahle et al*., 2009] (see Figure S1). Earlywood and latewood of each tree ring were measured separately at 0.01 mm precision using a LINTAB table [*Rinn*, 2005], and crossdating was verified using the COFECHA software [*Holmes*, 1983].

2.3. Chronology Development

To evaluate coherence within the northeastern Spanish network, we calculated a correlation matrix of the 22 detrended latewood site chronologies. To remove biological trends and other perturbation effects in radial growth, the latewood series were standardized following the approach detailed in *Tejedor et al*. [2017]. This standardization method is based on the principles of regional curve standardization [*Mitchell*, 1967; *Briffa et al*., 1992; *Esper et al*., 2003]. Nevertheless, instead of considering the cambial age of the trees as the independent variable, we used their (stem) basal area in the year prior to ring formation. Indices were

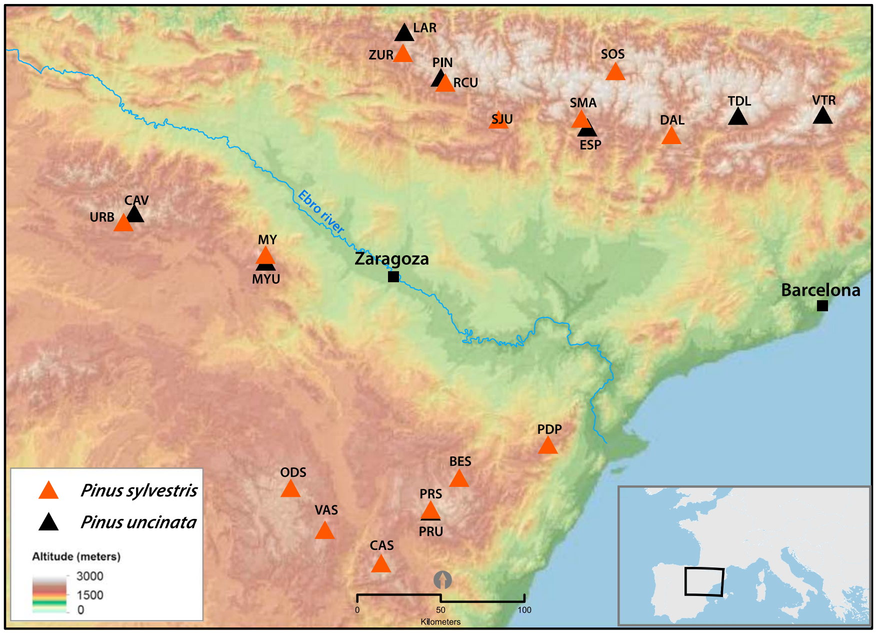

Figure 1. *Pinus sylvestris* and *Pinus uncinata* latewood network in northeastern Spain.

derived by calculating ratios between observed and predicted latewood values using a Poisson regression model, and a biweight robust mean was applied to develop a network composite chronology (BasPoisLW).

Chronology confidence was estimated using running interseries correlations (Rbar) and the express population signal (EPS) metric [*Wigley et al*., 1984]. The resulting latewood width (LW) chronology and basic statistics are detailed in Figure S2 and Table S2.

2.4. Climate Data, Calibration, and Transfer Model

We used monthly mean, maximum, and minimum temperatures as well as precipitation data from the gridded (0.5° resolution) Climate Research Unit TS v.3.23 data set [*Harris et al*., 2014]. The climate series from 18 grid points covering the tree ring network were averaged to develop a regional time series. We restricted the time series to 1950–2013 due to the absence of original measurements prior to 1950 in the study area. The SPEI drought index was calculated by applying the R Package "SPEI" [*Vicente-Serrano et al*., 2010]. The index was calculated for different seasonal windows from 1 to 12 months and at different starting months (from January to December) for the period 1950–2013.

The BasPoisLW chronology was calibrated against the SPEI time series, and a correlation matrix was developed detailing the coefficients for different periods. The seasonal window which best adjusts to the chronology was selected to calculate the transfer model and evaluate past drought variability. The model was assessed considering split calibration/verification over the periods 1950–1981 and 1982–2013 using Pearson's correlation (r), coefficient of determination (r^2), reduction of error (RE), mean square error (MSE), sign test [*Cook et al*., 1994], and Durbin-Watson test [*Durbin and Watson*, 1951]. Pearson's correlation (r) indicates how well the data fit a statistical model. RE is a measure of shared variance between actual and estimated series and provides a sensitive measure of the reliability of a reconstruction [*Cook et al*., 1994; *Akkemik et al*., 2005; *Büntgen et al*., 2008], ranging from +1 indicating perfect agreement to minus infinity. MSE quantifies the difference between the actual observations and those predicted, and the sign test compares the number of agreeing and disagreeing interval trends from year-to-year among the observed and reconstructed series [*Fritts et al*., 1990; *Čufar et al*., 2008].

The BasPoisLW chronology was transferred into a climate reconstruction using a linear regression model [*Esper et al*., 2005]. The strength and spatial extent of signals were evaluated by correlating the reconstruction against each SPEI grid point of the Iberian Peninsula, and the reconstruction was compared against proximate grid points of the Old World Drought Atlas, a spatially resolved reconstruction of the Palmer Drought Severity Index (PDSI) in Europe [*Cook et al*., 2015]. Extreme SPEI deviations were identified considering ±1.5

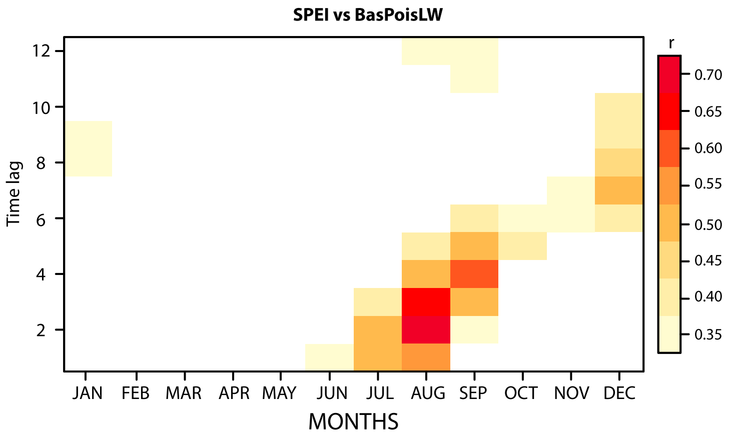

Figure 2. Correlation between the BasPoisLW chronology and SPEI index up to 12 months of cumulative time lag. Only significant values ($p < 0.01$) are shown.

standard deviation thresholds of the reconstruction, and an 11 year running mean was used to emphasize lower frequency variance in the reconstruction. The reconstruction is denominated Ebro Basin Summer Drought Reconstruction (EBSDR). A more detailed discussion of the methodology can be found in the supporting information [*Briffa et al.*, 2008; *Cook et al.*, 2015; *Tejedor et al.*, 2016].

3. Results

3.1. Latewood Chronology

The correlation matrix (Figure S3) demonstrates substantial synchronicity between latewood chronologies among sites and species. The mean correlation (r = 0.36) between the detrended series over the 1969–2010 common period suggests that despite local differences, there is a coherent intersite signal supporting the development of a regional mean chronology. This mean chronology, integrating 774 latewood series of *Pinus sylvestris* and *Pinus uncinata*, correlates on average at r = 0.52 against the 22 individual sites chronologies. The signal to noise ratio is 23.7, and lag 1 autocorrelation is 0.51. The variance explained by the first eigenvector is 27.6%, suggesting that a considerable fraction of variability might be commonly forced [*Levanič et al.,* 2013]. EPS exceeds 0.85 after year 1733, confining the period of suitable replication depth to 1734–2013.

3.2. Climate Signal and Transfer

The correlation of the BasPoisLW chronology and regional SPEI time series is shown in Figure 2. The signal is significantly stronger during the summer months and most coherent in August, including the cumulative

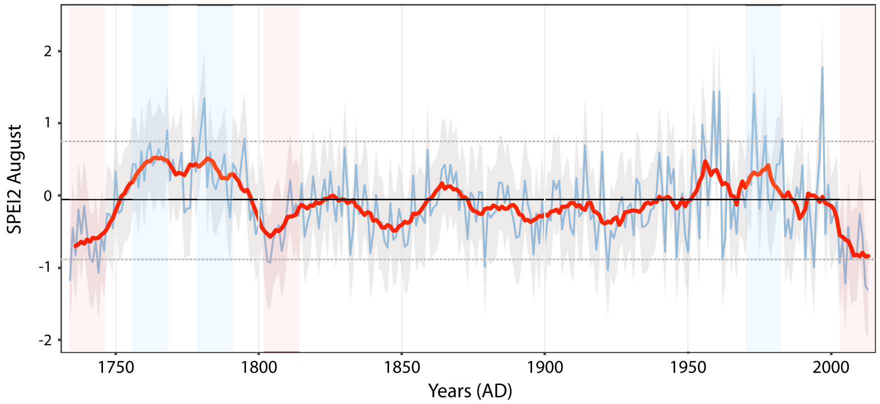

Figure 3. EBSDR reconstruction from 1734 to 2013 for the northeastern Iberian Peninsula. The blue curve represents the reconstruction, the bold red curve is an 11 year running mean, and gray shading indicates the mean square error based on the full calibration correlation period. Vertical shading indicates the extremely wet (in blue) and dry (in red) periods. Dashed lines indicate ±1.5 standard deviations (threshold to identify extremely wet and dry events).

Table 1. Reconstructed Dry and Wet Years Considering ±1.5 Standard Deviation Thresholds and Values (in Brackets) Sorted by Magnitude

	18th Century	19th Century	20th Century	21st Century
Wet extreme events	1781 (1.34)	1830 (0.65)	1997 (1.77)	
	1780 (0.98)		1961 (1.44)	
	1768 (0.90)		1959 (1.44)	
	1777 (0.79)		1973 (1.41)	
	1795 (0.78)		1955 (0.98)	
	1762 (0.72)		1977 (0.82)	
			1983 (0.77)	
			1964 (0.72)	
			1914 (0.69)	
			1974 (0.68)	
Dry extreme events	1734 (−1.18)	1879 (−0.98)	1922 (−1.03)	2013 (−1.31)
	1744 (−1.07)	1804 (−0.93)	1994 (−0.99)	2012 (−1.25)
	1742 (−0.91)	1803 (−0.90)	1962 (−0.88)	2005 (−1.22)
	1741 (−0.86)		1991 (−0.88)	2003 (−0.93)
				2007 (−0.88)

precipitation of the previous month. This correlation between BasPoisLW and $\text{SPEI2}_{\text{August}}$ equals 0.67 ($p < 0.01$). Accordingly, we selected $\text{SPEI2}_{\text{August}}$ as the variable to develop a drought reconstruction. Calibration/verification reveals highly significant correlations during 1950–1981 and 1982–2013 ($r^2 = 0.21$ and $r^2 = 0.52$, respectively) justifying the development of a SPEI reconstruction. The obvious correlation difference is likely affected by the sparser instrumental network during the early period. The models developed for the calibration/verification periods are valid for the final reconstruction (Table S3 and Figure S6 and S7), and the Durbin-Watson statistic calculated over the full calibrations period ($\text{DW}_{1950\text{–}2013} = 1.98$ $p < 0.0001$) indicates no significant autocorrelation in the residuals. We applied a lineal regression model over the full period 1950–2013, considering the $\text{SPEI2}_{\text{August}}$ data and BasPoisLW chronology (equation (1)), to develop the Ebro Basin Summer Drought Reconstruction:

$$\text{EBSDR} = 0.3004 \times \text{BasPoisLW} + 0.2083 \left(r^2 = 0.45, p < 0.01\right) \tag{1}$$

3.3. EBSDR and Spatial Extent

The EBSDR provides estimates of 279 years of summer drought variability in northeastern Spain (Figure 3), including values ranging from −1.31 in 2013 to 1.77 in 1997, and a standard deviation of 0.50. Seventeen extremely wet and 16 extremely dry summers are identified since 1734 A.D. (Table 1). The 18th and particularly the 20th century accounted for most of the wet extreme events. On the other hand, it is remarkable that the 21st century included five summers classified as extremely dry. Longer-term moist periods, identified after smoothing the reconstruction using an 11 year moving average, occurred (in order of decreasing intensity) from 1777 to 1788, 1973 to 1984, 1757 to 1770, and 1955 to 1964, while dry periods occurred from 2003 to 2013, 1734 to 1746, 1801 to 1809, and 1841 to 1853.

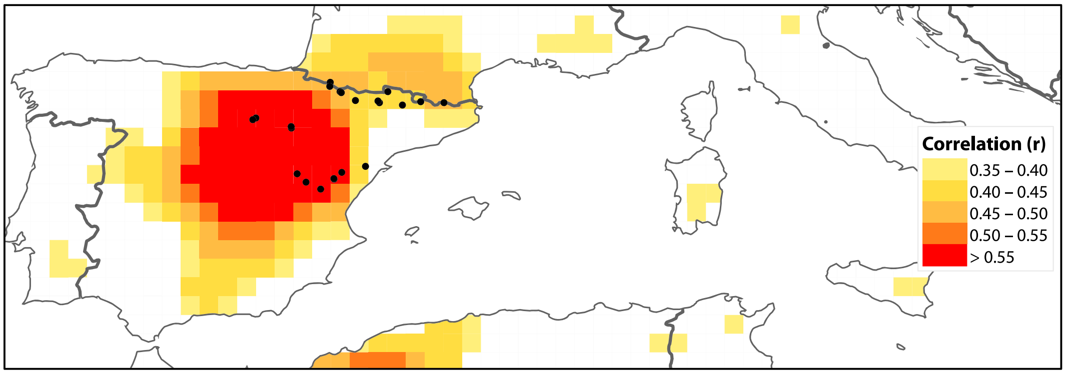

Figure 4. Spatial correlation pattern of the latewood chronology with gridded $\text{SPEI2}_{\text{August}}$ data. Correlation values higher than $r = 0.35$ are significant at $p < 0.01$.

The spatial extent of the reconstruction (Figure 4) reveals validity for the Pyrenees and Iberian Range but also for the northern and southern plateau of the Iberian Peninsula, with SPEI2$_{\text{August}}$ correlations exceeding $r = 0.4$.

4. Discussion

The worldwide importance of drought events has led to the development of several indices including the SPEI [*Vicente-Serrano et al*., 2010]. To date, only two SPEI reconstructions have been developed using tree ring width measurements (*Seftigen et al*. [2015] in Fennoscandia and *Ma et al*. [2015] in the Taihe Mountains). Based on a novel and consistent network of latewood series distributed throughout the Pyrenees and the Iberian Range, we developed a 279 year summer (July–August) drought reconstruction (EBSDR) representative for the northeast and central Iberian Peninsula. The spatial extent of the reconstruction demonstrates agreement not only within the mountain ranges of central and northeastern Spain but also with the northern and southern plateaus, mostly above 1000 m.

The calibration and verification statistics used to assess the reconstruction (r^2, RE, and sign test) are surprisingly high, considering the great variability of tree sites. Still, it is difficult to determine whether the increase in climate signal strength in the recent period is entirely due to the increasing quality of the observational data network or additionally to a temporally increasing moisture limitation of tree growth [*D'Arrigo et al*., 2006]. The short length of the climatic series does not allow performing a rigorous analysis on this effect. In addition, even though the oldest trees extend back to 1593, the reduced replication prior to 1734 limits the reconstruction period. To reconstruct the whole Little Ice Age period, more old trees need to be sampled. The sampling of wood from historical buildings known as "Masias" could also support extending the reconstruction back in time.

Despite these limitations, EBSDR represents the first record in Europe reconstructing SPEI based on latewood data. The use of latewood series as a proxy to reconstruct summer drought opens up new possibilities for paleoclimatic studies [*Meko and Baisan*, 2001; *Stahle et al*., 2009; *Griffin et al*., 2011]. The relationship between latewood growth and evapotranspiration during summer has already been explored in recent work from the Pyrenees, using maximum latewood density [*Büntgen et al*., 2008; *Dorado-Liñán et al*., 2012]. The latewood growth limitations of *Pinus sylvestris* and *Pinus uncinata* across the high elevation network analyzed here are expressed by highly significant correlations with the SPEI2$_{\text{August}}$, an index integrating cumulative precipitation of July and August and temperature in terms of evapotranspiration. In light of projected global warming, a higher water demand during summer would translate into a decrease in latewood width, which may have implications on forest sustainability. Since latewood substantially contributes to stem mechanical stability and stores large amounts of water, a lower proportion of this xylem tissue would tend to reduce drought resistance [*Domec and Gartner*, 2002; *Martinez-Meier et al*., 2008, *de Luis et al*., 2011]. Further studies are needed to assess this finding since in other species growing at lower altitudes under stronger summer stress, the reduction of photosynthetic activity during summer is compensated by the species' ability to resume growth in autumn when conditions are favorable [*de Luis et al*., 2007; *Novak et al*., 2013; *Martinez del Castillo et al*., 2016; *Prislan et al*., 2016]. Intraspecific plasticity of cambial phenology of *P. sylvestris and P. uncinata* needs to be studied in more detail to better evaluate the ecological consequences these our findings.

In addition to SPEI, different drought indices have been reconstructed worldwide using tree ring records. The Standardized Precipitation Index (SPI), based on monthly precipitation data and the cumulative probability of rainfall events [*McKee et al*., 1993], has been successfully reconstructed in regions in Europe (in Turkey, [*Touchan et al*., 2005], in Romania, [*Levanič et al.,* 2013], in Spain, [*Tejedor et al*., 2016]) and North America [*Griffin et al*., 2013]. Comparison between the EBSDR and the aforementioned drought reconstructions is limited as other records target differing seasons and larger spatiotemporal scales. For instance, in *Tejedor et al*. [2016] (Figure S8) the SPI of July was reconstructed considering cumulative precipitation over 12 months, which is the same season as considered in *Levanič et al*. [2013]. Still, there are extremely dry and wet years common in the precipitation data and drought reconstructions, suggesting coherent large-scale synoptic patterns throughout the Mediterranean basin. For instance, 1741, 1803, 1879, 1994, 2005, and 2012 correspond with extremely dry years indicated by *Tejedor et al*. [2016]. Some of these years (1803, 1879, and 1994) were also identified by *Génova* [2012] as years with very intense droughts in central Spain. *Vicente-Serrano and Cuadrat-Prats* [2007] indicated that 1803 was the second driest year according to rogation data from the cities of Teruel and Zaragoza. The extremely moist summers in 1762, 1914, 1959, 1964, 1973, 1977, and 1994 were also reported in *Tejedor et al*. [2016], indicating large-scale pluvial conditions in the northeast of the Iberian Peninsula (IP).

More reconstructions have been completed targeting PDSI, which is based on recent precipitation and temperature in terms of a supply and demand model of soil moisture [*Palmer*, 1965; *Wells et al*., 2004]. In Europe and western North Africa, three PDSI reconstructions have been developed for particular regions [*Esper et al*., 2007; *Nicault et al*., 2008; *Esper et al*., 2015]. Most recently, *Cook et al*. [2015] developed the Old World Drought Atlas (OWDA), a spatially resolved summer (June–August) PDSI reconstruction of the whole of Europe. When compared with the OWDA grid points over our study area, the EBSDR shows a weak but statistically significant correlation ($r = 0.15$; $p < 0.05$) during the common period (1734–2012), which might reflect a large-scale synoptic pattern affecting southern Europe (Figure S8). Particularly consistent is the mid-20th to 21st century period ($r = 0.48$; $p < 0.05$) when rising temperatures likely triggered evapotranspiration causing greater stress of trees and therefore enhanced signal strength. However, other periods such as the mideighteenth century reflect differences between the reconstructions that might be explained by the fact that the OWDA was designed to encompass a wider spatial scale using multiple tree ring width sites across Europe. The OWDA only integrates five tree ring chronologies across the whole of Spain including different climate zones, compared to the dense northeastern IP network of 22 sites used to develop EBSDR. It might thus be advisable, when compared with more regional reconstructions such as EBSDR, to focus on high-frequency extremes such as the drought years 1741, 1893, 1921, and 1994 that could explain historical and socioeconomical incidences.

In other regions of Europe, [*Büntgen et al*., 2010] and in North Africa, *Esper et al*. [2007] reported the late 20th and early 21st centuries to be exceptionally dry in context of the past 500 years. This is consistent with our reconstruction, as 2003–2013 is the driest period since 1734, suggesting that large-scale synoptic patterns related to the strength and position of the Azores High are affecting these time series [*Esper et al*., 2007]. The increased recurrence of wet and dry events during the mid-20th and early 21st centuries is consistent with the latest Intergovernmental Panel on Climate Change report (2013) connecting anthropogenic socio-economical activities with global climate change.

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