Rain in the desert; a precipitation reconstruction of the last 156 years inferred from Aleppo Pine in the Bardenas Natural Park, Spain.

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Abstract

Understanding the regional hydroclimatic variability beyond the instrumental period is essential to contextualize the current climatic period within a longer record. Dendrochronology has been used as a powerful tool for estimating the temperature and precipitation variability of the last centuries on an annual and even seasonal scale. However, most of the centenary trees in Spain are located in high-elevation mountain environments, so the reconstructed signal is not representative of the climate variability of the lowlands, where the main cities and most of the population are located.

Here we present a precipitation reconstruction of the Bardenas Natural Park, a semi-arid environment within the Ebro Valley, based on 61 new tree-ring width series of *Pinus halepensis* Mill. The new chronology, calibrated against high-resolution instrumental precipitation data, uncovers a high and robust relationship with the annual precipitation (from previous June to current May) (1951-2012 CE; $r=0.78$), representing the precipitation totals of the hydrological year. Our reconstruction explains 61% of the annual precipitation for the period 1951-2012 and is representative of the lowlands of the Northeast of Spain. We identified 12 extremely dry and 11 extremely wet years, finding the first half of the 20th century to be the period with most extreme episodes of the reconstruction. Additionally, we found a strong agreement between our tree-ring based reconstruction and the lowlands documentary-based drought estimators (rogation ceremonies). These findings contribute to improving our understanding of past hydroclimatic variability in semi-arid lowland areas where available proxy records are rare.

1. Introduction

Temperature and precipitation are the two primary meteorological diagnostics of climate. Changes in their normal values are linked to the occurrence of extreme droughts/ floods and heat waves/ cold surges, inducing substantial and direct influences on society and the natural environment (Sun and Ao, 2013). While there is a high consensus on the increase of the average global temperature in the next decades, such a trend is less evident in precipitation. In Mediterranean semi-arid environments, a probable decline in precipitation and an increase in the frequency and magnitude of droughts with high spatial variability and uncertainty have been predicted (Intergovernmental Panel on Climate Change, 2014). Multiple studies have analyzed instrumental precipitation data from the Iberian Peninsula (IP) to better understand its mechanisms (e.g. Lopez-Bustins et al., 2008), trends (de Luis et al., 2010; González-Hidalgo et al., 2011; Río et al., 2011) or the intensity and frequency of extreme events (e.g. Serrano-Notivol et al., 2017; Serrano-Notivol et al., 2018). Yet in spite of recent major efforts, our understanding of the hydroclimate variability of the IP is highly limited due to the fact that most of the historical instrumental climatic records do not begin until the 1950s (Gonzalez-Hidalgo et al. 2011). The paleoclimatic studies of high-resolution natural proxies provide a long-term perspective, which is key to understanding the climate system and better contextualizing current climate change. In the Iberian Peninsula, recent efforts have led to the production of three hydroclimatic reconstructions in high-elevation mountain ranges of the Northeast using tree-ring records (Esper et al., 2015; Tejedor et al., 2016, 2017b,). While they provide useful information to understanding, for instance, changes in the frequency and intensity of extreme drought years of the last centuries (Tejedor et al., 2016), their results are reflecting conditions during specific periods of the year and mostly limited to high-elevation areas (i.e. >1,000 m.a.s.l). Therefore, the long-term perspective of the precipitation using natural archives in low-elevation areas remains highly unexplored, mainly due to the limited number of long-living tree species therein. Spain, on the other hand, has a large amount of documentary-based data with a good degree of continuity and homogeneity for many areas, which enables important paleoclimate information to be derived at different timescales and for various territories (Tejedor et al., 2019). Related with the agricultural and meteorological conditions, the rogation ceremonies (religious act to ask God for rain or to stop it) have been used to estimate the occurrence and intensity of extreme hydroclimatic events in the last centuries of the main cities, which are located in low-elevation areas in the Northeast of Spain (Barriendos et al., 2010; Domínguez-Castro et al., 2012; Tejedor et al., 2019; Vicente-Serrano and Cuadrat, 2007). Despite major advances in generating continuous hydroclimatic indices (Barriendos et al., 2019; Tejedor et al., 2019), the rogation ceremonies are mainly estimators of the occurrence (or not) of an extreme event and its intensity and contain multiple years with no information (or absence of extreme events). In addition, its applicability is limited to specific periods in which the catholic religion had a great influence on society (~1850 CE, Tejedor et al., 2019). As a consequence, we hypothesize that the species *Pinus halepensis* mill., which grows in a low rainfall environment, will be limited by the variability of rainfall, and therefore, if sufficiently long-lived specimens are found, we could extend our knowledge of the climatic variability of the region beyond the instrumental period'.

The aim of this work is thus to fill the gap between the high-elevation tree-ring reconstructions and the low-elevation documentary-based hydroclimatic indicators by developing a dendroclimatic reconstruction using tree-ring records from an extremely scarce precipitation environment located in the center of the Ebro Valley. We therefore analyzed the hydroclimate sensitivity of the main tree species living under such stressfully conditions (*Pinus halepensis* Mill.) and explore its potential to develop long-term high-resolution hydroclimatic reconstructions. Additionally, we evaluate the statistical links between the tree-ring based hydroclimate reconstruction and the documentary-based hydroclimatic index of the nearby areas.

2. Material and methods

2.1. Study area

The study area is located on Northeastern Spain (Fig. 1) around and within the limits of the Bardenas Natural Park (BNP) and between the rivers Aragon and Ebro. The average altitude ranges between 280 m a.s.l. and 659 m a.s.l. Soils are composed of limestone, clay and sandstone (Marín and Desir, 2010). The climate is semi-arid with average monthly temperatures ranging from 10 °C to 24 °C and an annual average of 13 °C (Fig. 2). The average annual rainfall in the instrumental period (1950-2012) is 350.8 mm, which is distributed in two peaks at the end of spring and the beginning of autumn. During these highs, the rains are cyclonic and of low intensity, while the rest of the year, there can be stormy rains, mostly in summer. As a consequence of the arid conditions within this climate, tree species are scarce. *Pinus halepensis* Mill. is the most common, surviving erosion, drought and lodging in patches above 300 m altitude and accompanied by *Quercus coccifera* and *Juniperus phoenicea*. The rest of the uncultivated territory is covered by varied semi-desertic Mediterranean shrubs and xerophytic grasses, among which *Lygeum spartum* is the dominant species., revealing the strong and prolonged aridity that this territory experiences.

2.2. Data collection

In June of 2013 we collected 61 samples (i.e., the outermost ring is from 2012) from 35 trees in three patches of *Pinus halepensis* Mill. around the limits of the BNP (Fig. 1). We extracted two cores samples from each tree at breast height (1.3 m). Most samples were taken from dominant or co-dominant trees with healthy trunks and no signs of human intervention. These samples were processed according to standard procedures (Stokes, M. & Smiley, 1996). We then scanned each sample to identify and date the exact position of the annual rings. Next, we measured the ring-width of each tree-ring separately at 0.01 mm precision using a LINTAB table (Rinn, 2011). Crossdating was verified using COFECHA (Holmes, 1983). Maximum, minimum, and average ages of the analyzed trees are 172, 36, and 84 years respectively, including 10 series with more than 100 years old.

2.3. Chronology development

We used the 61 raw series to develop the tree-ring reconstruction. To preserve the inter-annual scale variability and eliminate the age-related trend in the radial growth, we standardized the individual 61 tree-ring width series using the dplR standardization package (Bunn, 2008). We fitted each ring width series with a cubic spline with a 50% frequency response cutoff at 67% of

the series length (Cook and Kairiukstis, 1990) and used a bi-weight robust estimation of the mean to develop the Bardenas standard chronology (BAR_{sd}). Next, we applied a first-order autoregressive model of the residuals and a bi-weight robust estimation of the mean (Cook and Peters, 1997) to assemble the Bardenas regional residual chronology (BAR_{res}). Finally, the chronology confidence-interval was estimated using running inter-series correlations ($Rbar$) and the subsample signal strength (SSS) metric (Wigley et al., 1984). The $Rbar$ indicates the common variance among ring width series averaged in a chronology. SSS is the appropriate measure to estimate the loss of explanatory power due to a decreasing sample size back in time (Buras, 2017; Wigley et al., 1984). Values equal to or above 0.85 are considered to ensure that a chronology is suitable for climate reconstruction (Wigley et al., 1984).

2.4. Climate data (CRU and SPREAD)

We compared the tree-ring growth response to precipitation variability through the use of two gridded datasets: the Climate Research Unit TS v3.23 (CRU, Harris et al., 2014) and the Spanish PRECipitation At Daily scale (SPREAD; Serrano-Notivol et al., 2017). The CRU, retrieved from the University of East Anglia, covers the 1901-2012 period of global data for multiple variables at a $0.5 \times 0.5^\circ$ spatial resolution and at monthly scale. We selected the spatial domain of the study area and extracted the precipitation data for 1951-2012. The CRU dataset uses 35 precipitation stations from across Spain. This the low spatial resolution provides information about regional precipitation variability that is useful for general characterization purposes, but clearly insufficient to represent local conditions in the study area. The SPREAD is a daily precipitation gridded dataset at a spatial resolution of 5×5 km and built from the complete precipitation network in Spain ($>12,000$ observatories) for the 1950-2012 period. In addition to its high-resolution, the estimates of precipitation are computed independently with linear models (GLM) for each day and grid point, using the nearest observations and geographical covariates rather than global models, emphasizing the local character of precipitation.

2.5. Climate-growth relationship, climate reconstruction and relationship with documentary data.

Based on previous studies (De Luis et al., 2013; Novak et al., 2013; Pasho et al., 2011) we primarily investigated the influence of precipitation on the growth of *Pinus halepensis* in the BNP. We calibrated both chronologies (BAR_{SD} and BAR_{AR}) against the monthly precipitation data of both SPREAD and CRU datasets. To account for the cumulative rainfall, we also included 15 months of lag (the cumulative rain). Then, we split the dataset into two equals periods (1951-1981; 1982-2012) for calibration and verification (Fritts, 1976) to assess the accuracy of the model used for climate reconstruction. We evaluated the consistency of the linear model using the Pearson's correlation coefficient (r), the reduction of error (RE), the sign test and the Root Mean Square Error (RMSE). RE provides a highly sensitive measure of reliability of a reconstruction (Akkemik et al., 2005), ranging from +1, meaning perfect agreement, to minus infinity. In general, positive RE values are interpreted as a reconstruction showing some skill (Fritts et al., 1990). The sign test compares the number of agreeing and disagreeing interval trends, from year to year, between the observed and reconstructed series (Čufar et al., 2008). Lastly, we transferred the residual chronology into a climate reconstruction using a linear regression model (using the full 1951-2012 period). Additionally, we identify and evaluate the

extreme events by selecting values of the reconstructed series exceeding the precipitation value of ± 1.76 standard deviations as indicated by Akkemik et al., (2005).

Next, we assessed the strength of the climatic signal by performing spatial correlations between the reconstruction, the instrumental data and all the gridded monthly precipitation SPREAD dataset (Roberto Serrano-Notivoli et al., 2017) for the period 1951-2012.

Finally, the tree-ring based precipitation reconstruction was subsequently compared with the Ebro Valley Drought Index estimated from documentary data (Tejedor et al., 2019). This particular index was inferred from the rogation ceremonies that were held in the cities of Calahorra and Zaragoza, 60 km Northwest of BNP and 100 km Southeast of BNP, respectively.

Rogation ceremonies were uniformly performed throughout the Catholic territories and triggered by droughts. The intensity of these religious acts was categorized into four levels from low to high intensity (from 0 to 3, see Tejedor et al., 2019 for the methodological details).

3. Results

We developed two chronologies combining the 61 detrended series from 35 trees for comparison with the instrumental and gridded data. Based on a better agreement with the precipitation data, we used only the BAR_{AR} chronology for creating the reconstruction (Fig. 3). The mean sensitivity is 0.56, and the correlation coefficient between trees (R_{BAR}) is 0.59 whereas the correlation within trees equals 0.71. The signal-to-noise ratio reaches 52.76, and the SSS exceeds 0.85 after 1856, confining the reconstruction period to 156 years until 2012. All of these metrics indicate that the trees share a very strong common climate signal.

The correlations between the regional chronologies and the regional precipitation series for the period 1951-2012 are presented in Fig. 4. The correlations in both SPREAD and CRU plots are very similar, although the high-resolution dataset (SPREAD) consistently shows higher values. The signal is significantly stronger during spring and summer when including the cumulative totals of 8 to 14 months. The highest correlation ($r=0.78$) is found with the BAR_{AR} chronology and SPREAD for the period of May including a lag of 11 months (i.e., the cumulative rainfall for 12 months), while the correlation with the CRU for that same period is reduced to $r=0.72$. The correlation for the same period using the standard chronology (BAR_{SD}) with SPREAD is a bit lower, though still remarkably high at $r=0.75$, and of $r=0.63$ against the CRU series.

Based on these results, we selected the chronology BAR_{AR} and the period of May including the previous 11 months (May_{11}), not only for its very high correlation but also as this period provides information on a time interval similar to the full hydrological year.

The calibration-verification is shown in Fig. 5a, indicating very high correlation coefficients for both periods, including a correlation of 0.84 for the 1982-2012 period. The robustness of the model is confirmed by the high correlation (0.78) and adjusted correlation coefficient (0.61) when using the full period (Table 1). The reduction of error (RE) is consistently high for both the calibration and verification periods (Table 1) with values above 0.5 indicating that there is skills in the reconstruction (Fritts et al., 1990). Finally, the sign test and the RMSE present very consistent values. Therefore, we use the full 1951-2012 period for the final lineal model (Fig. 5b) to develop the Bardenas Desert Precipitation Reconstruction ($BARDEPRER$) of the BNP reaching back to 1856 CE.

The BARDEPRER reconstruction provides estimates of 156 years of annual (from previous April to current May) rainfall variability in the BNP (Fig. 6). The annual total rainfall in the reconstruction ranges from 492.9 mm in 2007 to 119.4 in 1929 with an average of 286 mm when considering the full reconstruction period. We also identified 12 extremely dry years and 11 extremely wet years (Table 2). The wettest years are found in the 21st century, whereas the first half of the 20th century includes most of the extreme dry and wet years.

The spatial extent of the reconstruction (Fig. 7a) shows a good agreement for the Ebro Valley and some sectors of the Iberian Range, including correlations higher than 0.6. The comparison with the instrumental data (Fig. 7b) reveals a very similar coherent spatial correlation adding another element of validation to the reconstruction.

Finally, we compared the BARDEPRER reconstruction with the Ebro Valley Drought Index (Tejedor et al., 2019), which extends over a very similar area to the trees used in the analysis. We find a fairly good agreement ($r=-0.45$; $p<0.0023$) within the 50 years of comparison (see Fig. 8a) between the reconstruction and the rogation-based drought index. The extreme drought years (1896, 1882, 1893) coincide with an intense activity of *pro-pluviam* rogation ceremonies. Likewise, the wet extremes (1889 and 1856) occur during years of no rogation ceremonies (Fig. 8b).

4. Discussion

The hydroclimatic reconstructions from the Iberian Peninsula inferred with tree-ring records have helped us to better understand the recurrence, intensity and impacts of hydroclimate extremes during the last centuries (Andreu-Hayles et al., 2017; Esper et al., 2015; Tejedor et al., 2016, 2017b). However, all these reconstructions are derived from trees located in high-elevation mountain ranges and hence provide estimates of the hydroclimatic variability mainly of the mountain areas. Here, for the first time, we develop an annual precipitation reconstruction for low-elevation areas (Bardenas Natural Park) including high correlations coefficients to a tree-ring width reconstruction. Additionally, to the best of our knowledge, it is the first time that the precipitation variability is reconstructed using Aleppo Pine. The main statistics used to assess the strength of the reconstruction present values greater than other existing tree-ring width hydroclimatic reconstruction in the Iberian Peninsula (Esper et al., 2015; Tejedor et al., 2016) not only confirming the great plasticity (surviving with very low precipitation values) but also the high sensitivity of Aleppo pines to hydroclimatic variability in the Ebro Valley (De Luis et al., 2013).

The raw chronology is longer than the final reconstruction, however there are few living trees reaching back to 1850s thus limiting the reconstruction to the period 1856-2012 CE. Aleppo pine is not a very long-lived pine, living for up to 150-200 years (Barbéro et al., 1988; Quézel, 2000). Therefore, the only manner to extend the precipitation reconstruction further back in time would be to combine living-tree samples with tree-ring width measurements from historical structures, as suggested by Esper et al., (2015). The spatial extent of the reconstruction (Fig.7) shows a good agreement for the Ebro Valley, but to some degree also along the Iberian Range, where old living and relict *Pinus sp.* (Tejedor et al., 2016) might be suitable to be combined with the Aleppo Pine to extend the chronology.

The growth limitations of the *Pinus halepensis* in the study area are expressed by the high correlation with precipitation, especially when integrating rainfall values over 10 to 14 months in agreement with previous findings by Pasho et al. (2011). A similar metric was considered in Tejedor et al., 2016 in the Iberian Range, where a drought index (the Standardized Precipitation Index, (McKee et al., 1993) from July integrating 12 months was reconstructed. The correlations between the chronology and the drought index were, however, lower than the very high values shown in this study. The annual (from previous June to current May) sensitivity of the tree-ring growth is consistent with the long cambium activity season in *Pinus halepensis* living in Mediterranean environments (de Luis et al., 2011; Prislán et al., 2016). This is crucial especially because trees located in high-elevation mountain areas, such as the Pyrenees (although maximum latewood density is needed to develop skillful reconstructions; Büntgen et al., 2017, 2008) or the northern Iberian Range are sensitive to temperature instead (Tejedor et al., 2017a). In relation to the calibration approach, we discover a better agreement between the high-resolution instrumental dataset (SPREAD; Serrano Notivoli et al., 2017) than with the CRU dataset (Harris et al., 2014), which is more commonly used in dendroclimatology.

The factors affecting precipitation are more local than temperature which, together with the scarce precipitation in the study area, make the regional gridded product less accurate than the instrumental station-based series.

Using the BARDEPRER reconstruction we are able to identify extreme dry and wet events (see Table 2) some of which were also identified in previous drought reconstructions (e.g., the year 2012 was identified as the driest in the last 318 years in the Iberian Range (Tejedor et al., 2016)). However, there are multiple differences with previous dendrochronological reconstructions, including the very low-elevation sites and the very low precipitation totals. Because of the local nature of precipitation, this reconstruction is more suitable to be compared with low-elevation proxy records found in the Iberian Peninsula, such as historical archives. Local records document rogation ceremonies which were religious acts to ask God to stop or provide rain during harsh agricultural conditions and were extensively used in Spain between ~1200 CE (Barriendos, 2005) and the 17th century. The practice of rogation ceremonies in Spain gradually decreased as industrialization and the loss of religiosity took place (Tejedor et al., 2019). The good agreement between the tree-ring based precipitation reconstruction and the documentary-based drought estimator is crucial for two reasons; a) it endorses the validity of both archives and at the same time provides a new record for periods and areas where the instrumental data is scarce, and b) we are now able to combine two independent proxy records to better understand past hydroclimatic variability of areas with few proxy records (low-lands) and limited precipitation. The good agreement between both proxies increases our confidence that this reconstruction fills a temporal gap in our understanding of lowland hydroclimatology after rogation practices ceased and prior to the availability (or beginning) of high-resolution instrumental data in the study area (~1950s).

Finally, the BARDEPRER is showing that the Ebro Valley, including the BNP, has faced multiple years (12/156) with annual precipitation values lower than 200 mm, which might be suggesting a shift within the Ebro Valley climate from semi-arid to desert conditions (Beck et al., 2018). In addition, Beck et al. (2018) projected a shift in the Ebro Valley Köppen-Geiger climate classification from a semi-arid climate (1981-2010) to a desert climate (2071-2100). However, it

is also true that the two wettest years fall in the last decade of the reconstruction (2004 and 2007), which is consistent with the last International Panel on Climate Change report (Intergovernmental Panel on Climate Change, 2014), suggesting an increase in the frequency of extreme events towards the 21st century, and linking anthropogenic activities with global climate change.

Acknowledgements

ET was partially supported by the National Science Foundation (grant numbers OISE-1743738 AGS-1702439). RSN is funded by a “Juan de la Cierva” postdoctoral grant FJCI-2017-31595. ET, RSN, MAS, LAL, MDL, and JMC are partially supported by the Government of Aragón through the “Program of research groups” (group H38, “Clima, Agua, Cambio Global y Sistemas Naturales”). MDL, JMC, MAS, and LAL were partially supported by the Spanish Ministerio de Economía y Competitividad (grant no. CGL2015-69985- R). KN is supported by contract no. C3330-19-952011 for co-financing the operation of the “Researchers-2.1-UL-BF-952011” by the Ministry of Education, Science and Sport of the Republic of Slovenia and EU European Regional Development Fund.

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Figures

Figure 1. Location of the sampling sites are shown in triangles, and the Bardenas Natural park limits are highlighted in solid red. The satellite image is showing the semi-arid landscape of the Bardenas Natural Park surrounded by irrigated croplands.

Figure 2. Walter-Lieth diagram (done using the R Package ‘berryFunctions’; Boessenkool, 2019) of the study area with data retrieved from SPREAD (Roberto Serrano-Notivoli et al., 2017) and STEAD (Serrano-Notivoli et al., 2019).

Figure 3. BAR_{AR} chronology (green line); the residual 61 series used (in gray); number of samples (in blue) and RBAR (orange line) (RBAR computed over 30-y window lagged by 15 years) threshold in 1856.

Figure 4. Pearson correlation (only significant $p < 0.001$ values are shown) between the Bardenas chronologies (BAR_{SD} and BAR_{AR}) and the CRU and SPREAD precipitation datasets. Monthly precipitation is shown in the X axis while the cumulative precipitation in months (LAG) is shown in the Y axis.

Figure 5. a) Calibration and verification results of the station-based previous June to current May reconstruction. b) Full model between the chronology (BAR_{res}) and the SPREAD previous June to current May precipitation.

Figure 6. Bardenas Desert Precipitation Reconstruction (BARDEPRER) spanning 1856-2012 AD is shown with a bold blue line. The uncertainty of BARDEPRER is represented with the Root Mean Square Error of the residuals in grey. The instrumental precipitation data is shown in green. The dry and wet extreme years are indicated with red and blue dots respectively.

Figure 7. Spatial Correlation of the reconstruction and the instrumental-based precipitation gridded dataset (SPREAD) for the previous June to current May period. Only significant ($p < 0.001$) values are shown.

Figure 8. Relationship between the tree-ring based precipitation reconstruction (BARDEPRER) and the documentary-based Ebro Valley Drought Index (EVDI) for the lowlands of the Ebro Valley. a) Spearman correlation between the BARDEPRER and EVDI for the overlapping period (1856-1999 AD). b) BARDEPRER is shown in blue and the EVDI is represented in orange. A

higher value in EVDI indicates agricultural and meteorological stress (more rogation ceremonies being celebrated in order to ask God for rain). Red shades represent extremely dry precipitation years agreeing with a higher EVDI. Blue shades represent extremely wet precipitation years concurring with low values of EVDI (or absence of rogation ceremonies).

Table. 1. Calibration/ Verification statistics of the BARDEPRER reconstruction.

	Calibration	Verification	Calibration	Verification	Full Period
Years	1951-1981	1982-2012	1982-2012	1951-1981	1951-2012
r²	0.58	0.70	0.70	0.58	0.61
RMSE	44.78	31.07	31.07	44.78	36.38
Reduction of error	0.58	0.53	0.53	0.58	0.56
Sign Test	27+/4-	27+/4-	27+/4-	27+/4-	54+/8-

RMSE Root Mean Square Error

Table 2. Drought and wet extremes calculated from the mean $\pm 1.76SD$ in mm (± 36.6 RMSE)

<i>Drought extremes</i>	<i>Wet Extremes</i>
1929 (119.4)	2007 (492.9)
1896 (147.5)	2004 (465.2)
1943 (154.6)	1889 (437.6)
1904 (156.2)	1856 (432.6)
1905 (162.5)	1936 (421.5)
1949 (170.2)	1903 (405.8)
1882 (171.6)	1930 (402.8)
2002 (182.9)	1919 (402.2)
1918 (183.2)	1938 (393.2)
1893 (188.2)	1913 (387.5)
1944 (197.4)	1908 (382.3)
2012 (199.7)	