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The complex multi-sectoral impacts of drought: Evidence from a mountainous basin in the Central Spanish Pyrenees

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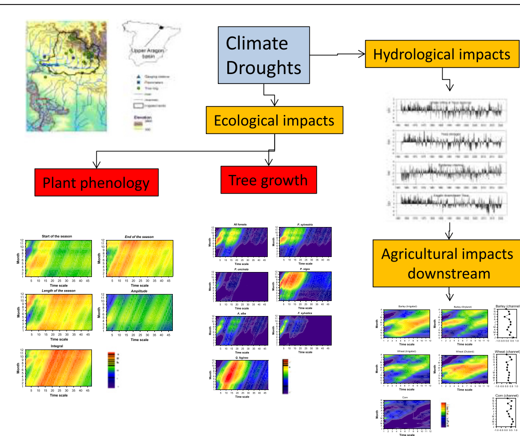
HIGHLIGHTS

- Strong spatial and temporal complexity when assessing drought impacts.
- Different responses not only as a function of hydrological subsystems, vegetation metrics and vegetation types
- Diverse impacts seasonally, over different drought time-scales, and water resources management policies.

GRAPHICAL ABSTRACT



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ABSTRACT

We analyzed the impacts of drought severity on a variety of sectors in a topographically complex basin (the upper Aragón basin 2181 km^2) in the Central Spanish Pyrenees. Using diverse data sources including meteorological and hydrological observations, remote sensing and tree rings, we analyze the possible hydrological implications of drought occurrence and severity on water availability in various sectors, including downstream impacts on irrigation water supply for crop production. Results suggest varying responses in forest activity, secondary growth, plant phenology, and crop yield to drought impacts. Specifically, meteorological droughts have distinct impacts downstream, mainly due to water partitioning between streamflow and irrigation channels that transport water to crop producing areas. This implies that drought severity can extend beyond the physical boundaries of the basin, with impacts on crop productivity. This complex response to drought impacts makes it difficult to

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Drought indices
Vegetation activity
Irrigated lands

develop objective basin-scale operational definitions for monitoring drought severity. Moreover, given the high spatial variability in responses to drought across sectors, it is difficult to establish reliable drought thresholds from indices that are relevant across all socio-economic sectors. The anthropogenic impacts (e.g. water regulation projects, ecosystem services, land cover and land use changes) pose further challenges to assessing the response of different systems to drought severity. This study stresses the need to consider the seasonality of drought impacts and appropriate drought time scales to adequately assess and understand their complexity.

1. Introduction

Drought is a recurrent and creeping natural hazard, which makes it difficult to quantify its characteristics (Lloyd-Hughes, 2014; Vicente-Serrano, 2016; Wilhite, 2005) or to analyze its possible impacts on both natural and human environments (Mishra and Singh, 2010; Wilhite et al., 2007; Wilhite and Pulwarty, 2017). Drought impacts span a wide spectrum of disciplines, including water resources (e.g. river flow, reservoir storage, groundwater) (Bloomfield and Marchant, 2013; Folland et al., 2015; Van Lanen et al., 2013; Van Loon, 2015), crop yield (Dalla Costa and Gianquinto, 2002; Kim et al., 2019; Webber et al., 2018), forest productivity and tree growth (e.g. Anderegg et al., 2018; Restaino et al., 2016; Sánchez-Salguero et al., 2013), in addition to a variety of environmental systems (e.g. Vicente-Serrano et al., 2020a, 2020b).

Drought is often a climate-driven phenomenon, and assessed using tailored climate indices (Heim, 2002; Mukherjee et al., 2018). In the literature, it is well-recognized that the sensitivity of any socioeconomic sector or environmental system to drought severity can be analyzed by means of drought indices that can be linked directly to sectoral impact data (Bachmair et al., 2016; Bachmair et al., 2015). This strong association has been evident for streamflow (e.g. Barker et al., 2016; López-Moreno et al., 2013), crop yields (e.g. Peña-Gallardo et al., 2019; Wang et al., 2016), vegetation activity (e.g. Liu and Kogan, 1996; Vicente-Serrano et al., 2013; Zhang et al., 2016), forest growth (Arzac et al., 2016; Pasho et al., 2011; Skomarkova et al., 2006), and even human health (Sena et al., 2014; Stanke et al., 2013). Hydrological droughts correspond to temporal anomalies in the river flows, characterized by a water deficit regarding to long-term average conditions (Van Loon, 2015), which may be related to different human, climatic and environmental factors. Numerous studies indicate that hydrological droughts can develop differently to climatic droughts, as a function of the dominant physiographic characteristics (López-Moreno et al., 2013; Peña-Gallardo et al., 2019; Tijdeman et al., 2016; Van Lanen et al., 2013) or human management (Rangecroft et al., 2018; Tijdeman et al., 2018). Moreover, numerous studies report a varying response of vegetation dynamics to drought, mainly due to the prevailing vegetation types (e.g. woodland, grassland, steppe, etc.) (Vicente-Serrano et al., 2020b), forest species (Anderegg et al., 2018; Anderegg et al., 2016; Gazol et al., 2017) and prevailing climate characteristics (Gazol et al., 2018; Pasho et al., 2011). Some of these studies established thresholds to identify drought vulnerability in response to different environmental factors (Slette et al., 2019).

Nevertheless, the majority of studies that assessed the impacts of drought have focused primarily on a specific socioeconomic sector or an environmental system. However, the multi-sectoral response to drought severity is poorly understood. This is probably due to data limitations, which hinders assessment of how multi-sectorial drought impacts can develop and compound in a particular catchment. This assessment is important in many environments to define the extent to which water and land management practices can modulate or accelerate drought impacts on different natural systems and socioeconomic sectors. Specifically, in some natural basins that are not affected by water regulation and human uses, drought impacts may exceed the locations where droughts occur. As such, these negative impacts may propagate downstream (Vicente-Serrano et al., 2017a, 2017b; Xu et al., 2019; Zhang et al., 2014), especially when water supply is essential for the development of different economic activities (e.g. irrigation, domestic use, industry, tourism, etc). Comprehensive assessment of the multi-sectoral drought impacts can also be important when establishing appropriate vulnerability thresholds, especially for ecosystems with complex drought impacts or diverse physiographical or phenological conditions (Allen et al., 2015; Sánchez-Salguero et al., 2013). In these regions, better understanding of multi-sectoral droughts can contribute to more effective monitoring, early-warning (Svoboda et al., 2002) and mitigation of drought risk (Wilhite, 2009; Wilhite, 2002). As such, given that accurate knowledge of the adverse impacts of drought on a variety of economic sectors (Bachmair et al., 2016; Bachmair et al., 2015) and environmental systems (Vicente-Serrano et al., 2020a, 2020b) is needed for reliable monitoring and management of drought, it is important to quantify comprehensively the multifaceted impacts of drought that may occur in a single territory.

The overriding objective of this study is to analyze the multisectorial impacts of drought severity in a basin of the Central Spanish Pyrenees (the upper Aragon basin). Specifically, we aim to i) determine the response of water systems to drought variability, ii) assess the varying response of natural vegetation and crops to drought, and iii) determine the possible impacts of drought severity downstream. Given its complex topography and high diversity of vegetation coverage and hydrological regimes, the upper Aragón basin presents a unique study domain to characterize the complex responses of different environmental and socioeconomic sectors to drought severity. Also, this basin has witnessed high competition among the different water uses in recent decades, especially in the downstream reaches.

2. Study area

With a total area of 2181 km^2, the upper Aragon basin is located in the Central Spanish Pyrenees (Fig. 1). The basin is characterized by a strong topographical gradient, with elevations varying from 600 to 2886 m.a.s.l. The Aragón River flows from north to south within a Paleozoic zone, with limestone, shale, and clay formations. It also crosses the Inner Sierras (limestone and sandstone), the flysch sector, and the Inner Depression (marls) before changing its direction westward. Climatologically, the basin receives an annual rainfall totals exceeding 1500 mm in the northernmost sector, declining to 800 mm in the Inner Depression. Apart from summertime, rainfall is distributed all over the year, albeit with higher intensities during spring and autumn. The mean annual air temperature is 10 °C. Snow cover appears in the period from December to April, especially at sites located above 1500 m.a.s.l (López-Moreno and García-Ruiz, 2004; López-Moreno et al., 2020). Long-term annual mean runoff is 915 hm^3, with a peak occurring mainly during springtime. This corresponds to the annual peak of rainfall and melting of the snowpack. With a capacity of 446.8 hm^3, Yesa reservoir, located at the basin outlet, is one of the largest reservoirs in the Pyrenees, providing water resources for irrigation purposes to the Bardenas region (81,000 has), located 80 km to the South of the basin (López-Moreno et al., 2004). This irrigated area is located in the central portions of the Ebro basin, where annual rainfall is generally below 300 mm, with a strong interannual variability and high rates of reference evapotranspiration (>1300 mm/year) (Tomas-Burguera et al., 2019). The main crops in the Bardenas irrigated

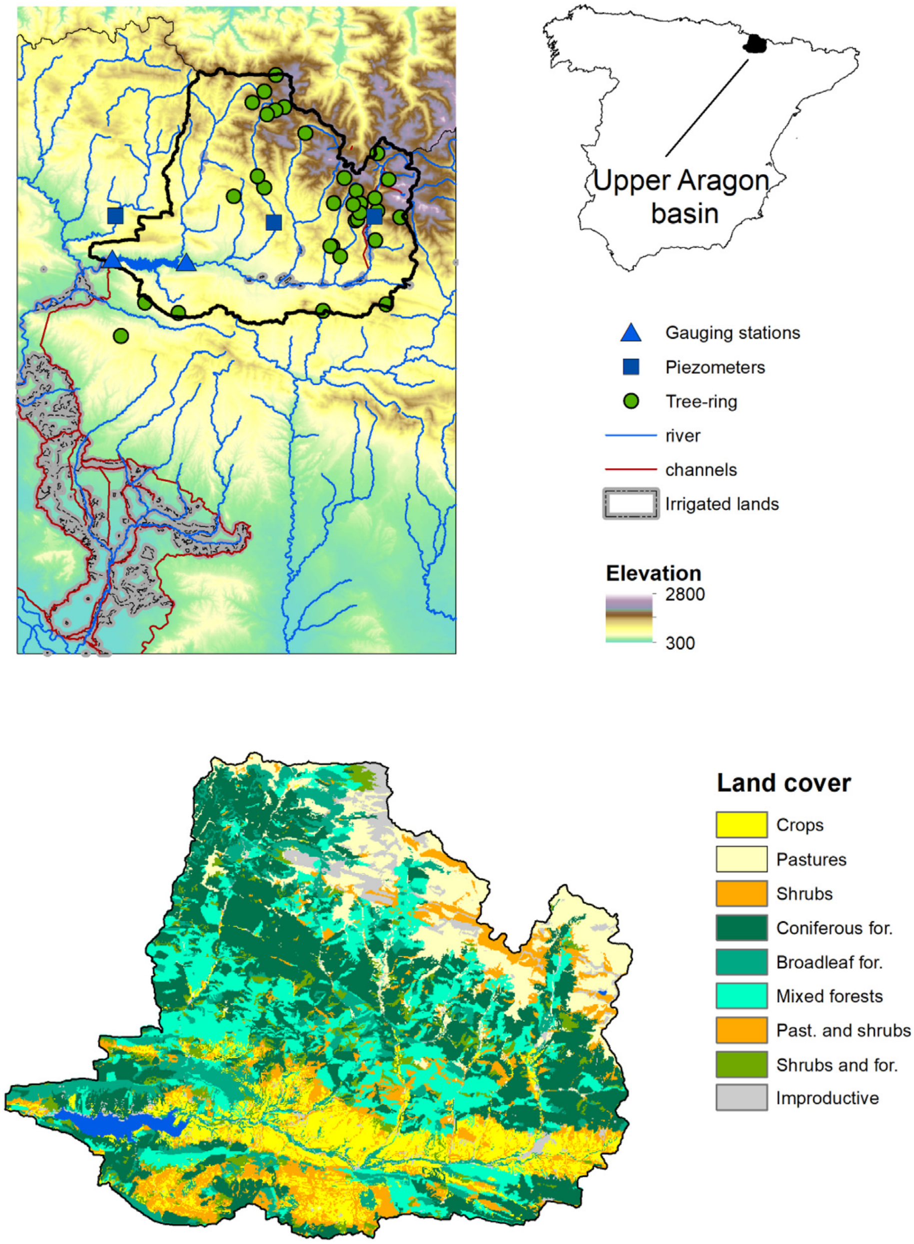

Fig. 1. Location of the study domain and the spatial distribution of hydrological stations, sites with piezometric data and tree-ring sampling sites (upper panels); and the main land cover (LC) types in ths study area (lower panels). As illustrated, the Bardenas irrigation channel transports water from the upper Aragón basin to the Irrigated lands of Bardenas in the South.

area are winter cereals (barley and wheat), which are harvested in June, and summer corn, harvested in September–October.

Vegetation cover in the upper Aragon basin is characterized by the dominance of conifers (*Pinus sylvestris* L., *Pinus uncinata* Ram., *Abies alba* Mill., *Pinus nigra* J.F. Arn.) and hardwood species (*Fagus sylvatica* L., *Quercus faginea* Lam.), while shrubs dominate the understory (e.g., *Buxus sempervirens* L.) or are distributed over the sunfaced slopes and in areas of poor soil (García-Ruiz et al., 2015). Natural vegetation has been strongly impacted by human activities. Historically, cultivated areas were located below 1600 m a.s.l., in the valley bottoms, perched flats and steep, south-facing hillslopes, which were managed even under shifting agriculture (García-Ruiz et al., 2015). Above 1600 m a.s. l. the basin is dominated by pastures generated during the middle ages to maintain big transhumant sheep folks, since the natural treeline was depressed by anthropogenic disturbances. During the 20th century, most cultivated fields were abandoned, except in the valley bottoms, and as consequence, the basin has been affected by a large natural re-vegetation process (Lasanta-Martínez et al., 2005; Lasanta and Vicente-Serrano, 2007) accentuated by the reforestation of some slopes by coniferous forests during the 1950s and 1960s (Ortigosa et al., 1990). Crops are dominant in the Inner depression and they are characterized by winter cereals: barley and wheat. Land cover changes have had an important impact on hydrological processes, and water production severely decreased over the last decades in the basin as a consequence of increased evapotranspiration (Beguería et al., 2003; López-Moreno et al., 2011).

3. Datasets description

3.1. Climatic dataset

The precipitation and reference evapotranspiration data for the basin were extracted from a gridded climatic dataset developed by Vicente-Serrano et al. (2017c) for the whole of Spain. This dataset includes information on a wide array of climatic variables (e.g. precipitation, maximum and minimum air temperature, relative humidity, sunshine duration, and wind speed) at high spatial (1.21 km^2) and temporal (weekly) resolution. This dataset was developed using the most complete register of observed climate records provided by the Spanish Meteorological Agency (AEMET), including meteorological stations located at different elevations. In particular, in the upper Aragon basin there are more than 50 meteorological stations from a range of 500 to 1750 m, although it varies among variables (more available for precipitation than for temperature). The dataset showed good performance in capturing drought characteristics (e.g. severity, spatial extent) in earlier studies over Spain (e.g. Domínguez-Castro et al., 2019; Noguera et al., 2020).

3.2. Hydrological dataset

Data on surface flows and storage levels for the Yesa reservoir were obtained from the Ebro Basin Management Agency (*Confederación Hidrográfica del Ebro*; http://www.chebro.es/) This also includes data on monthly inflows into the reservoir and releases downstream (i.e. to the Aragón River and the Bardenas channel). Yesa water inflow is directly influenced by the climatic conditions since there is not other regulation upstream), while all other hydrological variables (Yesa storage, Bardenas channel and the Aragón flows downstream Yesa) are dependent to water management practices. Also, data about the piezometric levels at four gauging stations in the basin were provided by the Spanish Ministry for the Ecological Transition (https://sig.mapama.gob.es/redes-seguimiento) for the period 1992 to 2017 (Fig. 1). These data were employed to assess the response of groundwater levels to climatic droughts. Given considerable amount of missing values and data gaps in the piezometric data before 2002, we only employ data for the period 2002–2017 to assess the links between piezometric levels and climate droughts in the basin. We also employ monthly snow depth data for highly elevated sites (above 1500 m. a.s.l). Data were obtained for the months between December and April for the period 1958–2017. A description of this dataset is outlined in López-Moreno et al. (2020).

3.3. Tree-ring data

Tree-ring width data were collected from six representative tree species in the basin: *A. alba, P. sylvestris, P. uncinata, P. nigra, F. sylvatica* and *Q. faginea*. Data from 37 sites with forest growth were used in this work. Overall, the tree-ring data were processed by means of standard dendrochronological protocols (Fritts, 1976). Specifically, at least 10–15 dominant trees located in undisturbed stands of each species were selected and cored at 1.3 m using increment borers. This procedure aimed to obtain 2–3 cores per tree in each forest. Cores were air dried, carefully sanded and ring series were visually cross-dated. Tree-ring width was measured to at least the nearest 0.01 mm using binocular microscopes and different measuring device systems (i.e. Lintab, RinnTech, Heidelberg, Germany; Velmex Inc., Bloomfirld, NY, USA). In order to check the accuracy of visual cross-dating and measurements, we used the COFECHA program (Holmes, 1983). Each individual tree-ring width series was detrended by fitting negative exponential curves. Then, the residuals were computed through dividing the observed values by the fitted ones. Autoregressive modelling was used to remove the first-order autocorrelation from the individual, detrended tree-ring width series. Finally, the detrended individual series of tree-ring width indices (hereafter TRWi) were averaged for each forest and species by computing the bi-weight robust means. These procedures were carried out using the ARSTAN software (Cook, 1985). Herein, the mean site-level chronology represents the average growth series of the variable number of trees associated with the same species and the same forest stand. A detailed description of the sampling procedure and data processing is documented in recent studies (e.g. Gazol et al., 2018; Peña-Gallardo et al., 2018; Vicente-Serrano et al., 2020a).

3.4. Vegetation activity

Vegetation activity was quantified by means of two-band Enhanced Vegetation Index (EVI2) from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite sensor for the period 2000–2020. EVI2 is more robust against the three-band EVI, which is sensitive to atmospheric disturbances caused by the blue band (Jiang et al., 2008). While EVI2 is an indicator of the photosynthetic activity, it can also be seen as a proxy of other vegetation parameters (e.g. the leaf area index, vegetation coverage, vegetation primary productivity and carbon uptake) (Huete et al., 2002). The MODIS reflectance data used for calculating EVI2 were from the MCD43A4 product, retrieved from the NASA repository (https://modis.gsfc.nasa.gov/data/dataprod/mod13.php) at a grid interval of 500 m and averaged to a temporal frequency of 16-days. Curve fitting was applied to the 16-day composite data to extract comparable monthly values using the TIMESAT software package (Jönsson and Eklundh, 2004). Typically, the use of EVI2 data is advantageous in areas with pasture and shrub lands, where samples of forest growth are unavailable. Nonetheless, these data can also be used in forest areas to determine the different impacts of drought, given that vegetation responds differently to drought in forest areas (Gazol et al., 2018; Peña-Gallardo et al., 2018). We also make use of satellite data available at more detailed spatial scales by computing the EVI2 using Sentinel-2 data at 10 m spatial resolution for the period 2017–2019. Sentinel-2 data were obtained from the European Space Agency (https://sentinel.esa.int/web/sentinel/sentinel-data-access) at a spatial resolution of 10 m and a daily temporal resolution. Curve fitting was applied to Sentinel-2 pixel values using a robust method (Jönsson et al., 2018; Cai et al., 2017) to generate comparable monthly values of EVI2 for each image pixel.

3.5. Vegetation phenology

As vegetation can be impacted by drought at different phenological phases (Reynolds et al., 1999; Sah et al., 2020; Wang et al., 2020), we employed a set of phenological metrics to assess ways in which drought can influence vegetation dynamics. These metrics included the start date, end date, length of season (duration), amplitude (peak vegetation index value minus the off-season base level value) and integral (seasonal sum of the vegetation index values) of the growing season corresponding to each year for the period between 2001 and 2019. The start and end dates represent the location of the growing season in time whereas the amplitude and integrals relate to vegetation production during the growing season. All metrics were retrieved from the EVI2 data using the TIMESAT software (Jönsson and Eklundh, 2004), after applying a function fitting procedure to obtain the different phenological parameters. TIMESAT-based phenology has been widely validated in different regions of the world with a high agreement between phenological ground observations and TIMESAT calculations using satellite data (Peng et al., 2017; Tan et al., 2011).

3.6. Land cover data

A land cover (LC) map developed by the Spanish Ministry of Agriculture (https://www.mapa.gob.es/es/cartografia-y-sig/publicaciones/agricultura/mac_2000_2009.aspx) was used to determine possible differential impacts of drought on vegetation activity and annual phenology in the dominant land cover types of the upper Aragón basin. Although this map was updated in 2010, it remains representative of the current dominant land cover classes in the basin.

3.7. Crop yield data

Crop yield data for the dry lands of the upper Aragón basin were obtained from the Spanish Ministry of Agriculture (https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/agricultura/esyrce/) for the period 2001–2019. Annual yield data (kg/ha) were provided for the two major cultivated crops: winter barley and wheat. This information is based on annual crop field surveys (Peña-Gallardo et al., 2019). In addition, we obtained crop yields in the irrigated area of Bardenas for barley, wheat and corn from 2003 to 2015; dry land crop yields were also available for barley and wheat in the municipalities that include these irrigated lands, so this information was used for comparative purposes.

4. Methods

To characterize climatic drought severity, we used the standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al., 2010). This is one of the well-established drought indices, which has been widely used for drought quantification over the past decade. The SPEI is computed as the difference between precipitation and reference evapotranspiration, accounting for the possible role of atmospheric evaporative demand (AED) in drought severity. Accordingly, it has been widely used for drought analysis and impact monitoring in different regions worldwide (e.g. Bachmair et al., 2018; Bachmair et al., 2016; Bachmair et al., 2015; Peña-Gallardo et al., 2018; Scaini et al., 2015). Herein, SPEI was computed at different timescales ranging from 1- to 48-month timescales. This is simply because the response of different systems to drought is strongly determined by the time scale at which drought is quantified. This dependency has already been evident in different studies, including natural ecosystems (e.g. Pasho et al., 2011; Vicente-Serrano et al., 2013), hydrology (e.g. Barker et al., 2016; Lorenzo-Lacruz et al., 2017; Lorenzo-Lacruz et al., 2013; Peña-Gallardo et al., 2019), and crop yields (e.g. Peña-Gallardo et al., 2018). We computed a regional series of the SPEI for the whole basin using a simple arithmetic average of the available precipitation and reference evapotranspiration data. In the same manner, a regional series of the SPEI was also calculated for the Bardenas irrigation area.

Hydrological drought was quantified by means of the Standardized Streamflow Index (SSI) (Vicente-Serrano et al., 2012). The SSI was computed using data of monthly inflows, streamflow releases, and reservoir storages within the basin for the period 1962–2019. Similar to SPEI, SSI values are expressed in standardized units, with a zero-average and one-standard deviation, enabling direct comparison between streamflow systems with different magnitudes and seasonal regimes. For this purpose, monthly series of the raw hydrological data are fitted to a distribution probability. Given the strong differences in the distribution of the monthly streamflow series, the distribution that shows the best fit with each one of the monthly series is selected. The SSI is always calculated at the time scale of one month. Irrigation from the Bardenas channel was not operative at full capacity until 1970 so standardization and subsequent analysis were based on the period between 1970 and 2020.

The same standardization approach was implemented for data of snow depth. Nevertheless, as the records of piezometric levels were not sufficiently long to allow a fit to a probability distribution, the average and standard deviation of the monthly series were used, assuming a normal distribution. For tree-ring data, the standardized mean series were obtained for each forest and species. The detrended tree-ring series (with a range between 0 and 1) followed a normal distribution so they were also standardized considering the mean and standard deviation of each series. Following this approach the series of all of these variables had the same units (z-units) and they were perfectly comparable, spatially and seasonally, independently of the different magnitude and seasonality of each variable.

We employed the Pearson's r correlations to assess the links between the series of SPEI and those of the different available datasets (e.g. flows, tree-ring growth, phenology metrics, crop yields). Correlations were computed for all SPEI timescales (i.e. 1- to 48-month) and were calculated for each one of the 12 monthly series of the year. No lagged correlations were calculated. Herein, it should be noted that drought severity was computed using different SPEI thresholds, which represents different probabilities of occurrence. These thresholds included SPEI values of zero (1 in 2 years), −0.84 (1 in 5 years), −1.28 (1 in 10 years) and −1.65 (1 in 20 years). However, this analysis was restricted only to forest growth and hydrological variables, mainly due to the availability of longer timeseries to reliably assess the impacts of drought severity analyzing the anomalies recorded in these variables corresponding to different thressholds of the SPEI.

5. Results

5.1. Temporal variability of climatic droughts

Fig. 2 illustrates the temporal evolution of climatic drought over the Yesa basin using SPEI computed at timescales ranging from 3- to 24-

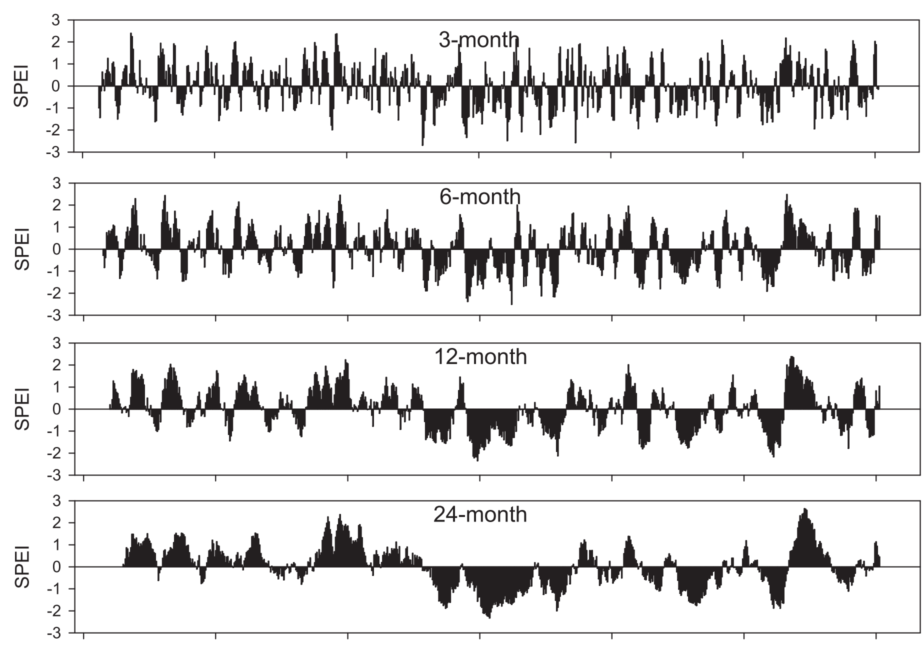

Fig. 2. Evolution of climate droughts in the Yesa basin based on SPEI computed at time scales of 3-, 6-, 12- and 24-month.

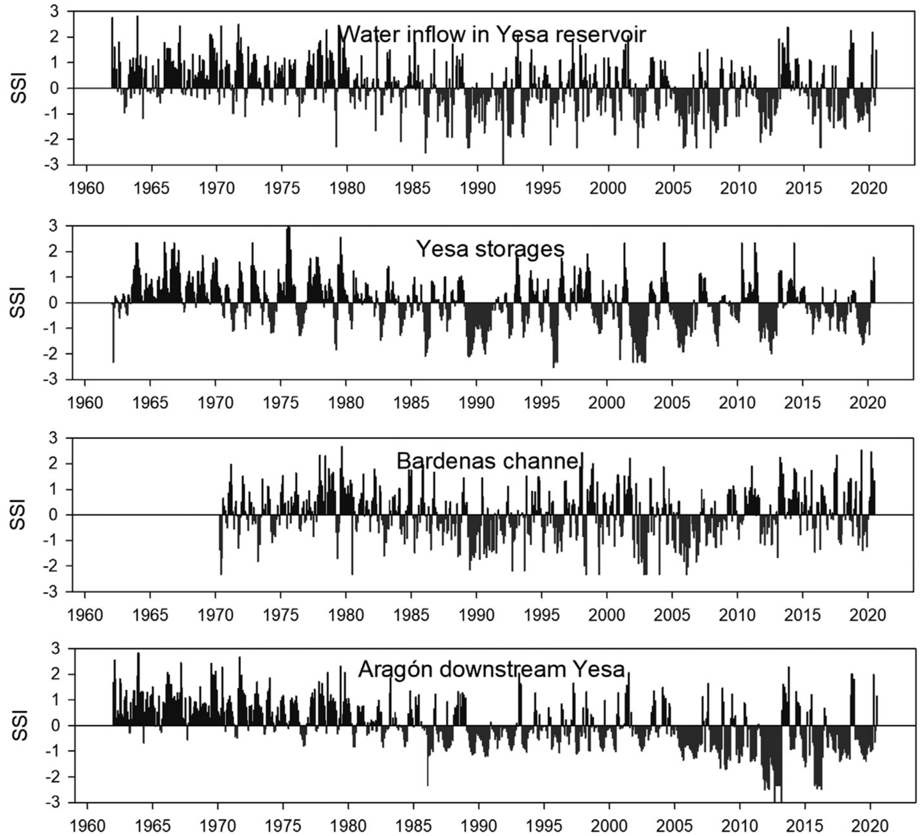

Fig. 3. Evolution of hydrological drought, as revealed by SSI, computed for the period 1962–2020. SSI was calculated using water inflows, reservoir storages, Bardenas channel flow and the Aragón River downstream the Yesa reservoir.

month. Results demonstrate that the basin has witnessed frequent drought events in the period 1961–2020, but with more frequent dry events in recent decades (mostly from the 1980s onwards). The longest and more intense drought events were observed during the 1990s, while wet conditions prevailed in the 1960s and 1970s. Nonetheless, it can be noted that the frequency of drought events varies considerably as a function of SPEI time-scale.

5.2. Links between meteorological and hydrological droughts

Fig. 3 shows the evolution of the SSI between 1962 and 2020, calculated using different hydrological data. Similar to SPEI evolution, the water inflows into the Yesa reservoir showed generally wetter conditions during the 1960s and 1970s, and more severe droughts in the early 1990s and between 2005 and 2020. Relative to SPEI, it seems that hydrological droughts exhibits higher interdecadal variability and a stronger negative trend over the concurrent period of record. A similar pattern was observed for the Yesa reservoir storage. Large important negative anomalies were recorded at the beginning of the 1990s and during the 2000s. A reversed pattern was observed for the water released to Bardenas channel during the 2010s, despite the pre-dominantly negative anomalies in the Yesa reservoir storage. In accordance with other hydrological data, the SSI computed downstream of the Aragón River showed a clear decreasing trend from the 1960s to 2020. Thus, from 1990 negative SSI anomalies are clearly dominant. These negative anomalies are much more accentuated and persistent than those identified from the inflows to the Yesa reservoir.

To further explore links between climatic and hydrological droughts, we computed the correlation between SPEI and SSI. Results demonstrate varying responses of hydrological variables to climate drought, which seem to be strongly related to water management in the basin (Fig. 4). As illustrated, the inflows to the Yesa reservoir showed the highest correlation with climatic drought at the 2-month timescale. In contrast, reservoir storages generally exhibited lower correlations with climatic drought. The highest correlations were recorded at the 6-month timescale. Fig. 4a reveals that the dependency between climatic drought and both inflows in Yesa reservoir and reservoir storages showed similar patterns at the different timescales, albeit with quite lower correlations with reservoir storages. Fig. 4a also shows low correlations between hydrological drought in the Bardenas channel and climatic drought, with values generally below 0.4. This weak association is evident for all timescales. These general correlations vary considerably on the monthly scale (Fig. 4b). Specifically, inflows showed high correlations with SPEI during all months, but with a stronger association in the period from September to May. Reservoir storages exhibited stronger correlations with SPEI from October to February and in July and August. However, this dependency seems to be more sensitive at longer time scales (10–15 months) during summertime. The sensitivity of SSI to SPEI indicated high seasonality downstream of the Yesa reservoir, with higher dependency between December and March and low dependency during summer months. As opposed to other hydrological variables, it seems that hydrological droughts in the Bardenas channel shows weaker response to climatic droughts, irrespective of the season. Exceptionally, in some years (e.g. 1990, 2003 and 2005), the channel flow was strongly constrained by climate drought events (refer to Fig. 3). In these three years the reservoir storages were reduced and they were not sufficient to supply the channel at the normal level. This pattern is not identified in all drought events. In 2013 a severe drought event produced low inflows and reservoir storages, but the SSI of the Bardenas channel only recorded small negative anomalies during a few months of the year. On the contrary, the releases to the

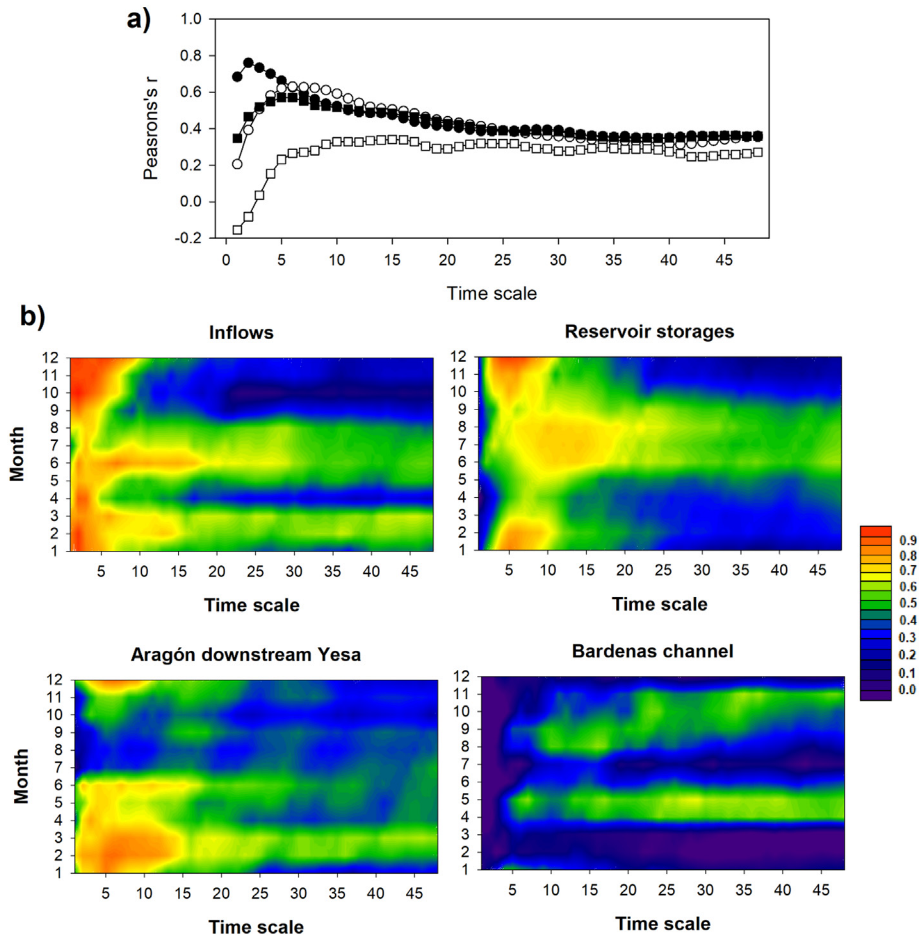

Fig. 4. a) Pearson's r correlations between climatic drought (as defined using SPEI at 1- to 48-month timescales) and hydrological drought (as represented using SSI computed for the four hydrological variables). Black circles: Yesa inflows, White circles: Reservoir storages, Black squares: Releases to the Aragón river downstream Yesa, White squares: Bardenas channel, b) same as panel a, but considering correlations at monthly scale. Significant correlations are set at Pearson's r = ±0.25 ($p < 0.05$, two-tailed), for inflows, reservoir storages and the Aragón flows downstream Yesa and at Pearson's r = ±0.27 (p < 0.05, two-tailed), for the Bardenas channel.

Aragón river, downstream of Yesa, showed the largest negative values during the 2013 drought.

An inspection of Figs. 3 and 4 illustrates that the slightly dry climate conditions between 2015 and 2020 coincided with predominantly negative anomalies of reservoir inflows, positive anomalies in the Bardenas channel, and strongly negative anomalies in the Yesa releases to the Aragón River. This behavior is illustrated in Fig. 5, which indicates that severe climate drought conditions, as represented by a return period of one event on average per 20 years, corresponded to negative anomalies in the flow of the Bardenas channel during the warm season (MJJAS). Rather, climatic drought showed relatively less impact on the releases to the Aragón River. Reservoir storages are also constrained by severe drought conditions in summer months. The situation is different during the cold season (ONDJFMA) since the inflows/outflows to/from the Yesa reservoir are more affected by drought severity than the anomalies in reservoir storages and the flows of the Bardenas channel, which show high spread with drought severity. Fig. 5 also shows that hydrological droughts downstream of the Aragon River are more sensitive to drought severity during the warm season, with notable variability in response to mild, moderate and extreme drought events.

To assess the impacts of climatic drought on groundwater, we correlated the piezometric levels across the study domain with SPEI. As illustrated in Fig. 6-a, the most anomalous drought events, which were recorded in 2005, 2012 and 2017, corresponded to a notable decline of piezometric levels. Fig. 6-b reveals a strong seasonality in the response of groundwater to the climatic drought variability. Specifically, the highest correlations were found for April, May and October, while a weak response was noted during wintertime. Similarly, winter snow depth in the study domain showed a strong interannual variability (Fig. S1), which can partly be linked to drought occurrence and severity. Results demonstrate that snow depth between January and April is highly correlated with SPEI at 4–6-month timescales (Fig. 7).

5.3. Drought impacts on vegetation activity

Fig. 8 depicts correlations between the EVI2, as a proxy of vegetation cover, and SPEI at 1- to 48-month timescales. Results suggest that the correlation is seasonally dependent, with remarkable differences among seasons and land cover types. Notably, vegetation activity in the upper Aragón basin is mostly impacted by climatic drought during summertime, especially at both 2- to 8-month and 20- to 24-month timescales. This dependency was less evident for other periods of the year.

The differences between land cover types were also important (Fig. 8). In particular, coniferous forests showed weaker response to drought variability, compared to shrubs and crops that were highly sensitive to SPEI at 2- to 5-month timescales during June and July. Interestingly, results reveal that spring pastures, mainly located in the bottom valleys, were more sensitive to climatic drought than mountainous summer pastures (>1600 m.a.s.l.). A similar pattern was also found

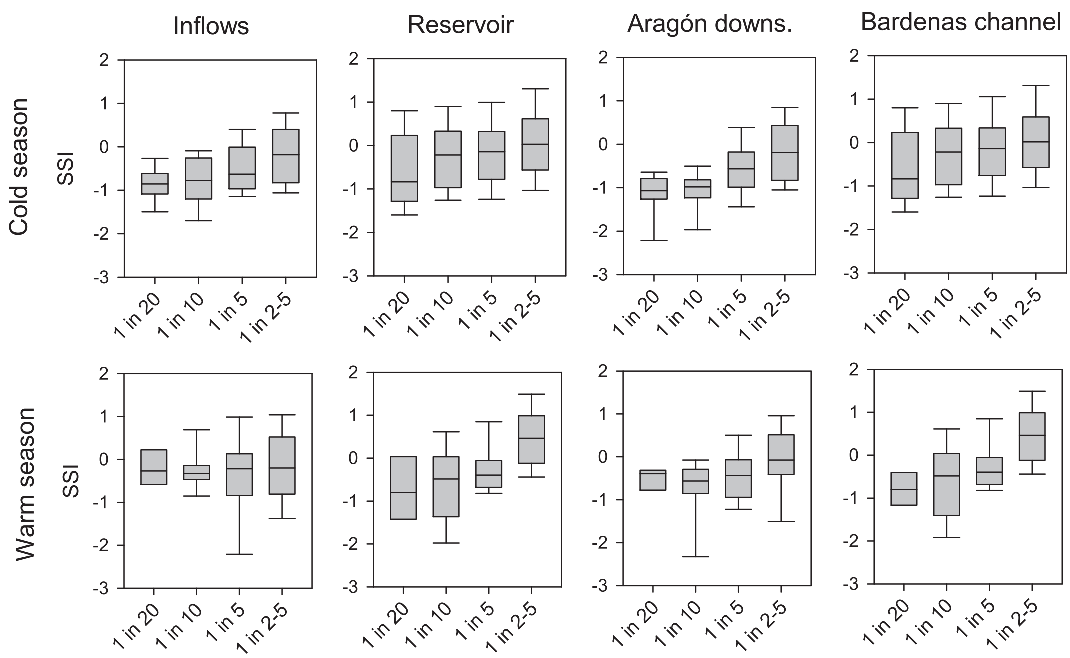

Fig. 5. Boxplots showing the values of SSI corresponding to the different climatic drought severities, as represented by return periods. Herein, results are presented only for drought timescales at which the different hydrological variables showed the best correlation (refer to Fig. 4). Warm season (MJJAS): Inflows (2-month); Reservoir storages, outflows and Bardenas channel (14-month); Outflows (14-month); Cold season (ONDJFMA): Inflows (2-month); Reservoir storages; outflows and Bardenas channel (8-month. The central solid line indicates the median. The whiskers represent the 10th and the 90th, while the 25th and the 75th are plotted as the vertical lines of the bounding boxes.

for different forest species. A representative example is *P. sylvestris,* which showed higher sensitivity to climatic drought than *P. uncinata (mainly located* above 1600 m a.s.l.). In the same context, apart from long SPEI timescales during summer, *F. sylvatica* (located in humid sites and N-NW-facing slopes) exhibited low sensitivity to climatic droughts. Fig. 8 also indicates that the mixed forest (mostly forests of *Q. faginea* and *P. sylvestris*) showed mixed responses. Fig. S2 shows that – regardless of the dominant land cover type – there is a significant association between EVI2 and SPEI over large areas of the basin during summertime. However, a more detailed assessment of this dependency using an improved grid resolution of Sentinel-2 images (from 500 to 10 m) suggests considerable spatial differences over the basin. In particular, it seems that this spatial variability is driven largely by terrain exposure and topographical gradient. This has been evident for the three years investigated using Sentinel-2 images, although drier conditions were found in 2019, compared to 2017 and 2018 (Fig. S3).

5.4. Drought impact on forest growth

An assessment of the tree-ring growth variability in the study domain reveals considerable differences among the dominant tree species (Fig. S3). This is reflected in the varying responses of these species to climatic drought variability. These differential responses among the forest species are highly coherent with those observed using EVI2 data, albeit with lower correlations. Results demonstrate that tree-ring growth in the forests of the Upper Aragón basin show better association with climatic drought at 3- to 5-month timescales in August, as well as

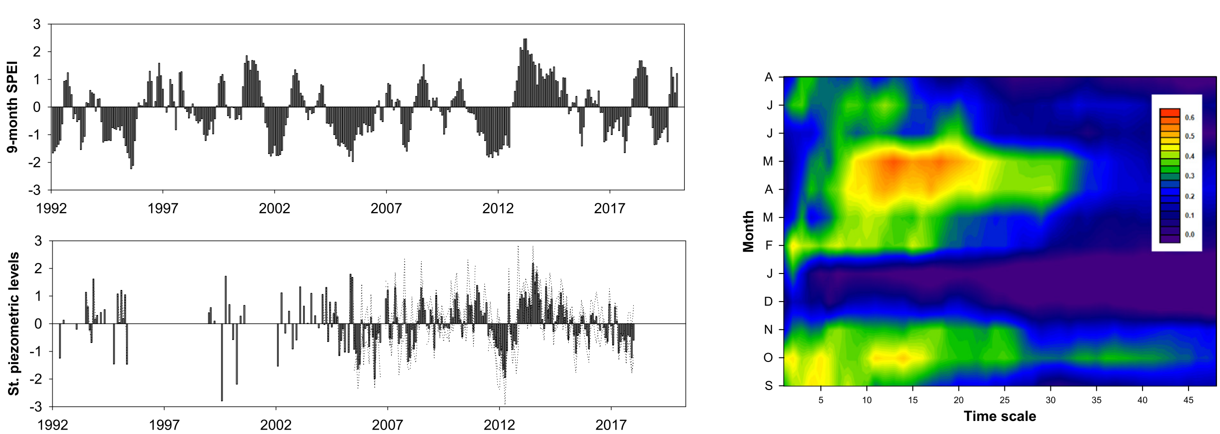

Fig. 6. Left: Evolution of both SPEI at 9-month timescale and the standardized piezometric levels. Right: Monthly Pearson's r coefficients calculated between the mean standardized piezometric levels and SPEI at 1- to 48-month timescales.

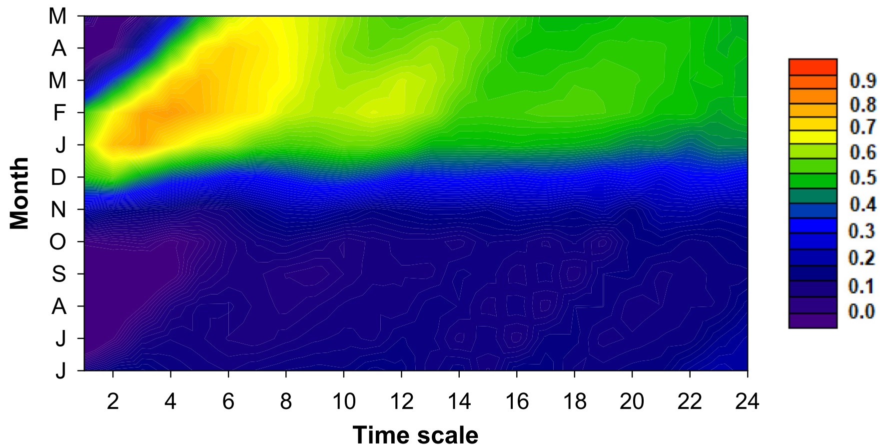

Fig. 7. Monthly Pearson's r coefficients calculated between snow depth over the period December–April and SPEI at 1- to 24-month timescales.

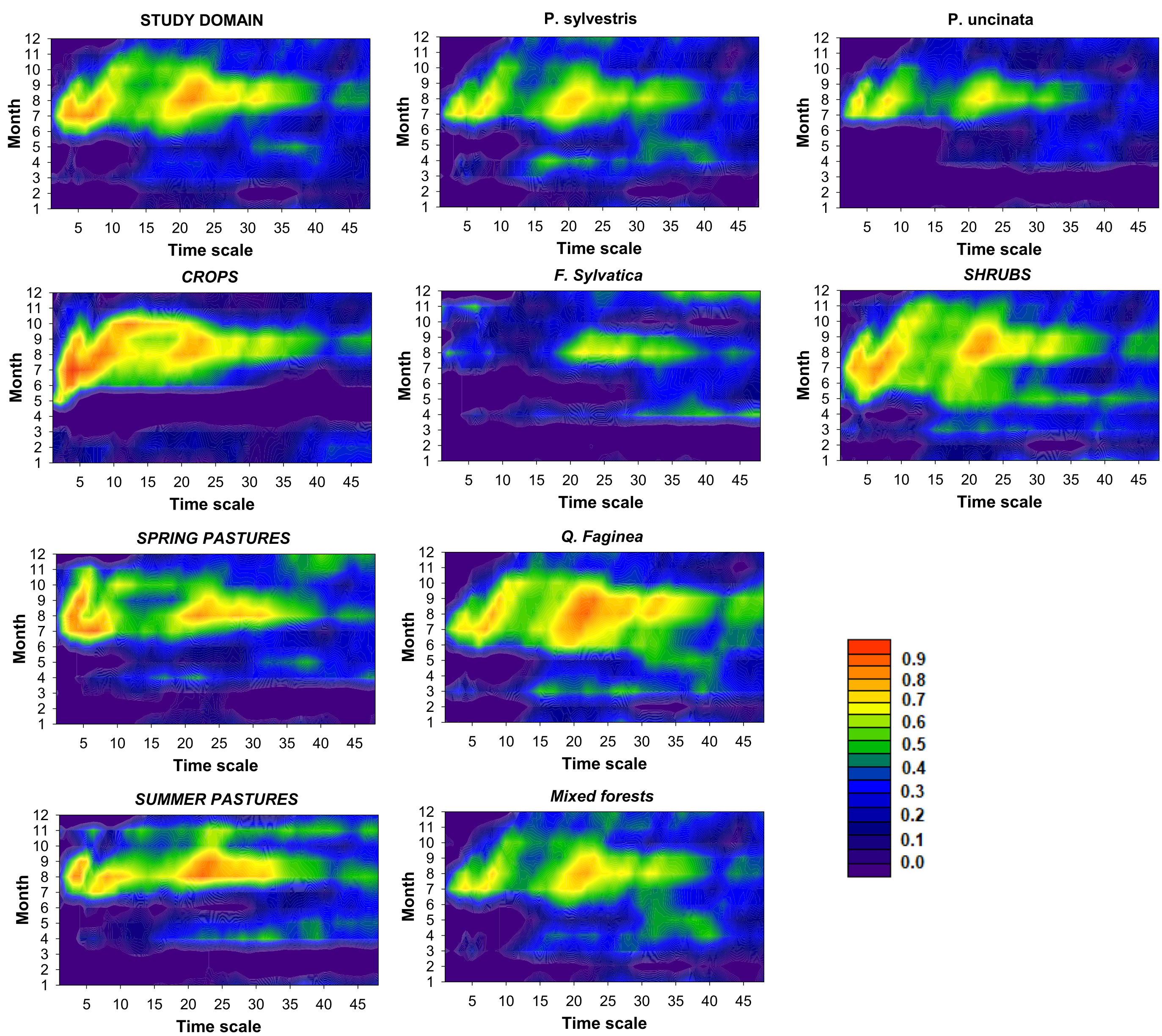

Fig. 8. Monthly Pearson's r coefficients between the values of EVI and those of SPEI 1- to 48-month timescales for the dominant land cover types of the upper Aragón basin.

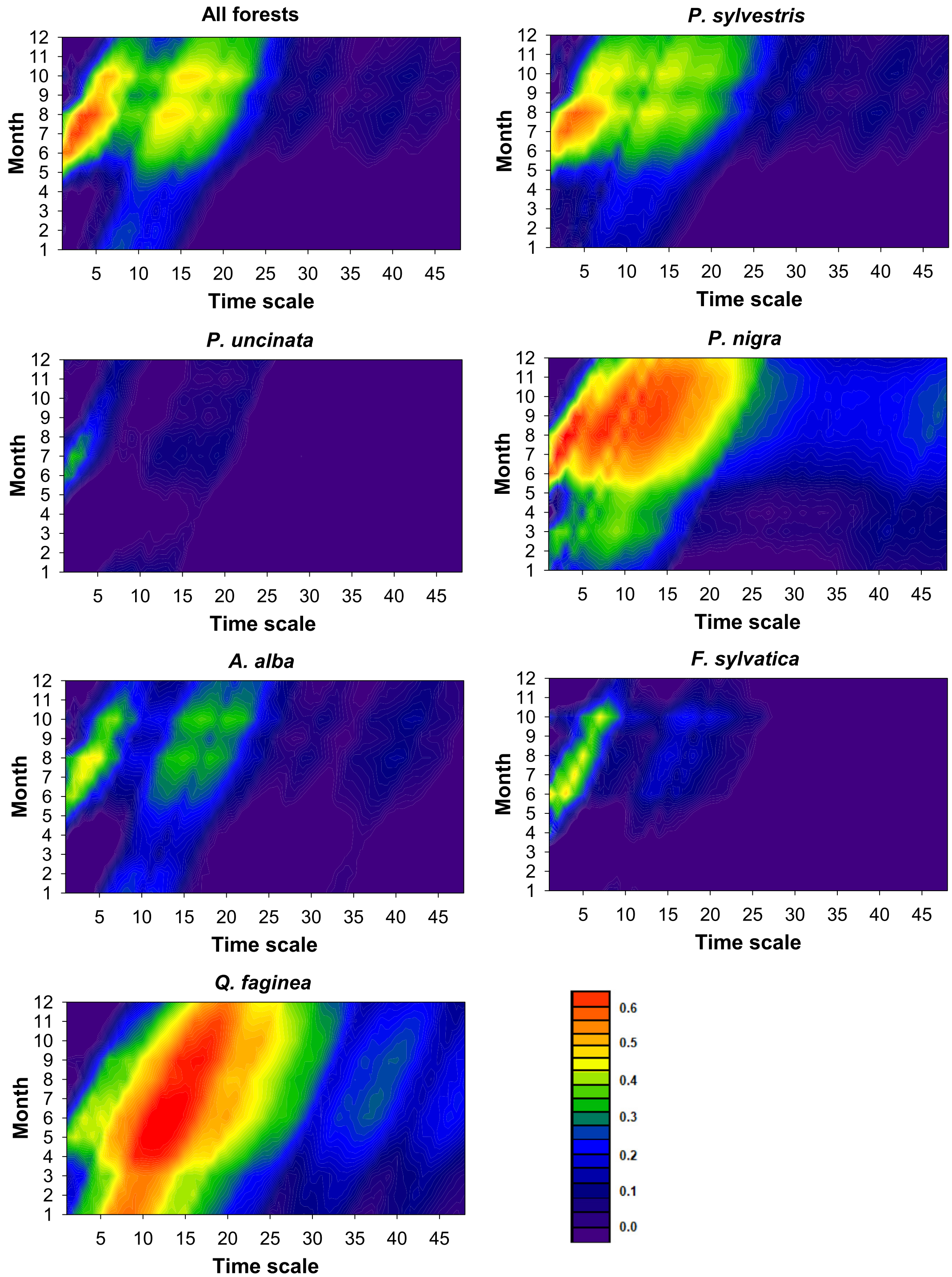

Fig. 9. Monthly Pearson's r coefficients between the values of the annual tree-ring growth and those of SPEI 1- to 48-month timescales for the dominant land forest species of the upper Aragón basin.

15–20 month timescales during summer months (Fig. 9). Interestingly, the forest types located at low elevations and drier areas (e.g. *P. nigra* and *Q. faginea*) showed stronger dependency on climatic drought than forest species situated in the most humid areas and at high elevation sites (e.g. *A. alba*, *F. sylvatica* and *P. uncinata*). Rather, *P. sylvestris* indicates an intermediate response between these two groups of species. Overall, regardless of the tree species, it is clearly evident that forest growth is more impacted by climatic drought during summer. Fig. 10 summarizes forest growth anomalies in response to drought events of different severities. It is evident that a clear gradient in the negative anomalies of forest growth in response to drought severity exists, with forest growth reducing largely during most severe drought events (i.e. 1 event in 20 years). A comparison between the different tree species reveals that *P. uncinata* is mostly insensitive to drought variability. In contrast, species of more humid habitats (e.g. *A. alba* and *F. sylvatica*) showed less dependency on climatic drought variability. However,

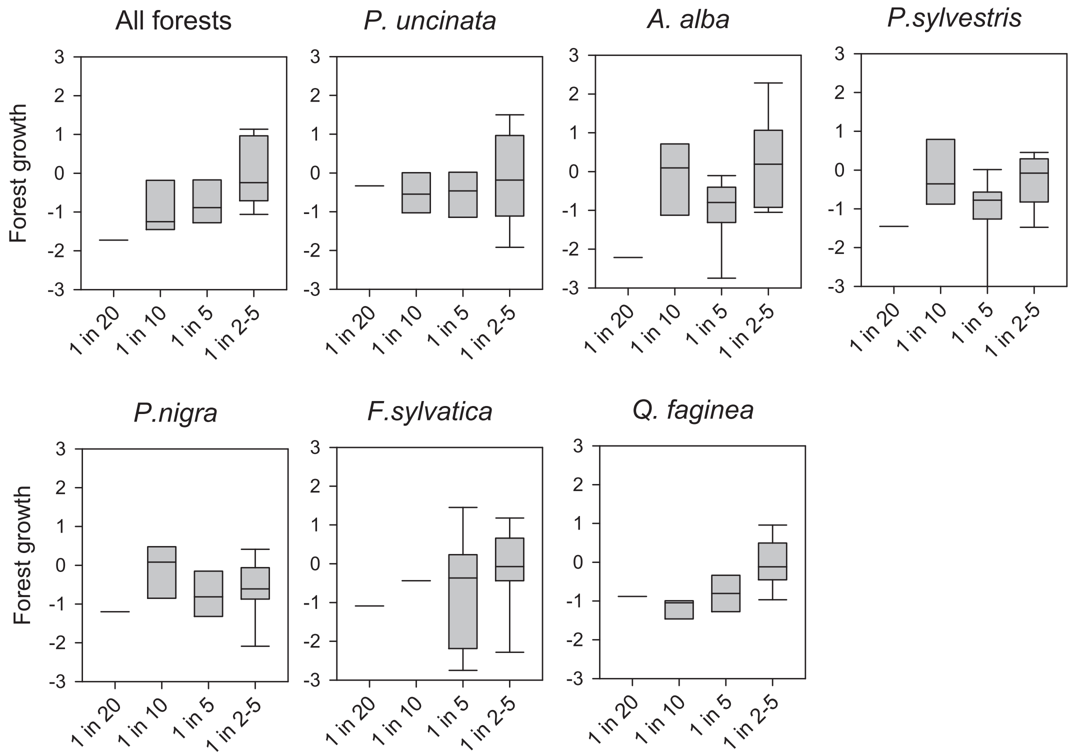

Fig. 10. Boxplots showing the standardized values of forest growth, as a function of the different drought severity thresholds (return periods). Herein, results are presented only for monthly SPEI timescales that showed the highest correlation with forest growth, as illustrated in Fig. 9. All: 3-month in July; *P. uncinata*: 2-month in July; *A. alba*: 4-month in August; *P. sylvestris*: 4-month in August; *P. nigra*: 3-month in August; *F. sylvatica*: 1-month in June; and Q. faginea: 14-month in June. The central solid line indicates the median. The whiskers represent the 10th and the 90th, while the 25th and the 75th are plotted as the vertical lines of the bounding boxes.

even the growth of those species is impacted notably by climatic drought during extreme drought episodes.

5.5. Drought impacts on plant phenology

The effect of drought on plant phenology is clearly visible although less seasonally distinct in as compared to those found for vegetation activity or forest growth. Correlations were found to be significant considering the onset of the growing season, which tends to advance in response to dry events. Notably, the highest correlations were found for the integral of the whole growing season (Fig. 11). Nonetheless, this dependency varies considerably over space (Fig. 12) and as a function of the different land cover types (Figs. S5-S9). The integral of the growing season is more sensitive to climatic drought in shrubs and *Q. faginea* forests, which are usually located in low elevated areas. Rather, the onset of the growing season and the total length of the active period seem to be more impacted by drought in areas where summer pastures dominate.

5.6. Drought impacts on crop yields

As opposed to the strong dependency found between climatic drought variability and vegetation activity (Figs. 8–10), the response of rainfed barley and wheat crop yields to variability of climatic drought seems to be minimal (Fig. 13). Results indicate that there is no crop failure in the upper Aragón basin, even during years with extreme climatic droughts. Thus, wheat and barley crop yields are characterized by a certain interannual variability but in general high yields are recorded during all years. The crop yields recorded in the upper Aragón basin show a similar magnitude to the irrigated lands of Bardenas (Fig. S10). These results together suggest that drought is not a key driver of barley and wheat yields in the rainfed crops of the upper Aragón basin.

5.7. Drought impacts downstream the upper Aragón basin

Fig. S11 demonstrates that the temporal variability of climatic drought shows a similar pattern in both the upper Aragón basin and the irrigated lands of Bardenas, with Pearson's r equal 0.85. However, although consistent drought episodes can be determined for both areas, the flows of the Bardenas channel from the upper Aragón basin to the Bardenas irrigated area are less correlated with climatic drought in the Bardenas irrigated fields (Fig. S12). The yield of irrigated crops was found higher than crops located in the dry lands of the Bardenas area (Fig. S10), which may suggest that the channel flows can be seen as an independent signal in relation to climatic drought in the basin. Fig. S13 confirms this finding, as the correlation between the interannual variability of irrigated wheat and barley yields and those of dry land yields was low, explaining only 25% of the total variability. Barley and wheat yields in the irrigated lands showed low temporal variability and accordingly more stable yields. For corn, the yields were higher, with an increasing trend from 2003 onwards (Fig. S14). Although the average vegetation activity in the Bardenas areas, obtained from EVI, witnessed an increase from 2000 to 2020 (Fig. 14a), the correlation between vegetation activity and climatic drought (i.e. SPEI) was generally low (Fig. 14b), mainly during summer climatic stress conditions. Accordingly, the monthly correlations between vegetation activity, as derived from EVI, and hydrological droughts in the Bardenas channel were much higher than those with local climatic drought (Fig. 14c). This dependency on hydrological drought is mostly seen during summer months, in which corn cultivation is determined largely by the availability of irrigated water. The wheat and barley yields in the irrigated and dry land cultivations of the Bardenas area showed clear differences in their response to climatic drought between 2003 and 2015 (Fig. 15). Specifically, in the irrigated lands, the higher correlations were found between February and April considering long time scales.

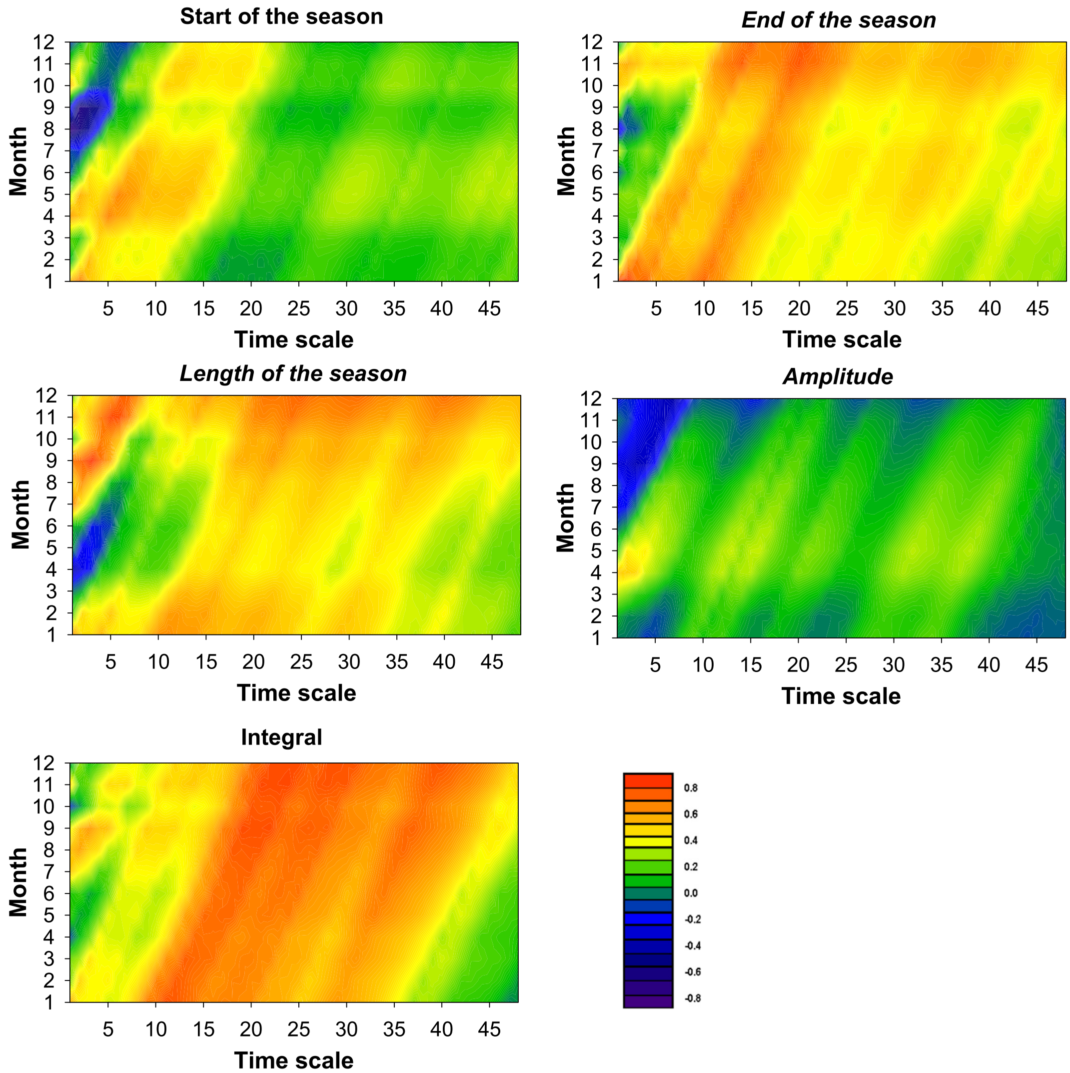

Fig. 11. Monthly Pearson's r coefficients between different metrics of plant phenology and SPEI 1- to 48-month timescales averaged for the whole upper Aragón basin.

On the other hand, the correlations for the crops in the dry areas were higher in the period from February to April, but considering shorter SPEI timescales (i.e. 3- to 5-month). For hydrological droughts, the correlation between the yields of wheat and barley in the irrigated lands and monthly SSI in the Bardenas channel was low during the period of crop development. Nevertheless, this correlation was high during summer in the case of the corn. Conversely, the dependency between corn yield and climatic drought in the Bardenas area was less significant.

6. Discussion

Overall, this study stresses that drought impacts vary considerably among the different hydrological, environmental and agricultural subsystems. These differences can also be further enhanced by the strong diversity of hydrological regimes, forest types and tree species, and land cover types. This complexity makes it difficult to characterize, monitor, and mitigate the adverse impacts of drought in the study domain. This concurs with earlier studies that indicated that the components of the hydrological cycle (e.g. soil moisture, streamflow, groundwater) can respond differently to precipitation deficits (Changnon et al., 2007; McKee et al., 1993). These natural differences in the hydrological response can be one of the main reasons to explain the strong diversity of the multi-sectorial drought impacts in our study domain since we have identified different responses to drought time scales between streamflow and reservoir storages. This strong dependency was confirmed in some earlier studies covering the study basin (e.g. Vicente-Serrano and López-Moreno, 2005).

6.1. Links between climatic and hydrological droughts

Our results indicate that hydrological drought, represented by SSI using different hydrological variables, is highly correlated with climatic drought using SPEI. This implies that the occurrence of extreme drought events has an important role in explaining water deficits in the basin. As expected, snow cover, streamflow, and groundwater showed a clear response to climatic drought variability in the basin. However, groundwater responded to drought at longer timescales than did streamflow and snow depth. This behavior can simply be seen in the context that groundwater droughts are characterized generally by their slow dynamics and delayed response to climatic drought. This agrees with the findings of Bloomfield et al. (2015), Lorenzo-Lacruz et al. (2017), and Marchant and Bloomfield (2018).

It should be stressed that although water resources are strongly impacted by climatic drought variability in the upper Aragón basin, human management and practices are dominant factors controlling

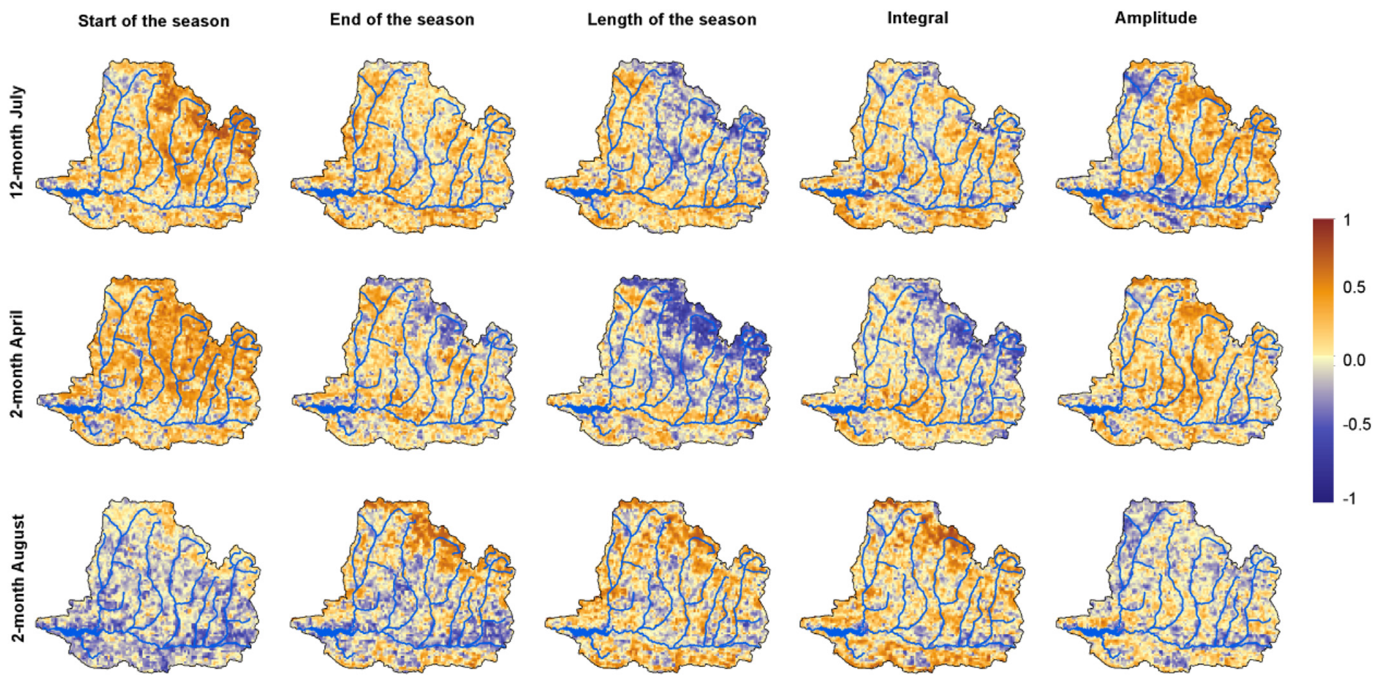

Fig. 12. Spatial distribution of the correlation coefficients between the annual values of different metrics of plant phenology and SPEI at selected months and timescales.

hydrological drought severity downstream. Different studies concluded that human management and water demands strongly alter the response of hydrological droughts to climate variability (e.g. López-Moreno et al., 2009; Tijdeman et al., 2018; Vicente-Serrano et al., 2017a, 2017b; Xu et al., 2019). In the upper Aragón basin, the Yesa reservoir determines considerably the response of hydrological droughts downstream. This is mainly because the Yesa reservoir has an accumulation capacity of almost 446 hm^3, which reduces the sensitivity of the reservoir storage to high variability of climatic drought severity. Thus, it is expected that the Yesa reservoir will only respond to climatic drought at longer time scales. A different behavior is found for streamflow and snow depth, which respond to climatic drought at shorter timescales, with a seasonally dependent response. The stronger response of reservoir storage anomalies to climatic droughts in the basin during summer months stresses the need for reliable water management practices to secure water transfers to the irrigated lands of Bardenas, although water releases to the Aragón river downstream Yesa are strongly reduced (López-Moreno et al., 2004).

Reservoir management reduces the sensitivity of the Aragón flows downstream the Yesa reservoir to climatic drought variability. A similar role can also be observed in the flow anomalies recorded in the Bardenas channel. This indicates that the management practices of the Yesa reservoir contribute significantly to the degree of hydrological drought severity downstream since they priorise the water releases to the Bardeas channel. For example, there were minimal effects of the severe drought recorded in 2013 on the flows of the Bardenas channel. However, the Yesa reservoir is important from seasonal perspective. In particular, the reservoir releases to the Aragón River basin responds to climatic drought variability only during winter, given that water demands in the Bardenas area are low and managers release all inflow downstream except the needed amount to progressively fill the reservoir storage capacity. In summer, the response of hydrological droughts downstream to climate variability is minimized because managers of the dam must satisfy the environmental flow assigned to the Aragon river by the Ebro basin authorities (López-Moreno et al., 2004). These alterations in the severity and frequency of hydrological droughts in the downstream reaches have already been identified in other catchments, especially with reservoir management for hydropower

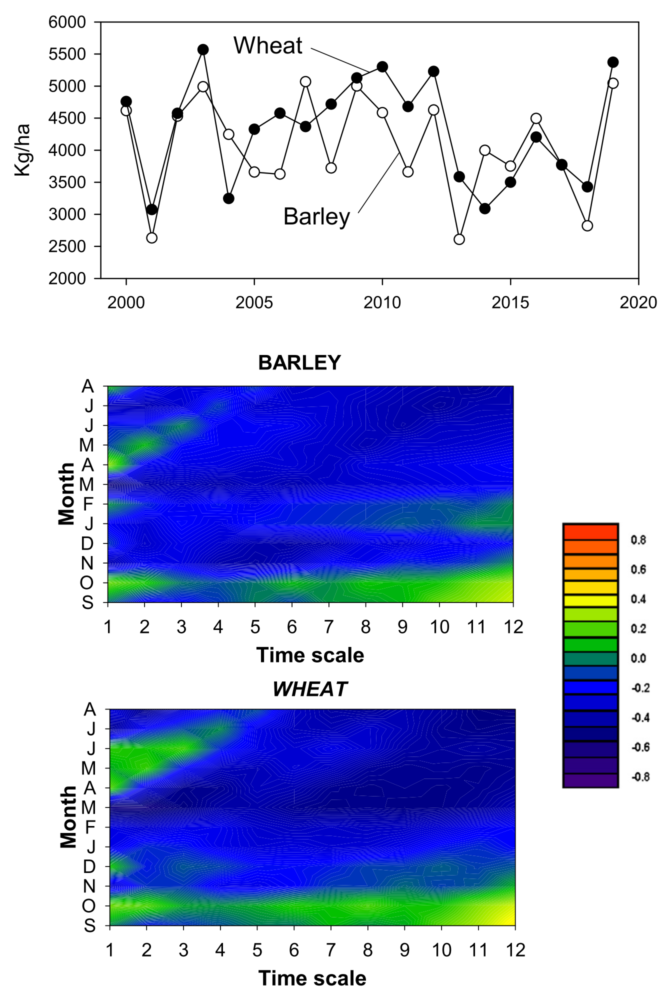

Fig. 13. Evolution of the Aragón basin annual yield of wheat and barley (upper panel), and their monthly correlations with SPEI at 1- to 12-month timescales (central and lower panels).

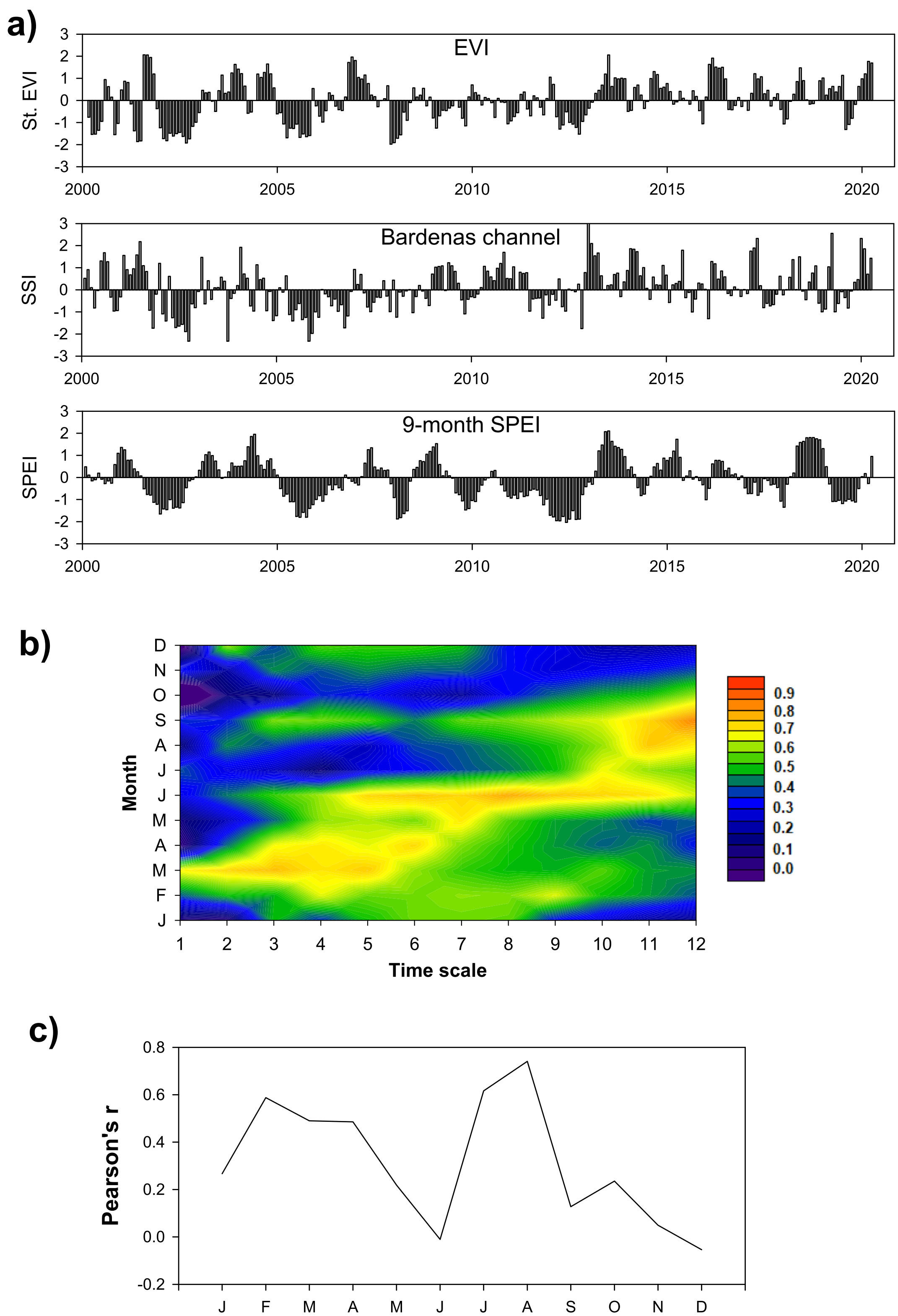

Fig. 14. a) Evolution of the mean standardized EVI and SSI from the Bardenas channel flows, as compared to the SPEI 9-month timescale in the irrigated lands, b) monthly correlations between the EVI in the irrigated lands and SPEI 1- to 12-month timescales, and c) the monthly correlations between the EVI and the Bardenas channel flows.

(López-Moreno et al., 2009; Morán-Tejeda et al., 2012; Nakayama and Shankman, 2013) and irrigation management (Vicente-Serrano et al., 2017a, 2017b; Zhang et al., 2009). Nevertheless, this study shows that although efforts should be oriented towards reducing the negative anomalies of water transfers to the Bardenas area, the reservoir storages historically witnessed drastic reductions (e.g. 1990, 2003 and 2005), as a consequence of extreme drought events. This situation induced a decline in the necessary channel flows into the basin downstream, with important socioeconomic impacts. This indicates that although hydrological management of the basin can alter the response to climatic

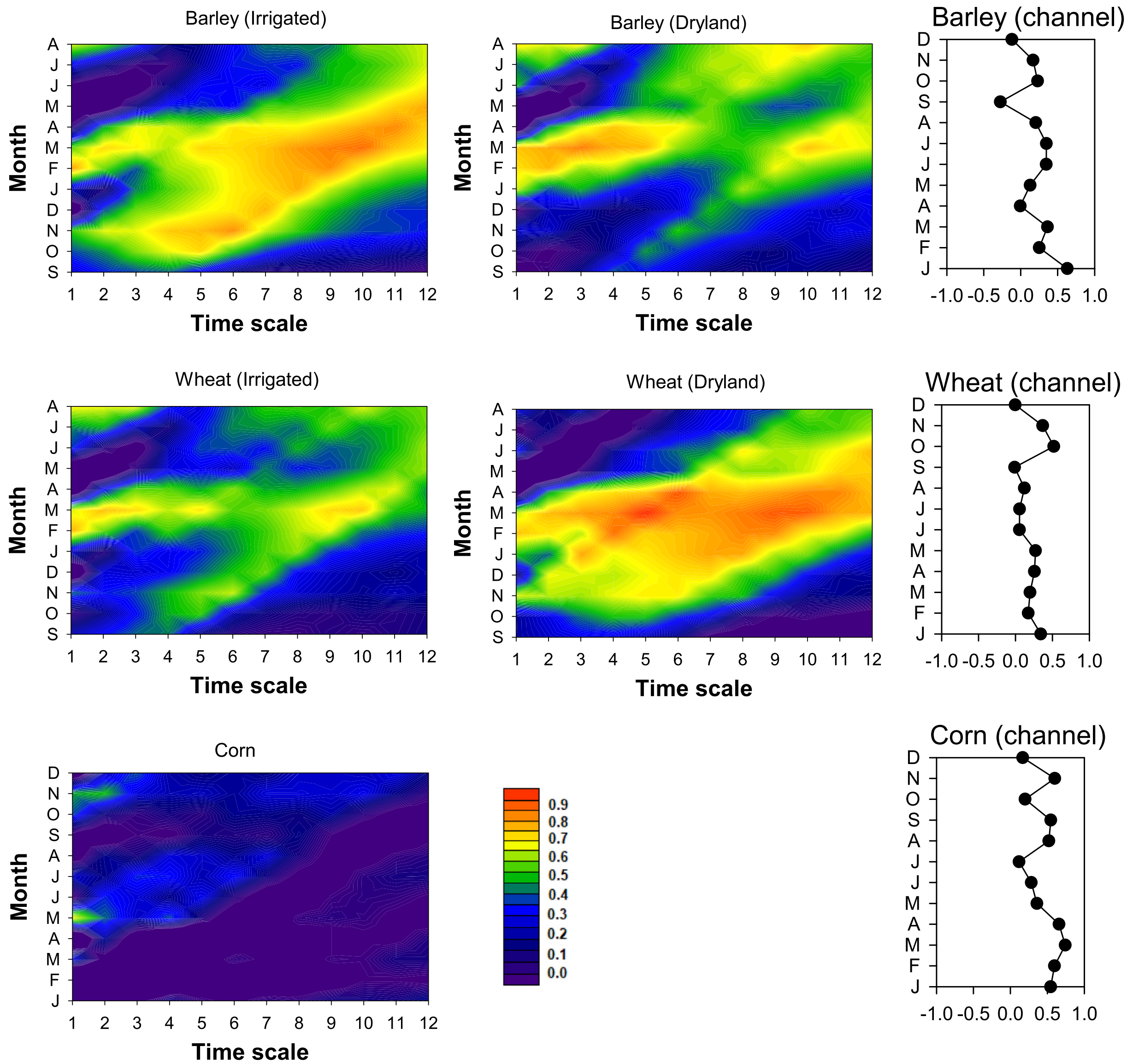

Fig. 15. Pearson's r correlations between the monthly SPEI 1- to 12-month timescales and the annual crop yields in the irrigated and dry lands for barley and wheat. The corn is only cultivated in irrigated lands. The right plots show the Pearson's r correlations between the annual crop yields and the Bardenas channel flows.

droughts, these practices cannot completely mitigate these effects. This is particularly likely during the most extreme dry events, which have consequences in the Aragón river downstream Yesa reservoir and also reduce the water transfers by the Bardenas channel.

6.2. Impacts of climatic drought on vegetation growth and activity

We have found a variety of drought impacts on the activity and growth of natural vegetation in the basin. This may be related to the presence of different vegetation types, with various cycles and resistance to water deficits, combined with differences in the average climatic conditions. Different studies discussed the mechanisms and strategies the vegetation adopts to cope with water deficits (e.g. Allen et al., 2010; Chaves et al., 2003; Sperry and Love, 2015; Vose et al., 2016). Thus, local site conditions (topography, soil depth, forest composition and structure, management) and species physiological traits seem to be key factors that determine the resistance and resilience of natural vegetation to drought (Anderegg et al., 2019; Anderegg et al., 2016; Peguero-Pina et al., 2011). In general, our study found strong impacts of climatic drought on vegetation activity, as revealed by EVI2, and to a lesser extent by tree-ring growth. This finding contradicts previous works in Spain, which suggested greater sensitivity to drought in terms of radial growth than the photosynthetic activity quantified by the Normalized Difference Vegetation Index (NDVI) (e.g. Gazol et al., 2018; Marina Peña-Gallardo et al., 2018). Nevertheless, we must stress that this study employed a different vegetation index i.e., the EVI2. As compared to NDVI, EVI2 is less affected by the possible saturation of the signal under very dense vegetation coverages (Giner et al., 2012; Huete et al., 2002), which could suggest a higher response to drought variability. Moreover, the length of the EVI2 series used in this study is still short and limits comparability with long-term data of tree-ring data (20 vs. 60 years, respectively). Nevertheless, although there are important differences in the response of vegetation types to climatic drought, we found two peaks of response to SPEI from the EVI and the tree-ring growth data: at short time scales but also longer timescales, characteristics of a two year period in summer. This suggests that drought conditions over the previous year could affect vegetation growth and activity during the following year given the role of non-structural carbohydrate reserves (Babst et al., 2014a, 2014b; Richardson et al., 2013; Skomarkova et al., 2006).

The forest types located in the drier and warmer locations (e.g. *P. nigra* and *Q. faginea*) showed a stronger response to climatic drought than forests of colder and more humid climates (e.g. *P. uncinata, F. sylvatica,* and *A. alba*). Humid forests are located in areas with water surplus (precipitation-evapotranspiration), which frequently generate runoff. This makes soil moisture almost sufficient for vegetation growth and activity, irrespective of precipitation deficit. In contrast, low elevation forests (e.g. *P. nigra* and *Q. faginea*) tend to receive lower amounts of precipitation, with enhanced atmospheric evaporative demand (Tomas-Burguera et al., 2019). This would explain the higher sensitivity of forest species at low elevations to climatic drought variability. Interestingly, in the upper Aragón basin, humid forest species showed a significant response to severe droughts. Different studies have suggested that resistance and resilience of vegetation types to drought varies strongly as a function of the regional and local climate conditions (e.g. Anderegg et al., 2016; Gazol et al., 2018; Gazol et al., 2017; Pasho et al., 2011). Thus, species from wet sites tend to show low correlations with drought variability and accordingly respond to drought at short timescales (Vicente-Serrano et al., 2014; Vicente-Serrano et al., 2013). This behavior was also identified in the upper Aragón basin. Nevertheless, although the forests of *A. alba* and *Q. faginea* are less impacted by climatic drought variability, they show stronger growth reductions than species from more xeric sites (e.g. *P. nigra* Q. faginea) under severe drought events. This can be seen in the context that species from mesic sites are characterized by their low acclimatisation to water deficits and accordingly they will quickly respond to severe water deficits. This mechanism would explain the higher correlations obtained considering SPEI at short timescales. Numerous studies have stressed a severe forest dieback and mortality in the *A. alba* forests over the western Spanish Pyrenees in response to recent drought events (e.g. Camarero et al., 2015; Camarero et al., 2011; Peguero-Pina et al., 2007). Conversely, the higher acclimatisation to water deficits would reduce the impact of drought severity on dry forests. Indeed, the drought threshold could play a major role (Slette et al., 2020) and, accordingly, vegetation from xeric sites could also be highly impacted in the presence of severe drought events.

All these processes and feedbacks stress that drought impacts on natural vegetation can be complex even over a small basin like the study domain. The important vegetation changes recorded in the basin over recent decades, as a consequence of the abandonment of traditional agricultural and livestock activities (García-Ruiz et al., 2015), can also be a source of uncertainty when assessing drought impacts on vegetation. With the exception of mature forests, which cover a small percentage of the total surface of the basin, the majority of the areas of dominant natural vegetation have been affected by different types of vegetation changes. The remaining shrubs have been colonized by conifers (e.g. *P. sylvestris*) (Vicente-Serrano et al., 2006a, 2006b), but there are also advances of oaks in previously colonized *P. sylvestris* forests. Finally, as a consequence of livestock abandonment in summer pastures located above 1600 m.a.s.l., they have been colonized by shrubs and *P. uncinata* (García-Ruiz et al., 2015). All these processes and the results forest encroachement would alter the sensitivity of vegetation to drought and the response to the most extreme drought events.

The response to drought of start and end of season dates, as measured by EVI, was weaker than for other vegetation variables. It should be stressed that it is very difficult to estimate these parameters with high accuracy since the precision in the data is limited by clouds and other disturbances, and phenological shifts are normally only in the order of fractions of a day per year. It also reflects the fact that the Aragon basin is located in a humid and cold region where temperature is the most important limiting factor to vegetation seasonality. In a recent study at northern European latitudes with predominantly cold climate, start of season showed very low sensitivity to change in precipitation (Jin et al., 2017). On the other hand, the integral of the growing season is an aggregated variable that is less noise sensitive and also more directly related to total net primary production. Natural cycles of vegetation are mostly driven by temperature behavior. For this reason, it is expected that variables like the onset, duration and end of the season show weak relationship with drought variability in the basin. As expected, the integral of the growing season is more linked to drought variability, as this variable is highly dependent on the total net primary production (Carlson and Ripley, 1997) and total vegetation biomass (Cihlar et al., 1991; Nicholson et al., 1990; Tucker and Sellers, 1986). Nevertheless, it is also important to note the important differences found between vegetation types. In any case, longer periods with data availability would be necessary to obtain more robust conclusions on this issue.

6.3. Impacts of climatic droughts on crop yield

Among the different drought impacts in the upper Aragón basin, we have found that the interannual variability of winter cereals (i.e. rainfed barley and wheat) yields in the basin over the past two decades does not exhibit a significant dependency on the variability of climatic drought. This finding sounds interesting in the context that previous studies in the Iberian Peninsula indicated a general high dependency of winter cereal yields on drought variability (e.g. Páscoa et al., 2017; Peña-Gallardo et al., 2019; Vicente-Serrano et al., 2006a, 2006b). However, we must consider the particular climatic characteristics of the study basin, in which precipitation amounts, even in the driest years of the available record, are generally sufficient to guarantee the yield of these two crops. Observed climate records between 2001 and 2020 reveal that, -even in the lowest elevated areas of the basin where winter cereals are mainly distributed, annual rainfall totals were above 600 mm in all years. This amount exceeds water requirements for cereal crops in the region (Vicente-Serrano et al., 2006a, 2006b). This would explain why there was no year affected by crop failure or by a noticeable decrease in the crop yield over the investigated period. Thus, crop yields in the upper Aragón basin are mostly similar to those recorded in the irrigated lands of the central Ebro basin, and even higher than those of the dry lands in the same region (Vicente-Serrano et al., 2006a, 2006b).

We indicated that the interannual variability of the EVI2 in the crop areas of the upper Aragón basin is correlated with climatic drought during summertime, which could suggest a possible role of drought on crop development. Nevertheless, our results on the relationship between the integral of the growing season obtained from the phenological analysis and drought variability is largely consistent with the correlations found between crop yield and drought variability. The integral of the growing season could be a better metric of total net primary production, compared to vegetation activity, in specific months. Thus, the EVI2 of any particular month could sometimes be less representative of the total crop yield or more sensitive to the growth of some natural herbaceous cover after crop harvesting. Overall, our results reveal that – with the availability of crop water requirements- cereal crop yield seems to be less sensitive to drought variability in the upper Aragón basin. Rather, thermal conditions (e.g. changes in degree days, late frost, early heat) could have more impact on crop yield, as suggested in similar cold and humid regions (e.g. Cammarano et al., 2019).

Finally, although crop yields were not noticeably affected by drought variability in the upper Aragón basin, climate droughts showed a remarkable influence on crop yield in the irrigated lands of Bardenas. A water manager's priority is to maintain the Bardenas channel flows against the water releases to the Aragón basin. This issue is not critical during the cold season, in which the channel flows did not respond to the drought variability of the upper Aragón basin. The good correlation between the EVI2 and flows of the Bardenas channel can be seen as an indicator of the role of water availability in the development of winter cereals. Thus, under irrigated conditions, the correlation of wheat and barley crops, with local droughts did not show clear patterns. In contrast, crops of dry areas showed significant responses to drought, especially with the high climatic variability during wintertime and early spring, which could influence soil moisture recharge (Austin et al., 1998), and thus determine crop yields (Vicente-Serrano et al., 2006a, 2006b). Nevertheless, the impacts of water availability in the Bardenas channel on crop yields are much more evident during summer months. In this dry season, water deficits could drastically affect both vegetation activity and corn yield, especially with the strong impacts of climatic droughts on water releases to the Bardenas channel. There has been a notable increase in the flows of the Bardenas channel, which has secured water requirements for corn yields. We have seen that although climatic droughts occurred during the last decade in the upper Aragón basin (e.g. in 2013), the decision of the water managers was to increase the severity of hydrological drought in the downstream reaches of the Aragón River to maintain the normal releases to the Bardenas channel.

7. Conclusions

Drought variability and severity can have serious hydrological, environmental, and agricultural impacts on both natural and human environments. This multifaceted character of drought can induce strong spatial and temporal complexity when assessing drought impacts. This study assessed the impacts of drought severity in a small mountainous basin (the upper Aragon basin) in the Central Spanish Pyrenees using a multi-sectoral perspective. Specifically, this study investigated the links between climatic drought (represented using SPEI), hydrological drought (represented using SSI), and a wide array of metrics that summarize groundwater levels, vegetation activity, and crop yield. This assessment was made considering different zones in the basin, with contrasted climatic, hydrological, and phenological perspectives, including downstream impacts.

This work identified – for the first time- the complex multisectorial impacts of climatic droughts in a single small basin in the central Spanish Pyrenees. The impacts of climatic droughts are found to be complex, with different responses not only as a function of hydrological subsystems, vegetation metrics and vegetation types, but also seasonally, over different drought time-scales, and water resources management policies. All these interactive processes and feedbacks make it a challenge to determine and monitor the diverse implications of climatic droughts in the basin, especially with the lack of real-time impact data. For this reason, governmental authorities should build their early-warning drought monitoring systems using a variety of climate-based drought indices (Svoboda et al., 2002; Trnka et al., 2020; Trnka et al., 2009). However, we stress that the response to climatic droughts can also be strongly diverse, which makes it necessary to comprehensively assess the utility of these drought metrics in terms of real drought impacts before establishing the appropriate drought mitigation strategies. Otherwise, we may misinterpret drought severity in particular systems, especially those characterized by complex hydrological and environmental systems like the upper Aragon basin.

Contribution

S.V·S conceived and designed the study, S.V.S., C.M., J.I., D.P.A. and F. D.-C. analyzed data, F.T, L.E., Z.C, J.J.C, R.S.S. and A.G. contributed with data, D.P.A., M.T.B., S.G., and I.N. shaped graphs, S.V.S. and A.E. wrote the first draft. All of the authors discussed the results and shaped the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.144702.

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