Relict deciduous oaks show high resilience to drought despite the effect of land-use legacies

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# Abstract

* Global change challenges forest ecosystems particularly in species-specific dry locations where land-use legacies have modified species composition and the forest structure as a result of intensive human pressure in the past. We analyzed forest resilience of adult trees to drought and climate change of relict Mediterranean *Quercus pyrenaica* Willd. populations in the Southern Iberian Peninsula. Forest resilience was analyzed using both dendroecological estimates of growth and MODIS satellite images as proxies of secondary and primary growth respectively.
* The studied relict populations showed expressions of management, likely reflecting the origin of the current forest structure. Both resilience indices of primary and secondary growth expressed that trees showed high resilience both to recent drought events and also to long-term climatic changes (*i.e.* warming), despite the ‘a priori’ vulnerability that we were expecting them to express in respone climate change on relict stands resulting from intensive land-use in history at their current rear-edge. Furthermore, we found a positive growth trend (stronger in high elevation stand) since the end of the 1970s matching the simultaneous increase in temperature observed.
* Resilience to drought followed a dryness gradient among the three populations studied: Northern populations thriving under a drier climate were less resilient to drought both in primary and secondary growth than Southern populations where lower altitudes were also less resilient than those at high-altitudes.
* Despite being considered relict stands at the dry rear-edge for the species, they showed high resilience in response to drought. Yet, the high sensitivity to water availability expressed and positive growth trends only in the coldest and more humid stands suggest divergent response to a changing climate along very short climatic gradients and suggest that dynamics (i.e. not only adult performance but also regeneration) of those stands located at the lowest elevations, hence the altitudinal rear-edge, need to be monitored under future expected drier and warmer climatic scenarios and, particularly, if high management pressure remains.

# Introduction

Drought is a natural phenomenon occurring when water availability is significantly below-normal levels (Dai 2011). It is one of the most frequent and widespread climatic extremes affecting ecological systems across every climatic zone worldwide (Dai 2011; Ummenhofer and Meehl 2017). Despite drought is considered a feature of Mediterranean climate (Lionello 2012), an increase in the frequency and severity of drought events has been recorded in the last decades (Hoerling and others 2012), particularly for southern Europe (Vicente-Serrano and others 2014b; Spinoni and others 2015; Stagge and others 2017) where a trend towards drier summers has been reported (Spinoni and others 2017a). This is especially important, since the climate change projections for the Mediterranean area forecast that climate extreme events, like droughts, will become more frequent and severe (IPCC 2013; Trenberth and others 2014; Spinoni and others 2017b).

Drought causes significant changes in ecosystem productivity and water dynamics that can severely affect forests through changes in plant physiology, phenology and carbon allocation (Allen and others 2010; Ummenhofer and Meehl 2017). The assessment of the drought impacts on ecosystems has gained attention in the last decades (Allen and others 2010; Clark and others 2016), and the functional response of vegetation to drought has been analyzed at global (*e.g.*, Vicente-Serrano and others 2013; Norman and others 2016) and at local scales (see Martínez-Vilalta and Lloret 2016 for a revision).

Ecosystem responses to drought are influenced by other drivers of environmental changes (Fischer and others 2006; Oliver and Morecroft 2014; Peñuelas and others 2017). In a global-change context, the impacts of drought on vegetation need to be evaluate considering the interactions with other drivers of change (Clavero and others 2011; Doblas-Miranda and others 2017). This is especially relevant for areas with a long history of landscape modification, such us Mediterranean region, where land-use change plays a significant role (Navarro-González and others 2013; Ameztegui and others 2016), considering also that the interactions of these two factors, namely drought and land-use change, are crucial for Mediterranean forests (Doblas-Miranda and others 2017).

The impacts of drought are also especially relevant for populations located in the rear edge (either latitudinal or altitudinal along climatic gradients) of their distribution, where climatic conditions often corresponds to the species-limits and the populations are likely to be more sensitive to small variations on climate (Hampe and Petit 2005). The response of rear-edge populations to variations on climate could be useful to estimate the adaptation of the species to predicted climatic changes (Jump and others 2010). It becomes even more important for relict populations driven by historical land-uses, which can harbour high levels of intraspecific genetic diversity (Valbuena-Carabaña and others 2010a).

Several studies analyzed the drought effects on Mediterranean tree species representing the southernmost limit of their distribution (*e.g.*, Sánchez-Salguero and others 2012; Linares and others 2014; Dorado-Liñán and others 2017b; Caminero and others 2018). Some of these studies focused on the resilience to drought of rear-edge populations (*e.g.*, Herrero and Zamora 2014). Resilience is the capacity of an ecosystem, community or individual to recover pre-disturbance structure and function after a disturbance (Holling 1973; Hodgson and others 2015). The assessment of resilience to climate disturbances provides critical information about the capacity of the forests to maintain their structure and to continue providing valuable ecosystem services. This is particularly relevant for populations located in the rear-edge of their current distribution, especially when they are located in Mediterranean mountains.

Here we assessed the resilience to drought of rear-edge populations of a tree Mediterranean species combining several approaches: remote sensing and dendroecologial estimates of growth. Remote sensing can be used for studying droughts impacts on ecosystems (*e.g.*, Michel Deshayes and others 2006; Zhang and others 2013; AghaKouchak and others 2015; McDowell and others 2015; Norman and others 2016). Vegetation indices obtained from satellite, such us EVI (Enhanced Vegetation Index) are used as a proxy for assessing vegetation functioning and aboveground net primary production (Huete and others 2002), and changes in the patterns of these indices are considered as an indicator of the forest response to external environmental factors, such us droughts (*e.g.* Vicente-Serrano and others 2013; Vicca and others 2016). Drought impacts on vegetation using remote sensing have been analyzed at different scales. For instance, a global-scale study showed a stronger influence of the drought for drier biomes (Vicente-Serrano and others 2013). For Mediterranean area, studies at regional and local scales found a large spatial and seasonal variability of the effects of drought on vegetation (Vicente-Serrano 2007; Gouveia and others 2017).

Dendroecological estimates of growth (*i.e.* tree-ring width) are a widely used proxy to study tree vitality (Fritts 1976; Dobbertin 2005; Bhuyan and others 2017) and the analysis of annual-tree ring widths can be used to study changes in growth as response to drought at the individiual tree-scale (Fritts 1976). The combination of both approaches (remote sensing and dendroecology), has been used to assess the effects of droughts on vegetation along ecological or elevational gradients (*e.g.*, Dorman and others 2013; Vicente-Serrano and others 2013; Coulthard and others 2017), and also for the analysis of growth resilience to drought on several tree species (Gazol and others 2018)

In this work we used remote sensing information and dendroecological methods to evaluate the drought impacts in both canopy greenness (as a proxy to primary growth) and tree-radial growth of a Mediterranean tree species (*Quercus pyrenaica* Willd.) located in Sierra Nevada, which is considered a rear-edge of species distribution and species performance is considered to be threatened. We also assess the resilience of these forests both to several extreme drought episodes and to climate change in the long-term in the last decades.  
Our hypothesis is that these relict populations driven by historical land-use at their climatic (either altitudinal or latitudinal) rear-edge are particularly vulnerable to climate change, and hence they will show low-values of resilience after several extreme droughts. Our specifics aims were: (*i*) To quantify how two recent extreme drought events influenced primary and secondary growth of *Q. pyrenaica* forests in their rear edge; (*ii*) to analyze the long-term resilience of these forests to extreme drought events using time-series of radial growth; (*iii*) and to explore differences in the resilience metrics between populations located in contrasting ecological conditions within the rear edge of the distribution of this species to detect vulnerability to climate change. In addition, within the region of study we were interested to assess whether the effect of aspect and microclimatic conditions expressed in northern and southern populations of Pyrenean oak forests differ in their resistance, resilience and recovery to extreme drought events.

# Materials and methods

## Tree species and study site

Pyrenean oak (*Quercus pyrenaica* Willd.) forests extend through south-western France and the Iberian Peninsula reaching its southern limit in mountains areas of northern Morocco (Franco 1990). In the Iberian Peninsula these forests live on siliceous soils, or soils poor in basic ions (Vilches de la Serna 2014) under meso-supramediterranean and mesotemperate areas and subhumid, humid and hyperhumid ombroclimate (Rivas-Martínez and others 2002). *Q. pyrenaica* requires over 650 mm of annual precipitation and a summer minimal precipitation between 100 and 200 mm (Martínez-Parras and Molero-Mesa 1982; García and Jiménez 2009), with summer rainfall being a key factor in the distribution of the species, which can hence be considered to have low drought tolerance compared to genuine evergreen Mediterranean taxa (Gavilán and others 2007; Río and others 2007).

The forests of this species reaches one of their southernmost European limit in Sierra Nevada, a high-mountain range located in southern Spain (37°N, 3°W) with elevations between 860 m and 3482 m *a.s.l.*. The climate is Mediterranean, characterized by cold winters and hot summers, with pronounced summer drought (July-August). There are eight Pyrenean oak patches (2400 Has) identified in this mountain range (Figure 1), ranging between 1100 and 2000 m *a.s.l.* and often associated to major river valleys. Sierra Nevada mountain is considered a glacial refugia for deciduous *Quercus* species (Brewer and others 2002; Olalde and others 2002; Rodríguez-Sánchez and others 2010). In this mountain region, *Q.* *pyrenaica* woodlands represent a rear edge of their habitat distribution, which is important for determining habitat responses to expected climate change (Hampe and Petit 2005). They are considered relictic forests (Melendo and Valle 2000; Vivero and others 2000), and the richest vascular-plant forest formation of Sierra Nevada (Pérez-Luque and others 2014), sheltering several endemic and endangered plant species (Blanca and others 1998; Lorite and others 2008). These forests undergone intensive anthropic use in history (Camacho-Olmedo and others 2002; Valbuena-Carabaña and others 2010a; Valbuena-Carabaña and Gil 2017). Furthermore, conservation status of this species for southern Spain is considered “Vulnerable” (Vivero and others 2000) and they are expected to suffer the impact of climate change, reducting its suitable habitats in the rear-edge due to their greater hydric requirements compared to other more drought-tolerant Mediterranean evergreen oak and pine species (Gea-Izquierdo and others 2013).

## Drought episodes

During the second half of the twentieth century the Iberian Peninsula suffered several extreme drought episodes (*e.g*. 1994-1995, 1999, 2005, 2012) (Vicente-Serrano and others 2014b; Guerreiro and others 2017).The 2005 and 2012 drought events have been documented among the worst droughts in the last decades for the southern Iberian Peninsula (Garcı́a-Herrera and others 2007; Trigo and others 2013; Gouveia and Trigo 2014; Gouveia and others 2015; Guerreiro and others 2017; Páscoa and others 2017) and they were characterized as extreme drought in our climatic data (Figures S1-S2; Table S3). We focused on these two drought events because they were included in the period where there is availability of high-spatial resolution remote sensing information (MODIS started on 2000; see below). Nevertheless, for radial growth-time series, a greater number of older drought events were also analyzed to contextualize results obtained in 2005 and 2012 drought events and analyze forest resilience to drought in a longer term (see Table S3). The identification of a drought event were done using the Standardized Precipitation-Evapotranspiration Index (SPEI) (Vicente-Serrano and others 2010) following similar procedure as proposed by Spinoni and others (2015). We used SPEI-12 months scale for all 0.5º grid cells covering Sierra Nevada obtained from Global SPEI Database (<http://spei.csic.es/database.html>). A severe drought event starts in the month when SPEI falls below the threshold of -1.28 (Páscoa and others 2017; Spinoni and others 2017b). A drought event is considered only when SPEI values are below the threshold for at least two consecutive months (*e.g.* Spinoni and others 2015, 2017b). Several indicators were computed for each drought event: ***duration*** as the number of consecutive months with the SPEI lower than a certain threshold; ***severity*** of a drought event is the sum of the SPEI values (absolute values) during the duration of the drought event; the ***intensity*** and the ***Lowest SPEI*** refer to the mean and lowest value of SPEI respectively during the drought event duration.

## Greenness data

Vegetation indices derived from remote sensing information have been widely used to derive descriptors of ecosystem functioning (*e.g* Alcaraz-Segura and others 2009) because they are linked with primary productivity (Ruimy and others). Here, vegetation greenness of *Q. pyrenaica* was characterized by means of the *Enhanced Vegetation Index* (EVI), derived from MOD13Q1 product of the *Moderate Resolution Imaging Spectroradiometer* (MODIS) sensor (Didan 2015). MODIS EVI Data (Collection 6) were obtanied using Google Earth Engine platform for the period 2000 - 2016. EVI data consits of 16-day maximun value composite images (23 per year) of the EVI value with a spatial resolution of 250 m x 250 m. We selected the pixels covering the distribution of *Q. pyrenaica* forests in Sierra Nevada (*n* = 928 pixels). Then, a data filtering was applied to select EVI valid values. For this purpose, complementary information accompanying the EVI data was used (VI Usefulness Indices and quality flags). Values affected by high content of aerosols, clouds, snow and shadows, were filtered out following recommendations for mountain regions (Reyes-Díez and others 2015).

As a surrogate of mean annual primary production, annual mean EVI () value was computed for each pixel for the period 2000 - 2016. To explore the effect of drought on greenness, the EVI standardized anomaly () was computed pixel-by-pixel, since it minimizes biases in the evaluation of anomalies, providing more information about the magnitude of the anomalies (Samanta and others 2012; Gao and others 2016). For each pixel, an annual EVI value was obtained by averaging EVI valid values. Then, the standardized anomaly was computed as:

where is the EVI standardized anomaly for year ; the annual mean value of EVI for year ; the average of the annual EVI values for the period of reference 2000-2016 (all except year); and the standard deviation for the reference period. Each pixel was categorized according the EVI standardized anomalies as “greening” (EVI standardized anomalies greater than + 1), “browning” (EVI standardized anomalies less than - 1) or “no changes” (EVI standardized anomalies between − 1 and + 1) (Samanta and others 2010, 2012).

Rather than other vegetation indices like the NDVI, was chosen since it is highly stable under the use of any filter (Reyes-Díez and others 2015) and because it showed high significant correlations with annual ( = 0.81) and seasonal EVI values ( = 0.76 and = 0.88). For exploratory purposes, temporal trends of were explored at a pixel scale. The nonparametric Mann–Kendall test (Kendall, 1975; Mann, 1945) was applied using the trend package in R (Pohlert 2017). The alpha level for the test was set to 0.05.

## Field sampling and dendrochronological methods

### Tree sampling

Tree sampling was carried out during autumn 2016. Trees were sampled at two locations in contrasting N-S slopes of Sierra Nevada: San Juan (SJ), a xeric site located at northern aspect; and Cáñar (CA), a humid but warm site located at southern aspect (Figure 1; Table 1). For the southern site two elevations were sampled: CA-Low and CA-High, which constitutes the current altitudinal tree-line in the sampled slope. All the sites were oak monospecific and representatives of the population clusters identified for the species in this mountain range (Pérez-Luque and others 2015a). In each site between 15 and 20 dominant trees were randomly selected. Two cores of 5 mm of diameter were taken from each tree at breast heigth (1.3 m) using an increment borer. Diameter at breast height (DBH) and total height were measured using a girth tape and a Vertex IV ultrasonic hypsometer (Haglöf, Sweden) respectively. Stand competition of target trees was assessed by recording distance, azimuth, DBH, species and total height of all neighboring living trees with DBH > 7.5 cm within a circular plot of 10 m radius. Several competition indices were calculated: the distance independent indices *density* (), and *basal area* (BA, ); and the distance dependent index size ratio proportional to distance (*srd*) as . Then, non-parametric Kruskal-Wallis rank sum tests (Sokal and Rohlf 1995) were used to analyse differences between sites for height, DBH and competition indices. When significant differences were observed, we run multiple comparisons using the Dunn’s-test (Dunn 1964) with Bonferroni adjustment to correct significance values. These analysis were performed uisng the PMCMR package in R (Pohlert 2014).

### Dendroecological analyses

Tree cores were air dried, glued onto wooden mounts and sanded. Annual radial growth (ring width, RW) was measured with a LINTAB measuring device (Rinntech, Heidelberg, Germany) coupled to a stereomicroscope, with an accuracy of 0.001 mm. Individual ring series were first visually and statistically cross-dated with TSAP software (Rinntech, Heidelberg, Germany), using the statistics Gleichläufigkeit (GLK), t-value and the crossdating index (CDI). Cross-dating validation was finally done using COFECHA software (Holmes 1983).

The growth trends were analyzed at different time scales. To study the response of growth to the inter-annual variability of climate (short-term response), pre-whitened residual chronologies (RWI) were used. They were calculated from ratios between raw growth measurements and individual cubic splines with a 50 % frequency cutoff at 30 years (Fritts 1976). Tree-ring width series were standardized and detrended using the dplR (Bunn 2008, 2010) package. Residual site chronologies were obtained computing the biweight robust mean of all prewhitened growth indices for the trees of the same site (Cook and Kairukstis 1990). The statistical quality of each chronology was checked via the expressed population signal. A threshold value of EPS > 0.85 was used to determine the cutoff year of the time span that could be considered reliable (Wigley and others 1984).

The long-term growth response was analyzed using basal area increment (hereafter BAI, ). Theoretically, BAI represents a more accurate indicator of growth than ring-width, since it removes variation in growth attributable to increasing stem circumference after 30-40 years of juvenile increasing growth (Biondi and Qeadan 2008). Raw ring-widths and measured DBH were used to compute BAI by subtracting twice the annual ring width from the annual diameter, starting from the measured diameter outside the bark (Piovesan and others 2008). We used the following equation:

where is the radius of the tree and is the year of tree-ring formation. For each individual tree, a mean BAI serie was calculated. Then, mean site BAI chronologies were obtained by averaging individual tree BAI time series.

Both RWI and BAI chronologies were compared to different climatic indices to analyse the low and the high-frequency response to climate of trees. Statistical descriptive parameters, including the mean, standard deviation, first-order autocorrelation of raw series, the mean sensitivity (a measure of the year-to-year variability) and the mean correlation between individual series of residual ring-width indices, were also calculated for each site chronology (Fritts 1976).

### Climate and growth

Climate data were obtained from the European Daily High-Resolution Observational Gridded Dataset (E-OBS v16) (Haylock and others 2008). Monthly precipitation and minimum and maximum temperatures were obtained at a 0.25 x 0.25 º resolution for the 1950-2016 period. We selected grid cells covering each sampled sites. Data were downloaded and preprocessed using the climate4R bundle (<http://www.meteo.unican.es/en/climate4R>) (Cofiño and others 2018; Frías and others 2018). The Standardized Precipitation-Evapotranspiration Index (SPEI), a multiscalar drought index that incorporates both precipitation and temperature (Vicente-Serrano and others 2010; Beguería and others 2014), was also used to characterize the drought conditions for the period 1961-2014. SPEI values with a temporal scale of 6 months and a spatial resolution of 1.1 km, were obtanied from the Drought indices dataset (<http://monitordesequia.csic.es/>), a high resolution database of drought indices for Spain (Vicente-Serrano and others 2017b).

Relationships between residual site chronologies and climatic variables were assessed ussing bootstrapped Pearson’s correlations estimated using the treeclim package (Zang and Biondi 2015). The bootstrapped confidence intervals were used to estimate significance (p < 0.05) of the correlation coefficients.

### Disturbance analyses

Disturbance chronologies were built using tree-ring width to identify abrupt and sustained increases (release events from competition) or decreases (supressions) in radial growth (Nowacki and Abrams 1997) as indirect estimates of possible disturbance events (e.g. logging, neighbor mortality) in the past. By using a temporal window of reasonable length this method is intended to filter out the response to short-term changes in temperature and precipitation and minimizes the long-term growth trends (Nowacki and Abrams 1997; Fraver and White 2005).

Growth changes (GC) were calculated for the individual tree-ring series using a 10-year running window as either positive (PGC) or negative (NGC) growth changes:

where is preceding 10-year median and is subsequent 10-year median. Medians were used since they are more robust estimator of central tendency than means (Rubino and McCarthy 2004; Camarero and others 2011). Site disturbance chronologies were constructed by averaging the individual disturbances series annually. To separate growth peaks produced by disturbance events and expressing stand-wise disturbances from those by climate, we considered a threshold of 50 % of GC and more than 50% of the individual trees displaying the same growth changes was considered a stand-wise disturbance.

In addition, the forest history of San Juan and Cáñar sites was inferred from a detailed analysis of historical land-use changes. For this purpose, an exhaustive review of historical documents was done to compile information about socio-economical activities affecting forest: land-uses, forest managment actions, mining, wildfires, etc. Several documentary sources were reviewed: historical documents and maps (*e.g.* Catastro 1752; MOP 1943; Titos 1990); detailed mining reports (*e.g.* Maestre 1858); official information about recent wildfires events (Regional Ministry for the Environment of the Government of Andalusia) and forest management practices (Bonet and others 2016); livestock farming (*e.g.* Moreno-Llorca and others 2014); traditional irrigation ditches (Martín-Montañés and others 2015; Ruiz-Ruiz 2017) and other studies reviewing the socioeconomic dynamics of forest of Sierra Nevada at different scales (Bonet and others 2014; Jiménez-Olivencia and others 2015; Moreno-LLorca and others 2016).

## Resilience

To evaluate the effects of drougth events on greeennes and tree growth (BAI) we used resilience indices proposed by Lloret and others (2011): resilience (*Rs*), resistance (*Rt*), and recovery (*Rc*). The resistance index (*Rt*) quantifies the severity of the impact of the disturbance in the year it occurred. It is estimated as the ratio between the performance during and before the disturbance (drought) event:

Resistance (*Rt*) = Drought / Predrought

The Recovery index (*Rc*) is the ability to recover from disturbance relative to its severity, and it is estimated as the ratio between performance after and during disturbance:

Recovery (*Rc*) = Postdrought / Drought

The Resilience index (*Rs*) is the capacity to reach pre-disturbance performance levels, and it is estimated as the ratio between the performance after and before disturbance:

Resilience (*Rs*) = Postdrought / Predrought

The values of these indices were computed for tree growth (BAI) and greenness (EVI mean) during each drought event. 2005 and 2012 were considered as single drought events. The predrought and postdrought values of each target variable (*i.e.* BAI or EVI) were computed as the mean value during a period of three years before and after the drought event respectively. A period of three years was chosen because we found similar results comparing periods of two, three and four years (Figure S6) and this length was used in other studies (*e.g.* Gazol and others 2017). To put in context in a longer-term the resilience observed for 2005 and 2012 drought events, as well as to test whether the resilience indices were ecologically meaningful, resilience metrics for BAI data were additionally computed for the most severe drought events since 1900 and compared them with drought severity (Figure 6, Table S3).

## Statistical analysis

For each of the three resilience indices studied, robust two-way ANOVAs were used to test for differences between drought events (2005 and 2012) and the two studied oak populations (northern and southern aspects). These tests were used because original and log-transformed data did not follow the assumptions of normality and homogeneity of variance (Wilcox 2012). Robust measures of central tendency (M-estimator based on Huber’s Psi) were used since they were close to the mean value in all cases (Wilcox 2012). When running the robust ANOVA test, data were boostrapped 3000 times and trimmed automatically to control the potential influence of outliers (Field and others 2012; Wilcox 2012). Post-hoc differences were assessed pairwise using a similar boostrap test. All the robust ANOVA and post-hoc tests were carried out using the WRS2 (Mair and others 2017) and rcompanion (Mangiafico 2017) R packages. The level of significance was set to 0.05 and adjusted for multiple comparisons. All analyses were carried out in R software (R Core Team 2017).

# Results

## Time trends in vegetation greenness

The analysis of greenness time trends showed that EVI in 78.9 % of the pixels of *Quercus pyrenaica* forests experienced a positive trend for the 2000-2016 period. During the 2005 the lowest values of EVI standardized anomalies were recorded, particularly for northern populations (Figure 2). In fact, a “browning” episode () was observed for *Q. pyrenaica* forests during this drought event, yet no changes in greenness were observed in response to the 2012 drought (Figure 3).

## Radial growth trends and growth disturbances

The trees of the southern population were older than northern ones, particularly for the high elevation site (CA-High) which had bigger and taller trees than the other sites (Tables 1, 2). Competition was similar among sites but plot basal area was greatest in CA-High (Table 1), which however also exhibited the highest individual BAI growth (Figure 4). Trees for southern sites showed significant positive growth trend since the late 1970s (Figure 4), being more pronunced for the highest site (CA-High). We also observed differences in growth for southern sites. CA-Low growth was lower than that of CA-High but similar to growth of the northern population (SJ) (Figures 4 and S6).

From a long-term perspective, drought events produced reduction of RWI for all sites (Figure S3), particularly in 1995 drought, when the greatest reduction of tree-growth were recorded for all chronologies. Southern sites (CA-High and CA-Low) showed weaker reductions than northern site (SJ), especially for 2005 and 2012 (Figure S3). Trees from northern site also suffered a great reduction during 1945-1946 drought event.

The analysis of growth changes revealed differences in forest history between sites (Figures 5 and S4). Northern site (SJ) showed two release events (GC > 50 %) detected at stand-wise scale (occurring in more than 50 % of sampled trees): the first during the 1940 decade and the second in the period 1995-2000. These periods alternate with periods of supression. Southern sites (CA-High and CA-Low) showed no release events except for CA-High at the beginning of the 1830 and no suppression events in the last 50 years.

## Resilience of greenness and radial tree-growth to drought events

At long-term perspective, the strength of the response of the resilience indices was related to drought severity. The exploration of resilience metrics of tree-growth for all severe droughts in our climatic data (1900 - 2017) (Table S3), revealed a positive relation between resilience (*Rs*) and drought severity ( = 0.336, p = 0.048) (Figure 6). A similar pattern was found for recovery (*Rc*; = 0.438, p = 0.019) but negative for resistance (*Rt*, = 0.155, p = 0.205). Trees showed the highest value of tree-growth resilience for the worst drought event in our study area (1995, see Table S3).

During the last two drought events, resilience metrics for greenness and tree-growth were significantly different bewteen drought events (Table 3). The 2005 drought event reduced greennes and growth more than that of 2012 (Tables S1 and S2). We obtained significantly higher Resilience (*Rs*) and Resistance (*Rt*) values for the 2012, the most severe event, than for 2005 in both variables (Tables S1-S2; Figure 7). Recovery (*Rc*) showed contrasting pattern for EVI and tree-growth. Recovery values for greenness was higher for 2005 than for 2012 drought event (Table S1, Figure 7).

Resilience metrics significantly varied between sites, except for Resilience (*Rs*) of tree-growth (p = 0.534; Table 3). Southern populations showed lower values for Recovery (*Rc*) than northern site for greenness and tree-growth (Tables S1 and S2). In opposite, Resistance and Resilience values were higher for southern sites than for northern ones (Tables S1 and S2).

## Climate and tree-growth

Tree-growth exhibited a significant greater response to water availability than to temperatures, as it can be expected for a Mediterranean site and a species located closer to its xeric/dry distribution limit (rear-edge). Cumulative precipitation of the hydrological year was the climatic variable with the highest relationship with growth and influenced similarly and positively the tree-growth for both northern and southern populations (Figure 8a). Precipitation of previous december was also positively correlated with tree growth in the northern population and in the highest location of the southern population. Hydrological, Spring and Summer SPEI showed a strong positive correlation with tree-growth (Figure 8a), specially for the northern population (r > 0.6). Relationships with temperatures were lower than those with moisture variables. Yet there were differences between northern and southern populations: spring maximum temperature was the most significant limitation for the tree-growth of the southern population at both elevations while no significant limitations were recorded for northen site regarding the temperatures (Figure 8b and 8c). Remarkably minimum and maximum temperatures of current September positively influenced the tree-growth only in the northern population. No positive relationship with temperature was found for southern trees.

# Discussion

## Rear-edge oaks show high resilience in response both to recent drought events and long-term climatic variability.

Severe drought events negatively affected to primary and secondary growth of *Q. pyrenaica* forests in the rear edge of their distribution. Our findings show that 2005 and 2012 drought events, provoked reductions in greenness and tree-growth of these forests. These results are consistent with previous studies that reported significant reductions of tree-growth for this oak species during extreme drought events (Corcuera and others 2006; Gea-Izquierdo and Cañellas 2014; Rubio-Cuadrado and others 2018). In fact, when we explore the effects of drought at a longer-term scale, we observed the greatest reduction of tree-growth during the 1995 drought, a characteristic pointer-year that caused severe and extensive damage to the Mediterranean vegetation across the Iberian Peninsula (Peñuelas and others 2001; Camarero and others 2018; Gazol and others 2018).

Although the south of Iberian Peninsula suffered severe drought events in the last decades (*e.g* 2005 and 2012 were considered two of the worst recorded drought; Garcı́a-Herrera and others 2007; Trigo and others 2013; Vicente-Serrano and others 2014b) (Table S3), we found a positive trend for vegetation greenness of *Q. pyrenaica* (78.9 % of the pixels showed a positive trend during the 2000 to 2016 period). This confirms previous findings that pointed out an increase in primary productivity for these forests (Pérez-Luque and others 2015b), being the most productive ecosystems in this mountain region during that period (Alcaraz-Segura and others 2016). For tree-growth, we also observed positive trends in the last decades, particularly for the southern high-elevation site (CA-High, Figure 4). Similar long-term trends were described for this species along their distribution range (Gea-Izquierdo and Cañellas 2014; Rubio-Cuadrado and others 2018) and could be related to the rising of the temperatures in the last decades (Gea-Izquierdo and Cañellas 2014) particularly after 1970 (Bladé and Castro-Díez 2010; Vicente-Serrano and others 2017a). Howewer, the observed pattern for our sites (a rear-edge) differs from the decline trends observed for several Mediterranean and temperate tree-species located in their rear-edges (*e.g.*, *Pinus nigra*; *P. sylvestris*; Sánchez-Salguero and others 2012; Camarero and others 2015b; *Fagus sylvatica*; Dorado-Liñán and others 2017a).

Resilience (*Rs*) values observed in our study sites for the latest drought events in both tree-growth and greenness were close to 1, except for the tree-growth during 2005 event (Tables S1 and S2). Despite the 2012 drought event was more severe and intense than 2005, according with our analysis with SPEI data (Table S3), resilience values for greenness and tree-growth were greater for 2012 than for 2005. These results could be explained by the different timing of the two droughts, *i.e.* the 2012 drought was a winter drought (Trigo and others 2013) that occurred earlier than the 2005 drought. The latter lasted less than 2012 drought, but matched the period of maximum growth for *Q. pyrenaica* forests (Pérez-de-Lis and others 2017) (Figure S7). Our results are in line with recently studies that indicate the timing of the drought as a key factor determining tree recovery after drought (Huang and others 2018), that also has been observed for other Mediterranean oak species (*e.g.* Holm oak; Camarero and others 2015a).

As we mentioned previously, we found strong declines of tree-growth during the most severe drought events occurred (1995 and 1999) (Table S3; Figure S3), matching similar declining patterns observed for other species in their rear edge (Sánchez-Salguero and others 2012; Camarero and others 2015b). But, interestingly, we obtained the highest values of resilience for tree-growth for these two drought events (Figure 6). In addition, the analysis from a long-term perspective of the severe droughts suggests a positive relation between the tree-growth resilience and drought severity (Figures 6). Surprisingly this result seems contradict our initial hypothesis in which we predict low resilience values for this oak species in their rear-edge after extreme drought events.

Rear-edge populations live in environmental narrow margins, and small variations in environmental conditions can increase the vulnerability of the species (Hampe and Petit 2005). A high vulnerability to drought is often assumed for populatios located at their rear-edge (Martínez-Vilalta 2018). However we obtained positive trends in greenness and tree-growth for the rear-edge of *Q. pyrenaica* and high values of resilience to severe droughts were also reported. Our findings are in agreenment with those studies that have showed that the assumed higher vulnerability of dry edges does not necesarily hold (Cavin and Jump 2017; Granda and others 2018). Martínez-Vilalta (2018) pointed out the importance of the local adaptation and plasticity, and also of the local environmental factors on the vulnerability showed by rear-edge populations. The high values of resilience to drought reported here together with previously works showing high values of genetic resilience for those forests at Sierra Nevada, seem to be indicative of high local adaptation of this oak to this mountain range. In addition the local environmental conditions of the sites where this species inhabit at Sierra Nevada would explain the low vulnerability to drought showed by this oak. Algunos autores han apuntando que cuando se estudian poblaciones del rear-edge, hay que poner atención a la forma en la que se define la marginalidad, esto es, si se define atendiendo a criterios geográficos, climáticos, o según otros factores ecológicos (Martínez-Vilalta 2018). En este sentido, los altos valores de resiliencia a los eventos de sequía que hemos observado, podrían sugerir que las poblaciones de *Q. pyrenaica* en Sierra Nevada están situados en un rear-edge geográfico, pero no climático.

A remarkably result is the higher values of resilience for tree-growth obtained during the worst and more severe drought events in our study area (1995 and 1999) (Table S3; Figure 6). A plausible explanation could be the water availability previously and after the drought event. For instance, cumulative precipitation of the 1992-1994 years (pre-1995 drought) had precipitation values below the mean of the whole period (Figure S1), while 1996-1998 years (post-1995 drought) showed a wet opposite pattern. In fact, the first months of 1996 recorded the highest cumulative rainfall of the past century for our southern site (Cáñar) (Mesa-Torres 2009). This could explain the higher values of recovery found for 1995 (Figure 6).

Greenness and tree-growth of *Q. pyrenaica* showed different sensitivity to severe droughts. During the last drought events EVI was reduced to 90.25 % (Table 1), whereas BAI was reduced to 70.83 % (Table S2), suggesting a lower sensitivity of the greenness than tree-growth to drought, particularly for sites under drier climate. For our driest site (SJ, the northern one), BAI were reduced to 44.5 % respect to that of the preceding period during 2005 drought event, whereas the EVI was reduced to 81.9 % (Tables S1 and S2). These findings are in accordance with previously works which showed that tree-growth are more sensitive metrics of forest resilience than net primary productivty (*e.g.* Babst and others 2013; Coulthard and others 2017; Gazol and others 2018). Besides the different scales of both approaches, *i.e.* tree-based *versus* pixel-based; the growth reduction seems to be more mediated by sink that by source limitations (Gazol and others 2018). Response of greenness to drought not only reflects response of tree, because remote sensing indices (EVI) captures signals from all vegetation covered by the pixel (not only tree but also understory vegetation) (see Dionisio and others 2012). On the other hand, tree-ring width data provide an accurate measure of growth responses to droughts (Bhuyan and others 2017; Gazol and others 2018).

## Site environment shapes differential sensitivity to climate and drought of rear-edge oak populations

Our results showed differences for greenness and tree-growth between northern and southern oak populations (Table 3). The former, which have drier conditions (Table 1), were more impacted by the drought events than the latter. For instance, the northern site showed more negative EVI standardized anomalies (higher browning intensity) than the southern sites during the 2005 drought event (Figure 2). In addition, the stronger correlations of tree-growth with SPEI (Hydrological and summer) observed for northern site (Figure 8), can be interpreted as higher sensitivity to drought of a drier site (Gea-Izquierdo and Cañellas 2014).

Moisture availability has been reported as the most limiting factor driving radial growth of *Q. pyrenaica* along their distribution range in Iberian Peninsula (Gea-Izquierdo and Cañellas 2014). We found a singnificant positive relation between precipitacion (hydrological year and previous December) and tree-growth (Figure 8a). Our results are consistent with previous studies highlighting the influence of precipitation on tree-ring growth (Roig and others 2009; Gea-Izquierdo and Cañellas 2014; Gea-Izquierdo and others 2014; González-González and others 2014; Leal and others 2015; Camisón and others 2016; García-González and Souto-Herrero 2017)

A striking result is the difference for tree growth between sites (Figure 4). The trees of CA-High site, which are located around 1900 m. *a.s.l.* and representing the upper limit of the treeline of the species in this southernmost location (Pérez-Luque 2011), showed higher BAI than those located at low-elevations sites (CA-Low and SJ) (Figure 4). This is especially interesting for southern sites, which are very close to each other. Our findings are in line with previous works that pointed out that tree growth and tree responses to drought are site-dependent (e.g. soil features, tree competence, etc.) (e.g.  Babst and others 2013; Vicente-Serrano and others 2014a), particularly for rear-edge populations (Cavin and Jump 2017; Dorado-Liñán and others 2017).

When we explored the chracteristics of the southern sites, we firstly observed a difference in elevation. Bhuyan and others (2017), in a recent work across the European continent, found a clearly effect of elevation on the resistance to drought of several tree-species, where stands located at higher elevations were less drought sensitive. The higher values of tree growth that we observed in CA-High site could be related with lower water stress at high-elevation sites, since moisture availability is a key factor limiting tree growth for *Q. pyrenaica* (Gea-Izquierdo and Cañellas 2014). Soil analyses along an elevational gradient in this location revealed higher content of available water for forest soils located on high elevation (Cobo-Díaz and others 2017). In this sense, a remarkable observation is the presence of traditional irrigation ditches which could provide an additional water supply. In most of the high-mountain watersheds of Sierra Nevada, there are systems of historical irrigation channels, know as *acequias de careo*, that was used since Middle Age to cultivated these valleys (Martín-Civantos 2014; Martín-Civantos and Bonet-García 2016). These ditches run through the hillsides of valleys releasing water through several points that filtrate the water to recharge the aquifer and then irrigates the foot of the slopes (Martín-Civantos 2014; Jódar and others 2017). Several works have recently described the network of traditional ditches for our southern sites (Cáñar), with detailed information about water use (Ruiz-Ruiz 2017) and its hydrological functioning (Martín-Montañés and others 2015). There is a ditch (*Acequia de la Era Alta*) located uphill the CA-High site, which functions from March to June (Ruiz-Ruiz 2017). It brings water from snowmelt and from a nearby stream, soaking the *Q. pyrenaica* forests. This traditional system could supply an extra of water that could be used by the trees located downstream of these channels. This extra of water is particularly important for trees of this dry-rear edge and could explain the higher values of BAI for trees located in CA-High site.

In addition to the lower water stress, it is likely that the sites at higher elevation had a lower anthropic impact and the abandonment of traditional uses was earlier, due to their farthest location from human settlements and therefore less access to forest resources.

## Land-use legacy effects shape distribution and sensitivity to climate change of read-edge oak populations

The Mediterranean mountains, even at high elevations, have suffered strongly transformation of the landscapes driven by human activities throughout history (Regato and Salman 2008). Multiple evidence from palaeoecological studies indicated an intense human impact on vegetation of Sierra Nevada since 3000 cal year BP (Anderson and others 2011; Jiménez-Moreno and others 2013; García-Alix and others 2017; Mesa-Fernández and others 2018). From that moment onwards, increases on fire occurrence and both grazing and mining activities, were recorded for this mountain region, with an sharp intensification of the human activities in the last 150 years (García-Alix and others 2017; Mesa-Fernández and others 2018). Mining, forest clearings, fuelwood and charcoal exploitations, pastoralism and also wars, have strongly impacted on the forest resources in Sierra Nevada. As a consequence of all those activities a loss of about 90% of broadleaf *Quercus* species cover from medium and low elevation occurred in this mountain region (Jiménez Olivencia 1991).

Our study sites have been subjected to an intense exploitation of forest resources. Although the estimated age for our sampled trees was not more than 180 years (Tables 1, 2), several documents reported the presence of oaks before. For instance, the inventories of trees made by the Spanish Navy during the second half of 18th century, recorded the quantity of trees, dividing them into three categories: *new*, *growing* and *old* (Wing 2015). For Cáñar site more than two millions of trees were reported, most of them *news*, and no *old* trees were counted, suggesting recent wood fellings. Less quantity were reported for San Juan location (circa 700 000 trees), which 220 *old* trees and 56 700 *growing* (Cruz 1991). These numbers are a reflect of the intense exploitation of the forest resources occurring up to the end of nineteenth century (Valbuena-Carabaña and others 2010b; Calatrava and Sayadi 2019) and also concur with the regeneration peaks observed for several Iberian oak woodlands (e.g.  Gea-Izquierdo and Cañellas 2014; Gea-Izquierdo and others 2015; Dorado-Liñán and others 2017a).

We found similar tree competence levels in our sampled sites (Table 1), but differences in tree size and age suggest different management origin (*i.e.* land-use legacy). The review of historical documents revealed that our study sites had different land-use trajectories driven mainly by the differential pattern of the natural resource use (Martín-Civantos 2014; Jiménez-Olivencia and others 2015). On the one hand, the northern sites (*e.g.* San Juan), show a sequentially distribution of the land uses along the elevational gradient (Zoido and Jiménez Olivencia 2015): grasslands and shrublands for cattle farming are located at high elevations; then forests formation with some croplands; and at lowlands, irrigated terraces with tree crops. Other activities (*e.g.* mining) could also determine the use of natural resources, and therefore the forest structure. For instance, the SJ oak woodland is located in an area with a high concentration of mines and quarries that have been exploited intermittently throughout history (Navarro and others 2014). Historical documents indicated two periods of intense mining activity: the second half of the 19th century after the publication of detailed mineralogical reports by (Maestre 1858); and during the first decades of the twentieth century until 1960, which is the last year in which there is evidence of the existence of mining activity (Martín Martín and others 2009). On the other hand, woodland areas of the southern slopes (Cáñar) are mixed with a greater percentage of croplands, even reached high elevation (mainly barley, rye and potatoes) (Calatrava and Sayadi 2019). Forest resources, like firewood, charcoal and acorns, have been continuously exploited in southern sites through history (Jiménez-Serrano and Serrano-Gutiérrez 2004; Valbuena-Carabaña and Gil 2013). In Cáñar site, there were an arraigated tradition of charcoal extraction since fifteenth century (Jiménez-Serrano and Serrano-Gutiérrez 2004) up to middle of the 20th century. From this moment to the present, there were a sharp decrease of the wood extraction, mainly due to rural abandonment (Mesa-Torres 2009; Bonet and others 2014). Acorn resources have been tradiotionally exploited in this location up to 1950s (Mesa-Torres 2009; Bonet and others 2014).

Those different patterns of resource uses can help to understand the tree-growth changes recorded in our chronologies (Figure 5). We observed a tree-growth release event at 1940s in the SJ oak woodland (Figures 5, S4) which concurs with one period of maximum mining activity for this area. Several documentary sources indicate an apogee of the mining activity during 1925 to 1957 period, supported by both the improvement of the paths to transport the mineral and by the creation of new railway connections (Titos 1990). During this period there were an increase on the use of timbers for the tunnels of the mines and several furnaces that required great quantities of fuelwood to melt the mineral were active in this area (Titos 1990). This heavily exploitation of the forest resources could affect to a major part of this oak woodland, since percentage of trees affected by GC > 50 % reaches values above 50 % (Figure S4). Our results also coincide with a concurrent but less intense tree-growth release event reported for a closed oak woodland (Gea-Izquierdo and Cañellas 2014). In addition, paleoecological studies carried out in nearby alpine bogs have recorded increases in the heavy metals concentration since the end of 18th century until mid-20th, which coincides with the maximum activity of the mining in this area (García-Alix and others 2017).

The other release event observed for SJ site during 1995-2000 was lower than the occurred at 1940, but affecting more trees (Figures 5, S4). We revised the forest practices carried out in this area in the last 30 years (Bonet and others 2016), but we did not find any clearing or cutting event during 1995 - 2000 period. Two non-mutually exclusive ways could explain the tree-growth release observed. Firstly it could be related with a natural drought-induced mortality event after 1995, as was reported for Mediterranean tree species (*e.g.* Peñuelas and others 2000; Lloret and others 2004; Gentilesca and others 2017). On the other hand, we obtained strong positive correlations of SPEI with tree-growth for this site (Figure 8), which suggests a high sensitivity to water availability of this slightly more xeric site (Table 1) (Gea-Izquierdo and Cañellas 2014). Previous works reported a sharp decline (or non-production) in latewood production during extreme drought events (Corcuera and others 2006). Since latewood are less vulnerable to embolism than earlywood vessels (Corcuera and others 2006), the reduction or even the non-production of former could negatively affect to tree-growth and also enhanced the mortality, particularly for drier sites (Corcuera and others 2006; Gea-Izquierdo and Cañellas 2014).

The only positive release events showed for CA-High site could be related with converiosn from closed forest to an open silvopastoral system, a common management applied in the past (Isabel Cañellas and others 2004; Gea-Izquierdo and Cañellas 2014) documented in this site (Valbuena-Carabaña and Gil 2013; Vila-Traver 2015).

Climatic drivers are key factors determining the growth of tree species, especially at the rear edge of their distribution (*e.g.* Gea-Izquierdo and Cañellas 2014; Herrero and others 2013; Matías and others 2017), but in Mediterranean forests we must also considered the management history, *i.e* *land-use legacies* (Navarro-González and others 2013; Ameztegui and others 2016; Doblas-Miranda and others 2017; Peñuelas and others 2017) since, as we inferred from our results, the land-use legacy can conditioned tree-growth and resilience of tree species. Although the abandonment of the traditional activities have provoked a stagnation for this species (Isabel Cañellas and others 2004), we have observed an increase in the growth, especially in the high elevation sites, where the water is less-limiting resource. This pattern concurs with a forest expansion into marginal abandonded croplands and an increase in the tree-cover (Camacho-Olmedo and others 2002).

# Conclussions

Using both dendroecological estimates of growth and MODIS satellite images as proxies of secondary and primary growth respectively, we analyzed forest resilience to severe droughts of *Q. pyrenaica* forests located at rear edge of their distribution. Severe drought events have provoked important reductions in primary and secondary growth of *Q. pyrenaica* forests. However, despite the expected vulnerability for those relict stands, we observed positive trends in primary growth (since 2000) and secondary growth (since 1970) of *Q. pyrenaica* in Sierra Nevada mountain range. Surprisingly we observed high values of resilience to drought, particularly at long-term scales. This results are consistent with research showing high genetic resilience values (Valbuena-Carabaña and Gil 2013, 2017), and overall suggest this mountain region still acting as refuge for deciduous *Quercus* to climate changes (Brewer and others 2002; Olalde and others 2002; Rodríguez-Sánchez and others 2010).

The differences observed in tree-growth and resilience to drought between very close sites seem to confirm that responses to drought are site-dependent (Babst and others 2013; Cavin2017; Dorado-Liñán and others 2017). This is particularly relevant for rear-edge populations where topographic and biophysical variablity facilitates the existence of microrefugia (Vilà-Cabrera and others 2019).

The analysis of tree-growth dynamics revealed suppression and release events that are consistent with socieconomic dynamic, derived from the review of historical documents. Recently works have combined information from both tree-ring and remote-sensing to analyze the resilience of forest to drought (*e.g.* Gazol and others 2018). The approach presented here, which also includes an exhaustive review of historical documents, help to identify the response of vegetation to climate and to land use changes. In this sense our results highligth the importance of landuse legacies for highly transformed Mediterranean systemas (Navarro-González and others 2013).

Growth projections have forecasted a decrease in productivity for *Q. pyrenaica* that would increase vulnerability of this species to climate warming at the dry edges locations (Gea-Izquierdo and others 2013). However, the positive trends for both primary (*i.e.* greenness) and secondary growth (BAI) observed ar our study site and the high resilience values to drought showed at long term scale, seem to suggest that Sierra Nevada constitutes still a refuge for some species. This is relevant for tree species with higher sensitivity to climate change, such us *Q. pyrenaica* (García-Valdes et al. 2013; Benito-Garzón et al. 2008), not only for conservation per se of this species, but for all ecosystem services that these singular forests offer at Mediterranean mountain.

The abandonment of traditional activities along with the increase in temperature since the 70s, could be explaining the positive growth trend observed. This trend and the increase of tree-cover observed in the last decades in this mountain region (Camacho-Olmedo and others 2002), would enhance the carbon sequestration of this forest promoting its role as carbon sink. However, the abandonment of traditional management has provoked a general state of degradation of this forest formation (Isabel Cañellas and others 2004; Corcuera and others 2006). In this sense, es necesario analizar con mas detalle como se verán afectados los servicios ecosistémicos que ofrecen estos robledales en su rear edge en un contexto de cambio global, identificando claramente los impactos del clima y del land-use change en la provisión de servicios ecosistémicos.

# Acknowledgments

We would like to thank Sammy Lucy Behle, M. Suarez-Muñoz and F.J. Bonet-García for their assistence in the field monitoring. A. Reyes and J. Blanco helped in the filtering of satellite data. We also are very thankful to F.J. Bonet-García for its valuable comments in an earlier version of the manuscript. Environment Department of Andalusian Regional Government and Director of Sierra Nevada National and Natural Park provided permission for field work. This research work was conducted in the collaborative framework of the “Sierra Nevada Global Change Observatory” Project from the Environment Department of Andalusian Regional Government (with the support of European Union FEDER Project). We also thank to LIFE-ADAPTAMED (LIFE14 CCA/ES/000612): *Protection of key ecosystem services by adaptive management of Climate Change endangered Mediterranean socioecosystems* and H2020 project *ECOPOTENTIAL: Improving future ecosystem benefits through earth observations* (<http://www.ecopotential-project.eu/>) (No 641762), for their funding support.

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