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2017

# 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 (Mishra and Singh 2010, Dai 2011, Ummenhofer and Meehl 2017). Summer drought is a characteristic feature of the Mediterranean climate (Lionello 2012), but an increase in the frequency and severity of drought events have been recorded for the Mediterranean region (Hoerling et al. 2012), particularly for southern Europe (Vicente-Serrano et al. 2014, Spinoni et al. 2015, Stagge et al. 2017) where a trend towards drier summers has been reported for the last three decades (Spinoni et al. 2017a). Climate change projections suggest that extreme events, like droughts, will become more frequent and severe (IPCC 2013, Trenberth et al. 2014), specially in the Mediterranean area (Spinoni et al. 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 et al. 2010, Ummenhofer and Meehl 2017). In the last decades the assessment of the drought impacts on ecosystems has gained attention (Allen et al. 2010, Clark et al. 2016), especially considering some studies that suggest an increase in severity, geographic extent and frequency of droughts as a result of climate change (Dai 2011, Trenberth et al. 2014). The response of vegetation to drought has been analyzed at different scales, from global (*e.g*. Allen et al. 2010, Vicente-Serrano et al. 2013, Norman et al. 2016) to local scales (see Martínez-Vilalta and Lloret 2016 for a revision).

Vegetation responses to drought are influenced by other drivers of environmental change (Fischer et al. 2006, Oliver and Morecroft 2014, Franklin et al. 2016, Peñuelas et al. 2017), and some authors states that the impacts of drought on ecosystem must be evaluated in a context of global change considering the interactions with other drivers of environmental change (Archaux and Wolters 2006, Clavero 2011), such us land-use change (Doblas-Miranda et al. 2017). This is specially relevant for areas with a long history of landscape modification as the Mediterranean region where land-use change is a key driver of the global change (Navarro-González et al. 2013, Ameztegui et al. 2016). For instance, Doblas-Miranda et al. (2017) in a recent review, found that land use changes and more especially drought, are crucial factors in the interactions among the drivers of global change for Mediterranean forests.

The impacts of drought are also especially relevant for populations located in the rear edge of their distribution, where climatic conditions often corresponds to the species-limits and the populations are likey 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 et al. 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 et al. 2010). Several studies analyzed the drought effects on Mediterranean tree species representing the southermost limit of their distribution (Camarero et al. 2011, Pasho et al. 2011, Sánchez-Salguero et al. 2012, 2017, Linares et al. 2014, Dorado-Liñán et al. 2017, Caminero et al. 2018), however only a few works have focused on the resilience to drought of rear-edge populations (*e.g.* Sánchez-Salguero et al. 2013, Herrero 2014). Resilience is the capacity of an ecosystem, community or individual to recover pre-disturbance structure and function after a disturbance (Holling 1973, Lloret et al. 2011, Hodgson et al. 2015). The assessment of forest resilience to climatic disturbances, such as extreme droughts, provides critical information about the capacity of forests to maintain their structure and to continue providing valuable ecosystem services. This is particularly relevant for populations located in their rear-edge of their distribution, especially when they are located in Mediterranean mountains.

Remote sensing can be used for studying droughts impacts on ecosystems (Michel Deshayes et al. 2006, Zhang et al. 2013, AghaKouchak et al. 2015, McDowell et al. 2015, Norman et al. 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 et al. 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 et al. 2013, Vicca et al. 2016). Drought impacts on vegetation using remote sensing have been analyzed at different scales (Vicente-Serrano et al. 2013, Assal et al. 2016) and for Mediterranean area there were studies covering all region (Gouveia et al. 2017) and others focused on local scales (**???**, Lloret et al. 2007, Vicente-Serrano 2007, Zribi et al. 2016).

Tree-ring width is a widely used proxy for tree vitality (Fritts 1976, Dobbertin 2005, Bhuyan et al. 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 (Gazol et al. 2018). Several studies combined the use of satellite information with dendroecological data to assess the effect of droughts on vegetation (Dorman et al. 2013, Vicente-Serrano et al. 2013, Sangüesa-Barreda et al. 2014, Coulthard et al. 2017); and recently, Gazol et al. (2018) evaluated the resilience of several forests in Spain combining information derived from remote sensing and tree-ring data.

In this work we used remote sensing information and dendroecological methods to evaluate the drought impacts in canopy greenness (as a proxy to primary growth) and tree-radial growth of a Mediterranean tree species (*Quercus pyrenaica*) located in the rear-edge of their distribution.

Relict populations driven by historical land-use at their climatic (either altitudinal or latitudinal) rear-edge can be particularly vulnerable to climate change. In this study we combined remote sensing information and dendroecological methods to evaluate the drought impacts in both canopy greenness (as a proxy to primary growth) and radial growth of a Mediterranean tree species (*Quercus pyrenaica*) forests in Sierra Nevada, which represent a rear-edge of their distribution. Wealso evaluated the resilience of these forest to several extreme drought episodes. Specifically, the aims of this work were: (*i*) To quantify how two recent extreme drought events influenced primary and secondary growth of *Q. pyreancia* forests in their rear edge; (*ii*) to analyze the resilience of these forests to successive extreme drought events, both in recent times and in the long-term 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. 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.

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# Materials and methods

## Species and study site

Pyrenean oak (*Quercus pyrenaica* Willd.) forests extend through south-western France and the Iberian Peninsula reaching its southern limit in 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 et al. 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 (Gavilan et al. 2007, Río et al. 2007).

This species reaches its southernmost European limit in Sierra Nevada, a high-mountain range located in southern Spain (37°N, 3°W) with elevations of 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 oak patches (2400 Has) identified (Figure 1) in this mountain range, ranging between 1100 and 2000 m *a.s.l.* and often associated to major river valleys. Sierra Nevada is considered a glacial refugia for deciduous *Quercus* species (Brewer et al. 2002, Olalde et al. 2002, Rodríguez-Sánchez et al. 2010) and these populations are considered as a rear edge of the habitat distribution, which is important in determining habitat responses to expected climate change (Hampe and Petit 2005).

The populations of Pyrenean oak forests at Sierra Nevada are considered relict forests (Melendo and Valle 2000, Vivero et al. 2000), undergoing intensive anthropic use in history (Camacho-Olmedo et al. 2002, Valbuena-Carabaña et al. 2010, Valbuena-Carabaña and Gil 2017). In fact, conservation status of this species for southern Spain is “Vulnerable” (Vivero et al. 2000). The relict presence of this species in Sierra Nevada is related both to its genetic resilience and high intraspecific genetic diversity (Valbuena-Carabaña et al. 2010). However, they are also expected to suffer the impact of climate change, due to their greater hydric requirements compared to other more drought-tolerant Mediterranean evergreen oak and pine species. Thus, simulations of the climate change effects on this habitat forecast a reduction in suitable habitats for Sierra Nevada (Benito et al. 2011).

## Drought episodes

The years 2005 and 2012 were chosen as drought years for this study because they have been documented as two of the worst drought years in the last decades for the southern Iberian Peninsula (García-Herrera et al. 2007, Trigo et al. 2013, Gouveia et al. 2015) and they were charecterized as extreme drought in our climatic data (Figure S1). Aunque sabemos que existen otros años de sequía extrema (e.g. 1995, 1981) (Vicente-Serrano et al. 2014), no se han elegido por una limitación metodológica, esto es, nuestro objetivo es analizar el efecto de la sequía y la resiliencia a los eventos de sequía utilizando información de satélite y de dendrocronología, y la información de satélite utilizada (ver mas adelante) solamente está disponible desde el año 2000 en adelante. We compare only these previous drought years in radial growth-time series, to place older drought events with those in 2005 and 2012 … DUDA GUILLERMO

* ¿Decimos aquí algo así como?: Para los datos de radial-growth hemos computado la resiliencia en los 10 eventos mas severos (ver tabla S1)

## Greenness data

As a proxy to primary growth, to characterize the vegetation greenness of *Q. pyrenaica* we used the *Enhanced Vegetation Index* (EVI) derived from MOD13Q1 product obtained by the *Moderate Resolution Imaging Spectroradiometer* (MODIS) sensor (Didan 2015). EVI and NDVI (*Normalized Difference Vegetation Index*) are the most common greenness vegetation indices. We used EVI instead of NDVI because EVI is more sensitive to changes in high-biomass areas (a serious shortcoming of NDVI); EVI reduces the influence of atmospheric conditions on vegetation index values, and EVI corrects for canopy background signals (Huete et al. 2002, Cabello et al. 2012, Krapivin et al. 2015).

MODIS EVI Data from 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). A data filtering was applied to select EVI valid values. The filtering was done using quality flags and VI Usefulness Indices accompanying the EVI data. We filter out those values affected by high content of aerosols, clouds, snow and shadows, following the filtering recommendations of EVI data for mountain regions (Reyes-Díez et al. 2015).

After the filter out process, we built the annual EVI profile for each pixel and then computed the EVI’s annual mean values and the EVI anomaly for each pixel for the period 2000 - 2016. EVI mean was chosen since it is highly stable under the use of any filter (Reyes-Díez et al. 2015) and because it showed high significant correlations with annual (r = 0.81) and seasonal EVI values ( = 0.76 and = 0.88). We explored the temporal trends of EVI at a pixel scale. We computed the nonparametric Mann–Kendall test (Kendall, 1975; Mann, 1945), using the trend package in R (Pohlert 2017). We set 0.05 the alpha level for the test.

To explore the effect of drought events on greenness we calculated the EVI standardized anomaly () pixel-by-pixel, since it minimizes biases in the evaluation of anomalies, providing more information about the magnitude of the anomalies (Samanta et al. 2012, Gao et al. 2016). For each pixel we annually averaged all the EVI valid values, and 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 et al. 2010, 2012).

## Field sampling and dendrochronological methods

### Tree sampling

Tree sampling was carried during autumn of 2016. Trees were sampled at two locations in contrasting slopes of Sierra Nevada: San Juan (SJ; northern aspect) and Cáñar (CA; southern aspect) (Figure 1; Table 1). – GGI: Diferencias microclimáticas Decir algo aquí sobre difrencias microclimáticas entre el norte (más seco, más continental?) y el sur (más húmedo pero más oceánico/cálido?). – For the southern site two elevations were sampled: CA-Low and CA-High. All the sites were oak monospecific and representatives of two of the three population clusters identified for the species in this mountain range (Pérez-Luque et al. 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. We assessed stand competition of target trees by recording distance, azimuth, dbh, species and total height of all neighboring living trees with dbh > 7.5 cm in a circular plot of 10 m radius. We computed two distance independent indices: *density* in , and *basal area* (BA) in ; and one distance dependent indices: size ratio proportional to distance (*srd*) as . We used non-parametric Kruskal-Wallis rank sum tests (Sokal and Rohlf 1995) to analyse differences between sites for height, DBH and competence 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) we used pre-whitened residual chronologies (RWI) 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 et al. 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). We used measured dbh and raw ring-widths to compute BAI by subtracting twice the annual ring width from the annual diameter, starting from the measured diameter outside the bark (Piovesa et al. 2008). We used the following equation:

where is the radius of the tree and is the year of tree-ring formation. We calculated a mean BAI serie for each individual tree. 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 et al. 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 et al. 2018, Frías et al. 2018). We also used the Standardized Precipitation-Evapotranspiration Index (SPEI), a multiscalar drought index that incorporates both precipitation and temperature (Vicente-Serrano et al. 2010, Beguería et al. 2014). SPEI values for the period 1961-2014 were obtained with a spatial resolution of 1.1 km from the Drought indices dataset for Spain database (<http://monitordesequia.csic.es/>), a high resolution database of drought indices for Spain (Vicente-Serrano et al. 2017). We selected a temporal scale for the SPEI of 6 months.

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) 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. We used medians since they are more robust estimator of central tendency than means (Rubino and McCarthy 2004, Camarero et al. 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.

## Resilience

To evaluate the effects of drougth events on greeennes and tree growth (BAI) we used three resilience indices proposed by Lloret et al. (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

We computed the values of these indices for tree growth (BAI) and greenness during each drought event. We considered 2005 and 2012 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 drougth event respectively. A period of three years was chosen because we found similar results comparing periods of two, three and four years (Appendix S7) and this length was used in other studies (e.g. Gazol et al. (2017)). In addition we calculated the same indices for BAI data for the most severe drought events (Appendix S4) since 1900.

## Statistical analysis

We used robust two-way ANOVAs to test for differences between drought events (2005 and 2012) and the two studied oak populations (northern and southern aspects) for each of the three resilience indices studied. These test 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 et al. 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 et al. 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) using several packages (see Supplementary S?)

# Results

## Time trends in vegetation greenness

The analysis of greenness time trends showed that 78.9 % of the pixels of *Quercus pyrenaica* forests experienced an EVI positive trend for the 2000-2016 period, of which 31.67 % were significant. The lowest values of EVI standardized anomalies were recorded in 2005, being singnificantly lower (-2.285 ± 0.029) than those in 2012 (-0.418 ± 0.029) (LSMEANS, t.ratio = -45.358; p\_value < 0.0001), particularly for northern populations (Figure 2). During 2005 drought, *Q. pyrenaica* forests suffered a “browning episode” () (99.36 % and 79.37 % of the pixels for northern and southern populations respectively), yet no changes in greenness were observed in response to the 2012 drought (Appendix S5).

## Greenness resilience to drought events

*Q. pyrenaica* forest showed significantly lower resistance (*Rt*) to the 2005 drought event than to that in 2012 (Table 3; Figure 3). Southern populations showed significantly higher values of resistance to drought than northern ones (Table 3), except for 2012 where non-significant differences were recorded (Table S1; Figure 3) .

Recovery (*Rc*) of greenness was significnatly different bewteen drought events and sites (Tables 3). In the 3-year period after the 2005 drought, greenness achieved was 112 % (Rc = 1.12) and after 2012 was 105.7 % (Rc = 1.057) (Table S1). For southern populations, a similar recovery after the 2005 and 2012 drought event was observed (p = 0.2453; Figure 3; Table S1).

Resilience (*Rs*) was significantly higher for the 2012 drought event than for 2005 (Tables S1, 3), although both values were close to 1 indicating that greenness level was rather similar after each disturbance event (Table S1). The southern populations showed higher resilience values than the northern ones, although these differences were not significant for the 2005 drought event (p = 0.036; Figure 3).

## Radial growth trends and climate

Likely as a consequence of their different management origin (*i.e.* land-use legacy), 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). The competition index was similar among sites but plot basal area was greatest in CA-High (Table 1). Yet the basal area increment (BAI) growth in the highest plot in altitude (CA-High) was the greatest (Figure 4). Trees from this location showed in addition a positive growth trend since the late 1970s. This positive trend was not found in any of the other two locations and the two altitudes sampled in the southern populations showed differences in growth, being more similar CA-Low with growth in the northern population (SJ) than with CA-High (Figure 4; Appendix S11).

1995 was the lowest pointer year (*i.e.* the lowest growth) since 1950 in all chronologies (Figure 5). For 2005 and 2012 we found a greater reduction of RWI for northern site (SJ) but weaker for southern sites (CA-High and CA-Low).

## Resilience of radial tree-growth to drought events

Although no significant differences were observed in the resistance (*Rt*) of oak radial growth between the two drought events (Table 3), the 2005 drought reduced growth more than that of 2012 (Rt = 0.721 and 0.819 respectively) (Table S2). Similar to results for greenness, the northern site, which is under a drier climate, showed resistance values lower than those of the southern site, especially for the 2005 drought event where the growth was reduced to 44.5 % respect to that of the preceding period (Figure 3).

Higher values of recovery (*Rc*) were observed after 2012 than after 2005 drougth events, staying at levels of *Rc* < 1 (Figure 3, Table S2). SJ site (northern aspect) showed significantly higher values of recovery than southern sites (CA-High and CA-Low) (Tables 3 and S2), which even not reach recovery values of Rc = 1 (Figure 3).

Similar pattern of resilience (*Rs*) values was found for growth than for greenness respect to drought event: significantly higher values of *Rs* for the 2012 drought event than for the 2005 (Table S2; Figure 3). However, no differences were observed between sites (Table 3). For 2005 drought event, *Rs* value of SJ (northern site) was lower than that of southern ones (CA-High and CA-Low), but opposite pattern was found for the 2012 drought event. All values of *Rs* for growth were below 1, except for the SJ site in 2012 (Rs = 1.031).

When we explored resilience values of growth (*Rs*) for other severe droughts, we found a relation between the resilience and drought severity ( = 0.336) (Appendix S6).

## 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 6a). 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 6b), 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 maximum temperatures of the previous August were the only negative significant for the northern one (Figures 6c and 6d). 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.

## Forest disturbances

The analysis of growth changes revealed differences forest history between sites (Figures 7 and 8). Northern site (SJ) showed two release events ( > 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 1994-2001. These periods alternate with periods of supression. Southern sites (CA-High and CA-Low) showed some weak suppression episodes, but not in the last 50 years.

## Oaks show high resilience in response to recent drought events

Hemos observado como las sequías severas, sobre todo la de 2005, provoca una reducción en el greenness y pero sobre todo en el crecimiento de *Q. pyrenaica*. Los datos de anomalías estandarizadas de EVI mostraron un browning para la mayoría de los robledales de Sierra Nevada durante la sequía de 2005.

El efecto de la sequía de 2005 en el crecimiento también se ha visto en otras especies en el sur de la P. Ibérica La sequía de 2005 fue una de las mas severas afectando significativamente al crecimiento. Esto se ha observado también en otras especies en el sur de la P. Ibérica (p.ej. P. nigra en Andalusia (Sánchez-Salguero et al. 2013), … INCLUIR otras especies y citas).

* P. nigra: Se observó una gran reducción de crecimiento en 1994-1995, 1999 y 2005 para Pinus nigra en el SE de Andalusia (Sánchez-Salguero et al. 2013) coincidiendo con años de sequía para esa zona. La máxima reducción en crecimiento fue observada para 2005, siendo significativamente mayor que para el resto de años (Sánchez-Salguero et al. 2013).

No obstante, a pesar de que 2005 y 2012 fueron dos de las sequías mas severas registradas para el sur de la P. Ibérica (García-Herrera et al. 2007, Vicente-Serrano et al. 2014) (Appendix S3), nuestros resultados muestran que los robledales de *Q. pyrenaica* en su rear-edge presentan una tendencia positiva tanto en el greenness (78.9 % pixeles con greeness) como en el crecimiento (tendencias positivas del BAI).

### La resiliencia de las poblaciones de roble de Sierra Nevada.

El greennness de los robledades en Sierra Nevada ha mostrado una tendencia positiva hacia mas verdor en los ultimos años, que coincide con lo que ya observamos con datos de NDVI (Pérez-Luque et al. 2015b), sobre todo para las poblaciones del sur. Esta tendencia positiva, obtenida de variables derivadas de remote sensing (EVI y NDVI), parece que también se observa en el crecimiento. Por ejemplo en las poblaciones del sur (CaHigh y CaLow) observamos en los últimos años una ligera tendencia de crecimiento.

Aún habiendo pasado varios periodos de sequía severa (sobre todo 2005, el crecimiento -BAI- en el N, se redujo hasta el 45 %), estos robledales han mostrado una alta resiliencia. Por ejemplo para las poblaciones del norte, los valores de EVI durante la sequía de 2005 descendieron hasta el 81 %, mientras que el BAI (sitio SJ) lo hizo hasta el 45 %. Sin embargo, la recuperación fue rápida, así los valores de Recovery (Rc) para el EVI tras la sequía de 2005 (en las poblaciones del norte) fue de 1.17, mientras que para el BAI el Rc fue de 1.112. En definitiva, estamos observando altos valores de resiliencia en estos robledales.

Algunas notas sobre la sequía de 2005: \* The southern half of Iberia received less than 45 % of the usual precipitation between October 2004 and June 2005 (García-Herrera et al. 2007).

Los valores de resiliencia observados para el greenness (cercanos a 1) muestran como esta especie, en su rear edge muestra una buena capacidad de recuperación frente a eventos extremos,

¿A que se debe esa resiliencia?

¿Casos parecidos?

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

Esta tendencia es importante sobre todo en las poblaciones situadas mas al sur, en donde observamos: menor br Encontramos diferencias entre poblaciones. Asi por ejemplo en las situadas mas al sur, vemos que las anomalias de EVI son menos negativas para el 2005; También vemos tendencias positivas en el BAI…

## metodologico

La vegetación es un reflejo de las condiciones ambientales, y los efectos de la sequía se pueden ver tanto con información de satélite (hablar del browning), como con información mas de campo (hablar aquí de lo del BAI). Indicar también las diferencias entre las resiliencias detectadas por ambas metodologías.

### Notas sobre metodologia

* Algunos trabajos han analizado la relación ente RWI y remote sensing (Vicente-Serrano et al. 2013); [(Bhuyan et al. Remote Sensing 9(6):526)]; [Vicente Serrano et al. <https://www.sciencedirect.com/science/article/pii/S003442571630373X>] …
* Nosotros aqui utilizamos la combinación de técnicas de remote sensing con dendro para analizar la vulnerabilidad de poblaciones de Q. pyrenaica situadas en su reaar edge frente a los eventos de sequía.

— notas para esto Se trata de expresar la idea de mezcla de aproximacioes: remote-sensing con dendro. Aunque existen algunos trabajos que utilizado RWI y remote sensing nuestra aproximación es importante, sobre todo para estudiar poblaciones que están en su límite de distribución (rear-edge) (Jump et al. 2010). De hecho, Jump et al. (2010) recomienda el uso de una aprox combinda de dendro, remote sensing y ground-based assessment para analizar los efectos del cambio global en las poblaciones situadas en el rear edge.

Para rear edge poblations es recomendable utilizar aproximaciones combinadas (Jump 2009) donde además de los datos de satélite, se utilicen datos groun based assessment (como por ejemplo la dendro), ya que éstos últimos, además de ser componentes esenciales del forest monitoring, son necesarios para estimar … (ver esto y completar)

Aunque el NDVI o similar ha sido utilizado para monitorizar la respuesta de bosques frente a sequía, su escala espacial limita su uso para estudiar cambios en poblacioens situadas en su rear edge.

Whilst lower resolution data, whether from remote sensing or ground-based monitoring, can inform on widespread regional changes in forest condition, these data are often not adequate for monitoring changes occurring at equatorial range margins owing to their complex distribution and/or topographical variability. In such regions, targeted collection of high-resolution data is necessary in order to identify currently occurring changes and predict the magnitude and spatial distribution of future decline. (Jump et al. 2010)

comentario de GGI

Gracias Antonio. Desde luego que debes resaltar a lo largo del artículo la combinación de sensores y dendro como fortaleza de tu trabajo al analizar el tema de resiliencia desde dos escalas espacio-temporales complementarias. Y eso independientemente que lo diga o no Alistair Jump (que las citas vienen bien, y seguro que el trabajo es bueno), combinar ambas escalas/datos es beneficioso no sólo en poblaciones rear-edge, sino en general. Es decir, desde mi punto de vista, aunque decidas no centrarte tanto en el aspecto metodológico como sugieren Regino y Curro, eso no quiere decir que este punto no lo presentes de forma explícita en tu trabajo (en abstract debe aparecer, luego en intro, discusión y tal vez una frase en conclusiones) como uno de los elementos fuertes (un término medio, vamos). Creo que ya hemos discutido esto cuando hemos hablado. No es el primer trabajo que lo hace, como bien señalas, pero tampoco hay que pensar que no tiene valor, pues no hay tantos trabajos que combinen ambas aproximaciones (habrá cada vez más de hecho). Así que ánimo que queda poco y el trabajo puede quedar interesante si somos capaces de escribir e interpretar bien los resultados que nos has enviado.

### Diferencias entre sitios

Llama la atención que en el rear-edge de la distribución de la especie, en el sitio mas meridional dentro de este rear edge, y en la parte mas alta (estas parcelas están en el treeline de la especie en SN (en torno a 1900)), es donde encontramos mayores crecimientos. Parece que los robles estuvieran mejor en esta zona. Algunas reflexiones sobre esto:

* Quizá están creciendo donde les están dejando (menor impacto antrópico en las zonas mas altas, al menos en los últimos años??)
* ¿Diferentes niveles de compentencia?. Parece que la competencia es similar en los tres sitios: no diferencias sig. para valores de Stand density ySize ratio proportional to distance (ver table 1).
* ¿Diferencias entre suelos?? En principio no. (“Taxonomic and functional diversity of a quercus pyrenaica willd. rhizospheric microbiome in the mediterranean mountains” 2017) en un trabajo sobre microbiota del suelo, explora diferencias en un gradiente altitudinal en Cáñar. Analiza 3 sitios: por encima del treline (XZF, el piornal), low altitudinal oak forest (LAF, en la zona baja del robledal) and high altitudinal oak forest (HAF). En su trabajo, LAF está mucho mas bajo, pero HAF está cerca de las parcelas caHigh. Restulados:
  + tipo de suelo: LAF es Sandy-loam, HAF es loam
  + HAF tuvo los valores mayores de disponibilidad hídrica (% available water tabla s1 en (“Taxonomic and functional diversity of a quercus pyrenaica willd. rhizospheric microbiome in the mediterranean mountains” 2017)) –> Esto es importante, creo
  + Los tres sitios eran pobres en materia orgánica, pero el HAF dobló los valores de los otros dos sitios
  + No diferencias en contenido de N, C/N ratio similares en HAF, y LAF
* ¿Menor estrés hídrico en zonas mas altas? Puede ser que tengamos menor estrés hídrico en esta zona?? Este robledal, está en la cara sur de SN, y en una ladera con bastante insolación. Algunos trabajos antiguos (de fitosociólogos) hablan de que su presencia aquí se debe a que reciben un aporte extra de humedad procedente de las brisas del mediterráneo, para suplir el mínimo de humedad que necesitan en verano. Quizá también tendríamos que incluir el papel de las acequias. La zona caHigh tiene una acequia muy cerca (y por encima) de donde muestreamos (recordad el roble mas grande, y el mas alto, esta justo en una acequia). No se si es interesante que lo comentemos.
* Otro punto de interés a introducir aquí es que frecuentemente se asume una alta vulnerabilidad a la sequía de las poblaciones situadas en su dry rear-edge (Martínez-Vilalta 2018), sin embargo algunos estudios están demostrando esto no es siempre así (ver por ejemplo (Cavin and Jump 2017, Granda et al. 2017)). Nuestros resultados creo que van en esta línea creo. Esto, como apunta (Martínez-Vilalta 2018)m tiene que ver con la que consideramos como habitat marginal de la especie (… When the focus is on marginal, rear-edge populations, proper consideration should be given to the different ways in which marginality can be defined (stressing geographical, climatic or other ecological factors).

En un estudio a escala continental, (Bhuyan et al. 2017) encontraron que para la misma especie (estudiaron 850 sites: Fagus sylvatica, Abies alba, Picea abies, Larix decidua, Pinus cembra, P sylvestris, P nigra, Quercus petraea y Q robur) los stands situados a mayores elevaciones fueron menos sensibles a la sequía que los situados a elevaciones inferiores (stands were less drought sensitive at higher elevations compared to lower elevations). The effect of elevation was seen clearly in the case of several species where high elevation sites showed greater drought resistance compared to stands at lower elevation in the same climate zone.

Otra cosa. Gea-Izquierdo and Cañellas (2014) encontró que a lo largo del gradiente altitudinal el BAI se estabilizó o disminuyó a partir de 1970. DUDA: Nosotros encontramos un ligero (y débil) aumento, sobre todo en caHigh.

### OTRA COSA

In fact, several authors have raise the need to consider land use y drought de forma conjunta en las environmental y forest management …. (ver Peñuelas et al 2017 y tb Doblas Miranda )

Environmental and forest management policies should take into account all these characteristics of Mediterranean forests and the social, environmental and climatic conditions that are projected for the coming years and decades.

#### Climate and tree relationship

Frase de resultados que tenemos que poner en discussion: 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 7b), specially for the northern population (r > 0.6), … **which can be interpreted as higher sensitivity to drought of a drier site (Gea-Izquierdo and Cañellas 2014)**.  
#### Disturbance Estos periodos se relacionan bien con eventos antrópicos: mineria (el primero de ellos) y actividades forestales el segundo (esta frase de la minería y demás la dejamos para la discusión??).

### ¿Que factor es mas limitante para el crecimiento en el rear-edge de Q. pyrenaica?

Aquí pueder ser interesante comentar algo de el peso de las variables climáticas en el crecimiento para poblaciones situadas en el borde de distribución (pesa mas la temperatura o la disponibilidad de agua?).

Para *Q. pyrenaica* moisture availability was reported to be the most limiting factor driving radial growth in Iberian Q. pyrenaica populations (Gea-Izquierdo and Cañellas 2014) (Prec hidrológica y SPEI) (ver también Gea-Izquierdo et al. 2015 European Journal of Forest Research). Lo que hemos obtenido aqui (analizando solo el rear edge) también van en esa línea.

Podríamos complementarlo con lo que le pasa a otras especies en su borde de distribución: por ejemplo en Baza, Herrero et al. 2013, encontraron para Pinus nigra y sylvestris que la temperatura tenía mas peso que la disponibilidad de agua). O también ver algunos de los trabajos de Camarero et al 2013 para el P. nigra en su borde de distribución u otros similares (el de Sanchez-Salguero et al. 2013, 2015) …

* Vicente-Serrano:
  + We found that some forests from cold and humid areas respond to shorter drought time-scales than forests from dry areas, which usually respond to longer time-scales
  + Growth and responses to drought are modulated by site conditions such as soil type, specific functional traits and the intensity of competition among neighbouring trees (Orwig & Abrams, 1997; McDowell et al., 2008; Linares et al., 2010; Pasho et al., 2011).
  + Our findings provide evidence that the patterns of growth response to drought do not follow a general geographical structure and that these patterns are driven by the biogeographical, topographic and climatic conditions of each site, showing that forests located in different continents have the same pattern of response to drought time-scales.

duda –> las proyecciones de crecimiento que hiciste (Gea-Izquierdo et al. 2013) sugerían un declive en el crecimiento. Nosotros estamos obteniendo algo diferente no? DUDA

## historia forestal de ambos sitios

Incluimos lo que conocemos de la historia forestal de los sitios?? Me explico, tenemos datos de manejo y uso antrópico de las dos zonas que proceden de varias fuentes. En resumen, mas o menos, tenemos:

* Minería: datos de minería, que afectan sobre todo a la población de SJ (los tenemos localizados temporalmente)
* Actuaciones forestales: Tenemos una bd con actuaciones forestales, y he contactado con varios de los responsables de proyectos de actuaciones forestales en ambas zonas, y tenemos con bastante detalle la información sobre actuaciones forestales (al menos espacial y temporalmente)
* Incendios, Carboneo, Ganadería, etc –> Tenemos información menos estructurada sobre estos ámbitos, procedentes de varias fuentes, que tienen una incertidumbre mayor espacial y temporalmente.

Todo esto lo comento, porque quizá podemos utilizar dicha información para la discussión, o a lo mejor mete mas ruido (¿que opináis?)

Por otro lado, sabemos que estos robledales han estado sometido a muchos ciclos de coppiccing, lo que podrían haber reducido su diversidad genética, y por tanto su resiliencia. Pero varios trabajos (Valbuena-Carabaña and Gil 2013, 2017) han encontrado que esta especie en su límite de distribución sur, muestra unos altos niveles de resiliencia (en este caso genética).

## refugio??

Los robledales de SN estén situadas en su borde rear-edge donde se supone que sufren mas estrés climático. Hemos observado un aumento en el greenness en los últimos años. Por otro lado, hemos encontrado que son poblaciones resilientes a la sequía, tanto para el crecimiento como para el greenness. Además, estos robledales tienen una alta resiliencia genética (Valbuena-Carabaña and Gil 2013, 2017). ¿Sierra Nevada (regiones de montaña) como refugio?? quizá este rear-edge esté actuando como refugio?? (esto es muy especulativo)

## MAs cosas diferentes

Otras especies: rear edge

Evaluar el crecimiento en el rear edge de F. sylvatica

<https://link.springer.com/article/10.1007/s10342-016-0982-7?wt_mc=Internal.Event.1.SEM.ArticleAuthorOnlineFirst>

¿Que limita al crecimiento en el borde sur de su distribucion? –> Ver esto <http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2486.2006.01250.x/abstract>

Pinus sylvestris (Baza) (Matias et al 2017) Radial growth was maximal at medium altitude and treeline of the southernmost populations. Temperature was the main factor controlling growth variability along the gradients, although the timing and strength of climatic variables affecting growth shifted with latitude and altitude.

<http://onlinelibrary.wiley.com/doi/10.1111/gcb.13627/full>

Idea –> algunos autores comentan que puede existir una alteración en el balance competitivo entre especies en mixed stands. Por ejemplo en Montseny, borde equatorial para F. sylvatica, se está viendo que el F. sylvatica está siendo reemplazado por Q. ilex. … En SN, el artículo de B. Benito (Climatic Change) habla del remplazo que existirá de Q. pyrenaica por Q. ilex, sin embargo, estamos viendo que los crecimientos son muy grandes y que Q. pyrenaica tiene mucha resiliencia –> entonces que pasa con las predicciones de dichos modelos ???

### Esto viene del apartado Radial growth trends and climate

* Aqui me comentó GGI que distribuyera esto bien entre results y discussion Los tres sitios mostraron una reducción en los valores de BAI durante las sequías de 1995 y 2005, y menos evidente para el año 2012 (Figure 5). La población del norte (SJ) mostró una gran liberación en torno a 1945 fruto quizá de cortas asociadas a la actividad minera de la zona. Asimismo, esta población mostró un marcado descenso en BAI durante el periodo 1986 - 1999.

### Notas de comparación metodológica

Babst et al. 2017 hablan tambien de combinar ambos métodos

Jump et al habla de utilizar combinaciones de ambos métodos para estudiar esto, y esto es importante para las poblaciones del rear edge.

### Otras

Existen trabajos que han analizado los efectos de la sequía en especies situadas en su rear edge (Asier, por ejemplo; Matias) y algunos de ellos se han centrado en ver como responde el crecimiento de las especies en el rear edge utilizando dendro (Herrero Rigling.. // dorado-liñan // sanchez salguero

trabajos rear edge: \* sanchez salguero Is drought the main decline factor at the rear edge of Europe? The case of southern Iberian pine plantations \* sanchez salguero Assessing forest vulnerability to climate warming using a process-based model of tree growth: bad prospects for rear-edges \* dorado-liñán: Climate threats on growth of rear-edge European beech peripheral populations in Spain. \* herrero rigling: Varying climate sensitivity at the dry distribution edge of Pinus sylvestris and P. nigra \* dorado-liñan: Large-scale atmospheric circulation enhances the Mediterranean East-West tree growth contrast at rear-edge deciduous forests. buscar otros

Sin embargo el estudio de las poblaciones situadas en su rear edge requiere de una aproximación combinada donde se estudie la respuesta de las poblaciones al cambio climático y su resiliencia utiliznado diferentes aproximaciones metodológicas, por ejemplo combinando dendro y remote sensing (Jump et al. 2010).

.. ver (Vicente-Serrano et al. 2013) impacto de las sequías en diferentes zonas (i.e montañas)

# Otras notas:

* To guide sustainable forest management, forest researchers are asked to provide concrete answers about forest resilience in response to expected climatic trends, and extreme climatic events (Lindner et al., 2014) <https://www.sciencedirect.com/science/article/pii/S030147971400379X?via%3Dihub>
* Hablan de incorporar ademas de RS, el conocimiento ecológico (los principios ecológicos) para comprender las consecuencias de las disturbances analizadas con RS, y sobre todo para predecir futuro. (McDowell et al <https://www.sciencedirect.com/science/article/pii/S1360138514002726>)
* Proyeccciones de crecimeinto de para *Q. pyrenaica* sugieren un declive en el crecimiento en las proximas decadas a lo largo de su rango de distribución en la P. Iberica, en diferentes escenarios climáticos (Gea-Izquierdo et al. 2013): Predictions suggest that QUPY productivity would decline in the next decades all along its distributional range in the Iberian Peninsula for all the climate scenarios studied. Este declive debería ser mas dramático en las baja altitudes de las zonas mas calientes del sur de su distribución

–> vulnerabilidad local (related to rear-edge) La tendencia de reducción drástica sugerida por el modelo para el dry-edge de la distribución de la especie podría expresar una aumentada vulnerabilidad de los árboles al incremento del estrés hídrico forzado por un clima mas cálido (Gea-Izquierdo et al. 2013).

Negative trends over recent years and the greater response to moisture availability found at warmer and drier low elevations in the south suggest vulnerability to warming at the local low elevation dry edge of the species’s range (e.g. QUPY9). Otros estudios en la zona Mediterranea reportaron un descenso similar en la productividad con un incremento en la vulterabilidad a la sequía ()

Muchos trabajos han analizado la respuesta de la vegetación a las sequías (eg. Allen et al. (2010); Vicente-Serrano et al. (2013); Martínez-Vilalta and Lloret (2016); Norman et al. (2016)), y algunos de ellos han mostrado el efecto de las sequías en especies Mediterráneas (ver por ejemplo Pasho et al. <https://www.sciencedirect.com/science/article/pii/S016819231100253X#fig0020>; Camarero et al. (2011) combina uso y sequía; añadir alguno mas de GGI). Algunos Some of these species represent southernmost populations in the Mediterranean ambit, which explains their vulnerability to the warmer conditions (Andreu et al., 2007; Sánchez-Salguero et al., 2016).

Case studies that focus on multiple scales - including local scales - and also valuables (Dale et al. 2018 Frontiers) –> Se necesitan casos de estudio que se enfoquen en escalas multiples (incluyendo las locales) y que combinen varias metodologías (Jump et al. …)

1. rear edge

* además (Vulnerabilidad de los bosques a los eventos climáticos extremos …):
* Existen evidencias que sugieren que muchos bosques son vulnerables a eventos climáticos extremos … (Zhang) y esto puede ser especialmente relevante para especies situadas en el rear edge (completar) …

… Varios trabajos han apuntado la existencia de vulnerabilidad local al aumento de temperaturas en los sitios del sur de distribución de esta especie (Gea-Izquierdo et al. 2013, Gea-Izquierdo and Cañellas 2014) así como una strong response to moisture availability…; Además teniendo en cuenta que en los últimos años estamos viendo un aumento en las sequías (menor disponibilidad de agua) –> por ello queremos analizar como están respondiendo esta especie, sobre todo en esas zonas dry-egde, y analizar su resiliencia…

—- old ### Efectos de la sequía en el greenneess y en el crecimiento.

Hemos observado como las sequía, sobre todo la de 2005, provoca una reducción en el greenness y pero sobre todo en el crecimiento. Los datos de anomalías estandarizadas de EVI mostraron un browning para la mayoría de los robledales de Sierra Nevada durante la sequía de 2005.

La sequía de 2005 fue una de las mas severas afectando significativamente al crecimiento. Esto se ha observado también en otras especies en el sur de la P. Ibérica (p.ej. P. nigra en Andalusia (Sánchez-Salguero et al. 2013), … INCLUIR otras especies y citas).

Algunas notas sobre la sequía de 2005:

* 2004/2005 hydrological year is considered one of the worst drooughts ever recorded in the Iberian Peninsula, particularly in the central and southern sectors (García-Herrera et al. 2007).
* The southern half of Iberia received less than 45 % of the usual precipitation between October 2004 and June 2005 (García-Herrera et al. 2007).
* The hydrological year from October 2004 to September 2005 was the driest on record at several locations throughout Iberia (García-Herrera et al. 2007).
* An analysis of the long term series from meteorological stations (n=54) of Iberian Peninsula (1961-2011) reveals that major drought episodes in the Iberian Peninsula were recorded in 1981, 1995, 2000 and 2005 (Vicente-Serrano et al. 2014).

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