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The impact of drought spells on forests depends on site conditions: The case of 2017 summer heat wave in southern Europe

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Abstract

A major component of climate change is an increase in temperature and precipitation variability. Over the last few decades, an increase in the frequency of extremely warm temperatures and drought severity has been observed across Europe. These warmer and drier conditions may reduce productivity and trigger compositional shifts in forest communities. However, we still lack a robust, biogeographical characterization of the negative impacts of climate extremes, such as droughts on forests. In this context, we investigated the impact of the 2017 summer drought on European forests. The normalized difference vegetation index (NDVI) was used as a proxy of forest productivity and was related to the standardized precipitation evapotranspiration index, which accounts for the temperature effects of the climate water balance. The spatial pattern of NDVI reduction in 2017 was largely driven by the extremely warm summer for parts of the central and eastern Mediterranean Basin (Italian and Balkan Peninsulas). The vulnerability to the 2017 summer drought was heterogeneously distributed over Europe, and topographic factors buffered some of the negative impacts. Mediterranean forests dominated by oak species were the most negatively impacted, whereas *Pinus pinaster* was the most resilient species. The impact of drought on the NDVI decreased at high elevations and mainly on east and north-east facing slopes. We illustrate how an adequate characterization of the coupling between climate conditions and forest productivity (NDVI) allows the determination of the most vulnerable areas to drought. This approach could be widely used for other extreme climate events and when considering other spatially resolved proxies of forest growth and health.

KEYWORDS
extreme drought, forest canopy, heat wave, Mediterranean species, MODIS NDVI, plant functional groups

1 | INTRODUCTION

Forest productivity, vegetation dynamics and tree species distributions have been altered by the impacts of climate warming at the global scale since the middle of the 20th century due to an increase in atmospheric water demand and evapotranspiration (IPCC, 2014). Increases in the intensity and frequency of climate extremes such as heat waves and dry spells, which have been forecasted to increase, could lead to detrimental effects on forest ecosystems (Della-Marta, Haylock, Luterbacher, & Wanner, 2007; Reyer et al., 2013). Severe droughts can alter the global carbon balance (Reichstein et al., 2013) and alter or reduce the value of forest ecosystem services (Hanewinkel, Cullmann, Schelhaas, Nabuurs, & Zimmermann, 2013), ultimately impacting forest compositions and dynamics. For these reasons, an increase in the occurrence of climate extreme 'events-focused' experimental research has been observed in recent decades, accounting for one-fifth of all published climate change studies (see, Jentsch, Kreyling, & Beierkuhnlein, 2007 for a review).

Several studies have documented either exceptional, site-specific and event-related responses (i.e. reduction in canopy photosynthesis, canopy dieback and tree mortality) or long-lasting lagged effects on the components of forest dynamics (e.g. phenology, growth, structure, mortality and composition) triggered by extreme climate events (Allevato et al., 2019; Boisvenue & Running, 2006; Nolè, Rita, Ferrara, & Borghetti, 2018). The serious negative consequences of prolonged heat waves and dry spells include forest dieback, which can be caused by the starvation of carbohydrate reserves or hydraulic failure as well as result in an increased risk of pest/pathogen attacks, which might contribute to reduced productivity and increased forest mortality (Allen, Breshears, & McDowell, 2015; Anderegg et al., 2015).

To date, the effects of climate extremes on vegetation have been widely studied in drought-prone regions such as the Mediterranean Basin (Della-Marta et al., 2007). Here, the prominent examples of exceptional climatic conditions characterized by very high temperatures associated with dry spells include the summer droughts and heat waves of 1994–1995, 2003, 2005–2006 and 2010, a so-called 'mega-heat wave' (Barriopedro, Fischer, Luterbacher, Trigo, & García-Herrera, 2011; García-Herrera, Díaz, Trigo, Luterbacher, & Fischer, 2010). In more mesic regions, such as temperate central Europe, 2003 was the warmest summer in the past 500 years (Ciais et al., 2005; García-Herrera et al., 2010; Schär et al.,). Over large areas, the summer temperatures exceeded the 1961–1990 average by +3°C, a value equivalent to 5 *SD*s above the 30 year summer average (Schär et al.,). Many studies agree that extreme weather during the summer of 2003 negatively impacted carbon allocation patterns (e.g. Granier et al., 2007), plant species composition (e.g. Kreyling, Jentsch, & Beierkuhnlein, 2011), tree resistance to pest attacks (e.g. Rouault et al., 2006) and forest productivity (Ciais et al., 2005) over much of Europe, but these impacts depended on geographic location, topography (elevation, aspect) and vegetation type (Gartner, Nadezhdina, Englisch, Čermak, & Leitgeb, 2009; Jolly, Dobbertin, Zimmermann, & Reichstein, 2005). For instance, in addition to the general response of forests shifting from carbon sinks to carbon sources in low, mesic sites (Ciais et al., 2005; Reichstein et al., 2007), at high elevations, enhanced vegetation growth is driven by high temperatures (Jolly et al., 2005). Differences among forest types/species were also found either in the extent of damage (for instance Bonal, Pau, Toigo, Granier, & Perot, 2017; Bréda, Huc, Granier, & Dreyer, 2006) or recovery rate (He et al., 2018; but see also Pretzsch, Schütze, & Uhl, 2013 for mixed vs. pure forest stands comparison) following the 2003 European drought.

These changes in forest productivity due to severe and recurrent droughts have also been identified as a major contributing factor in the recently accelerated rates of tree growth decline and mortality in southern Europe. Examples of widespread forest die-offs are well documented after droughts (Bréda et al., 2006; Camarero, Gazol, Sangüesa-Barreda, Oliva, & Vicente-Serrano, 2015; Camarero, Gazol, Tardif, & Conciatori, 2015; Peñuelas, Lloret, & Montoya, 2001). In these areas, leaf shedding and background mortality rates have increased rapidly in recent decades due to elevated temperatures and/or water shortages (Carnicer et al., 2011). Although Mediterranean forests are adapted to recurrent seasonal droughts and an irregular precipitation regime and have a high resilience capacity (Gazol, Camarero, Sangüesa-Barreda, & Vicente-Serrano, 2018), unprecedented extreme climatic events in either duration or intensity could have detrimental impacts on forest ecosystems that transcend the tolerance of some tree species (Gazol, Camarero, Vicente-Serrano, et al., 2018). Therefore, our understanding of the impacts of extreme climate events on vegetation represents a crucial challenge from the perspective of an increasing frequency and/or intensity of heat waves and dry spells (Della-Marta et al., 2007; Spinoni, Naumann, Carrao, Barbosa, & Vogt, 2014).

Many of the aforementioned studies characterized the 'signal' of extreme climatic impacts on vegetation using different methods based on multiple approaches, which provided a geographically widespread archive for studying spatio-temporal variations in climate conditions. Such methods span from monitoring radial growth changes through the use of dendrometers in experimental plots (e.g. Hanson, Todd, & Amthor, 2001; Ogaya, Peñuelas, Martínez-Vilalta, & Mangirón, 2003) to using annual tree-ring analysis (e.g. Gazol, Camarero, Vicente-Serrano, et al., 2018; Sánchez-Salguero, Camarero, Carrer, et al., 2017) or monitoring ecosystem carbon fluxes using the eddy-covariance technique (e.g. Ciais et al., 2005). In other cases, remote sensing information has been used for analysing vegetation responses to drought at multiple spatial and temporal scales (Ivits, Horion, Fensholt, & Cherlet, 2014; Vicente-Serrano et al., 2013, 2016).

Remote sensing based on multispectral scanners provides moderate resolution images that cover nearly the entire globe and allow the estimation of several indices that are useful for ecosystem-level monitoring, biomass estimation and land cover change assessments (Wang, Rich, Price, & Kettle, 2004; see, Pettorelli et al., 2005 for an interesting review). The normalized difference vegetation index (NDVI), which is the most widely used index of vegetation greenness, is considered an efficient proxy of fractional absorbed photosynthetically active radiation (Tucker, 1979). This index is strongly correlated with the leaf area index and green biomass (Pettorelli et al., 2005) and thus provides valuable information for estimating long-term spatio-temporal changes in net primary production (Running et al., 2004; Vourlitis et al., 2003). The NDVI has been used to assess the negative impacts of severe drought events on forests at a global scale, which are particularly pronounced in water-limited regions and in species with low hydraulic safety margins (Wu et al., 2018). The responsiveness of NDVI to precipitation changes is well established at various spatial and temporal scales (Zhao, Gao, Wang, Liu, & Li, 2015). Significant relationships have also been found between the NDVI and drought indices, such as the standardized precipitation evapotranspiration index (SPEI), revealing distinct responses of forest vegetation to drought at different characteristic timescales across regions and biomes (Vicente-Serrano et al., 2013, 2016).

By mid-July 2017, several European regions were affected by prolonged drought conditions (World Weather Attribution, 2017). A significant warming over south-central Europe resulted in a heat wave that mainly affected the centre of the Mediterranean Basin, where the maximum temperatures reached 42°C across Italy and the Balkans. Extended regions of southern France, the Iberian Peninsula and central Italy also suffered from a rainfall deficit over the summer months that, combined with unexpectedly high temperatures in July–early August, resulted in very dry conditions (Masante et al., 2017; European Drought Observatory, see: http://edo.jrc.ec.europa.eu/). This study used the extreme climate event that occurred in the summer of 2017 as an opportunity to understand how forests were impacted. We analysed spatio-temporal variations in the NDVI across southern European regions. In particular, we aimed at (a) identifying regions where the summer drought most affected the vegetation; (b) evaluating the influence of topographic factors on the vegetation response; and (c) exploring the variability in the vegetation response to the severe drought among biogeographic regions and among the dominant tree species. We thereby hypothesized the existence of non-linear vegetation responses to droughts contingent on local factors, such as latitude, elevation, aspect and vegetation type.

2 | MATERIALS AND METHODS

2.1 | Satellite-based data and study area

In this work, nine-tile mosaics of MODIS Terra NDVI data covering the entire European continent, spanning from 35°N to 55°N and −10°E to 30°E, were acquired from the Land Processes Distributed Active Archive Center (https://lpdaac.usgs.gov/) at a 250 × 250 m resolution and 16 day compositing period (MOD13Q1 collection 6 product) covering the period from 2013 to 2017. We focused our analysis on August NDVI data to detect the peak of the drought that occurred between the end of July and the first part of August. The data set pre-processing included clipping the images to the study area, re-projecting the images onto the geographic lat/long (WGS 84) projection and excluding burnt areas from 2013 to 2017 using MOD45A1 (shapefile at 500 m resolution). Finally, 16 day NDVI data were aggregated to mean monthly values. Then, the August NDVI departures (hereafter $NDVI_{diff}$) from the average 2013–2016 values obtained for contiguous Europe were obtained by calculating the residuals extracted from a linear regression model between the average values of August NDVI from 2013 to 2016 (*x*) and the NDVI of August 2017 (*y*).

Extreme $NDVI_{diff}$ values were defined as those corresponding to the 10th and 90th percentiles of the available data for each pixel, that is, those above or below the upper and lower thresholds of NDVI values.

2.2 | Climate data and drought index

Temperature data sets from 1950 to 2017 were retrieved from the E-OBS v16.0 0.25 interpolated gridded version of the European Climate Assessment & Dataset (Klein Tank et al., 2002) in a regular 0.25° grid. Global Precipitation Climatology Centre monthly gridded precipitation data sets were used to generate gridded precipitation data at the same spatial resolution.

Drought effects have been assessed using several drought indices, such as the SPEI, which has been widely used in the last decade among ecologists and is considered to be more appropriate for the Mediterranean climate (Vicente-Serrano et al., 2013). The SPEI is a multi-scalar metric of drought that accounts for precipitation as well as changes in evaporative demand caused by temperature variations. This index is based on the difference between precipitation and potential evapotranspiration (PET) and is computed using the Penman–Monteith equation. The 1 month SPEI was calculated for the 2017 summer period (June–August, JJA) at a 0.25° spatial resolution. We selected 1 month SPEI values because they accounted for short-term droughts, and analyses using 3 month SPEI values yielded similar results. The PET was derived using the Food and Agriculture Organization (FAO-56) Penman–Monteith equation with the Hargreaves–Samani simplification for net radiation. Furthermore, summer temperature and precipitation anomalies were calculated based on the 1981–2000 reference period.

2.3 | Vegetation categories

To analyse the response of forest vegetation to the SPEI, we discriminated between forested and non-forested areas using the Corine Land Cover 2012 (CLC2012; https://land.copernicus.eu/pan-european/corine-land-cover) vectorial map of Europe. According to the legend definitions, we selected the land cover classes 'Broad-leaved forests', 'Coniferous forests' and 'Mixed forests' assuming that the canopy NDVI values in the dense forests under study area were mostly determined by the dominant tree species.

In addition, we further classified the forest community composition according to European biogeographical regions (EAA, 2016) and the dominant tree species in Europe (Brus et al., 2012) to investigate the differential vegetation community response to the 2017 summer drought. The biogeographical regions delineate and describe ecologically distinct areas in Europe; these designations were developed to serve the Habitats Directive of the European Community with the aim of describing habitat types and species that live under similar conditions on the basis of climatic, topographic and botanical data (European Topic Centre on Biological Diversity, 2006).

2.4 | Topography data

For the topographic information, Space Shuttle Radar Topography Mission (SRTM v4.1) data were downloaded from the Consultative Group on International Agricultural Research (Jarvis, Reuter, Nelson, & Guevara, 2008). The data were aggregated from 90 to 250 m, and the elevation, slope and aspect were also computed.

2.5 | Analyses

A linear association was used to detect areas showing clustered patterns between the $NDVI_{diff}$ and summer SPEI. For this purpose, we used bivariate local indicators of spatial association (BiLISA) analysis to detect local significant positive (clusters) or negative (dispersion) spatial autocorrelation between the features of two different variables in nearby locations (Anselin & Rey, 2014). BiLISA displays the degree of linear association between the value for one variable at a given location and the average of another variable at neighbouring locations (Anselin, Sybari, & Smirnov, 2002). Positive and negative spatial associations were classified into four correlation types, including two cluster categories: high–high and low–low. The output would be high–high if a pixel with a high value is surrounded by the same high observed values, and the result would be low–low if a pixel with a low value is surrounded by neighbours with low values. Moreover, the outputs consisted of two outlier categories that implied a negative spatial association and appeared when a high value was surrounded by low values (high–low) and vice versa (low–high). The BiLISA was tested under the null hypothesis of non-spatial autocorrelation at 0.001, 0.01 and 0.05 significance levels. The entered spatial data consisted of a hexagonal tesselated map that was used to manage the large data set to clarify the spatial structure, which accounted for the average $NDVI_{diff}$ in an ~2,350 km^2 area (~180 km perimeter). The hexagonal grids were generated by using the *make_grid* function from '*prioritizr*' v0.1.2 package (Strimas-Mackey, 2016) in R statistical suite (R Core Team, 2018), where the grid values were the weighted average of pixels value. Other main packages used in this these analyses included '*raster*' (Hijmans, 2019) for handling raster layers, '*rgdal*' (Bivand, Keitt, & Rowlingson, 2019) for providing bindings to the Geospatial Data Abstraction Library, '*sp*' (Pebesma & Bivand, 2005) for handling shapefiles and '*rgeos*' (Bivand & Rundel, 2019) for topology operations on geometries.

The relative NDVI changing trend in August was also quantified (via MOD13Q1 collection 6 product) for angiosperms and gymnosperms considering the sub-periods 2000–2005 and 2013–2017. We analysed the forests where significant negative SPEI-$NDVI_{diff}$ correlations (i.e. high–high clusters) were detected within the latitudinal boundaries from 37°N to 47°N (excluding Atlantic regions), in order to explore the presence of a common vegetation pattern among tree species affected by the extreme summer 2017.

Additionally, we applied general additive models (GAMs; Hastie & Tibshirani, 1990) of pixelwise extracted $NDVI_{diff}$ data from significantly (p < .05) positive SPEI correlated areas to explore the univariate response curves of the $NDVI_{diff}$ to the summer SPEI, elevation and aspect (details on the procedures and applied GAM are provided in the Appendix).

3 | RESULTS

3.1 | The 2017 heat wave

In the summer of 2017, a widespread positive temperature anomaly affected mainly central and southern Spain, south-east France, central Italy and the Balkans, with temperatures exceeding 25°C and a duration ranging from 20 to 35 days (Figure 1a,b; Figure S1). The extreme temperatures recorded together with large negative precipitation anomalies along the Balkans, the northern Italian Apennines and south-eastern Spain contributed to increasing the drought stress that characterized the summer in southern Europe (Figure 1c,d). The combination of high temperatures and reduced summer precipitation led to a low SPEI in southern Spain, most of the Italian peninsula and the Balkans (Figure 1d). The magnitude of the correlation between the SPEI over Europe for the period under consideration increased with the precipitation deficit and temperature anomaly (see Figure S2).

3.2 | Associations between drought and the NDVI in 2017

In 2017, extremely negative $NDVI_{diff}$ values were observed in south-eastern France, north-eastern Spain, the Balkans and most of the Italian peninsula, whereas positive $NDVI_{diff}$ values were observed in central and eastern Europe, northern Spain and southern Greece (Figure 2).

The spatial analyses (BiLISA) between the $NDVI_{diff}$ and SPEI revealed areas of significant high–high correlation in Germany, Poland and south Britain, while areas of significant low–low correlation appeared across Italy, the Balkans and some regions near the Carpathians and north-western France (Figure 3). Areas of significant high–low and low–high correlations appeared in north-western France and central and eastern Europe (see Figure S3 for the detailed significance of clusters).

3.3 | Impacts of the 2017 drought on forests according to biogeographic region, tree species and topography

Further inspection of the significant spatial association analysis revealed that the Mediterranean regions situated in the Italian peninsula, south-eastern France and the Balkans experienced a higher drop in NDVI values than the other regions (Figure 4). In contrast,

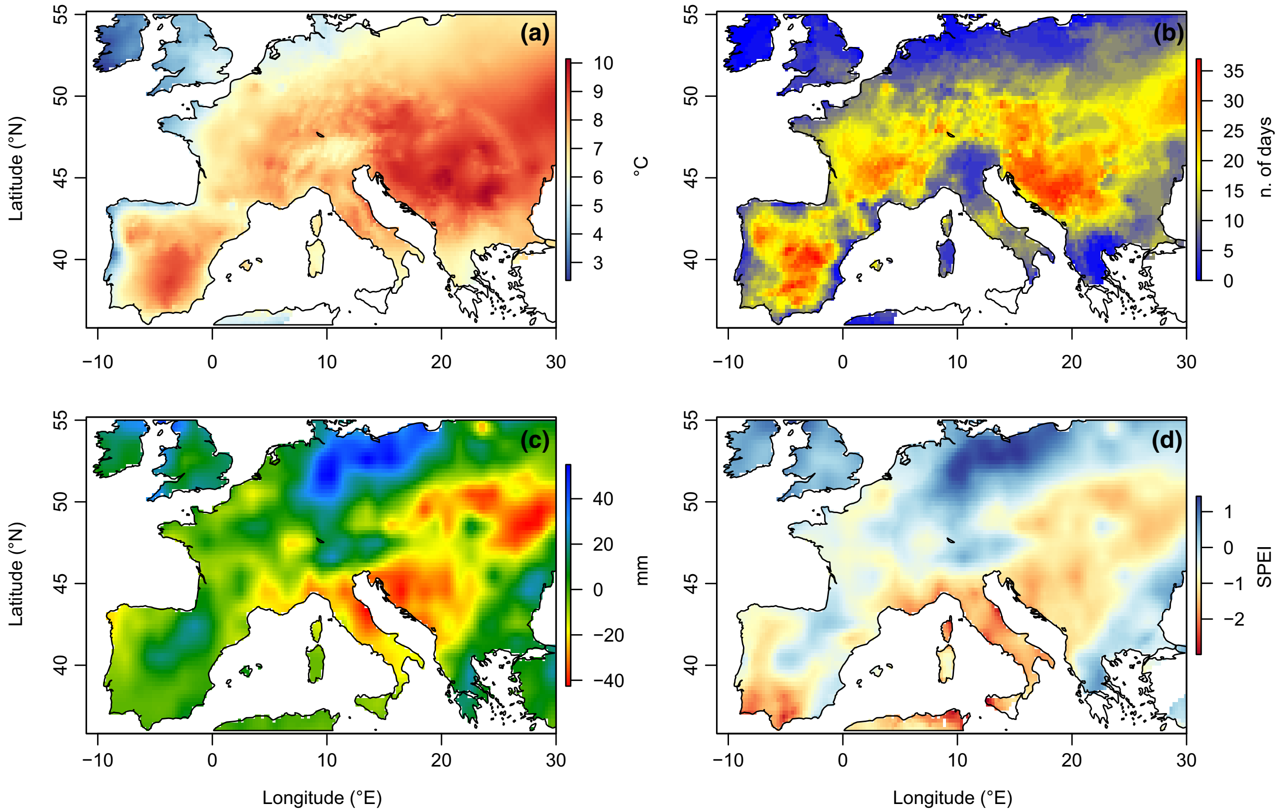

FIGURE 1 Components of the summer (June–August) 2017 drought in Europe: (a) temperature anomaly (°C) with respect to the period from 1981 to 2010, (b) duration of temperature anomaly (no. of days), (c) precipitation anomaly (mm) and (d) standardized precipitation evapotranspiration index [Colour figure can be viewed at wileyonlinelibrary.com]

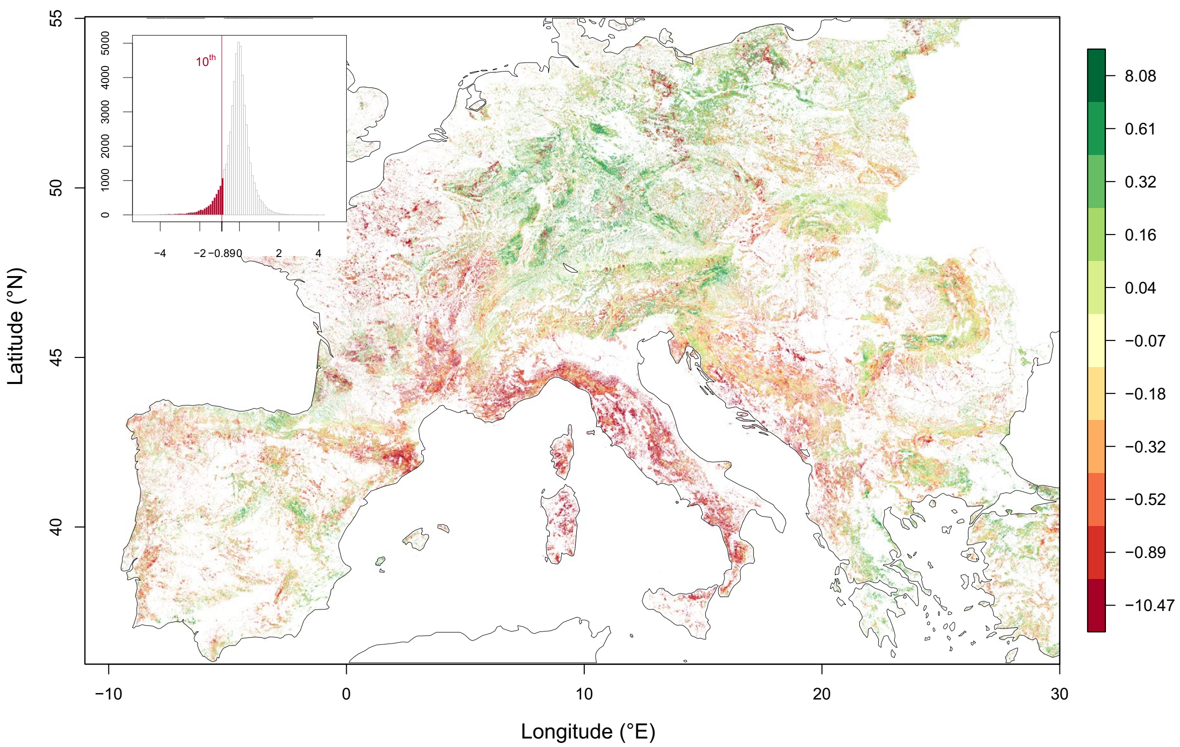

FIGURE 2 Map showing the extreme positive and negative values of $NDVI_{diff}$ (i.e. below the 10th and 90th percentiles), which are colour coded in green and red respectively. The inset shows the distribution of $NDVI_{diff}$ with the 10th percentile threshold. NDVI, normalized difference vegetation index [Colour figure can be viewed at wileyonlinelibrary.com]

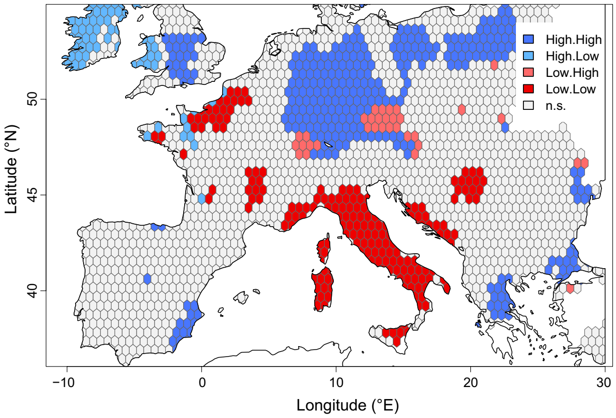

FIGURE 3 Cluster map of significant (p < .05) spatial correlation between the $NDVI_{diff}$ and SPEI drought index in the summer of 2017 based on bivariate local indicators of spatial association. NDVI, normalized difference vegetation index [Colour figure can be viewed at wileyonlinelibrary.com]

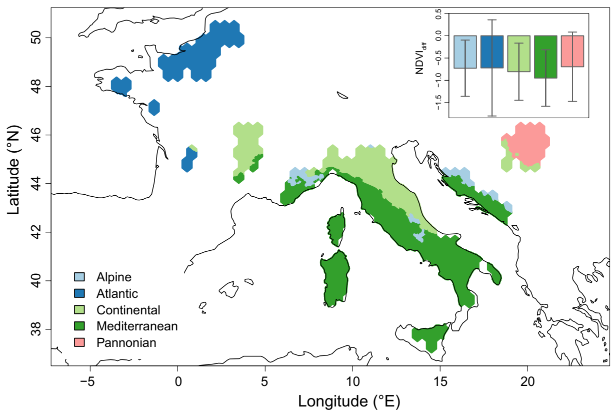

FIGURE 4 Map of the biogeographical boundaries of the significant low–low cluster areas based on bivariate local indicators of spatial association (BiLISA). The inset bar chart represents the mean ± *SD* of the $NDVI_{diff}$ for the masked areas, with different colours corresponding to different biogeographic regions. NDVI, normalized difference vegetation index [Colour figure can be viewed at wileyonlinelibrary.com]

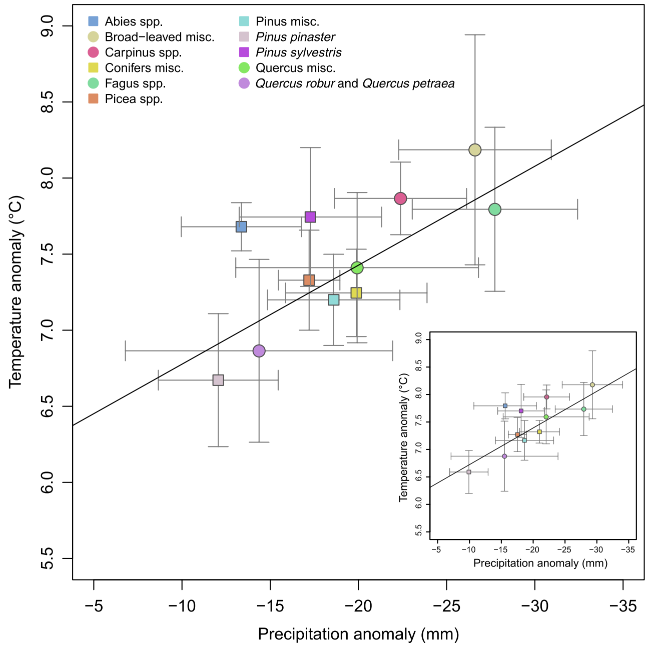

FIGURE 5 Mean values and standard deviations of the summer precipitation and temperature anomalies in the summer of 2017 at forests comprised of dominant European tree species. The data refer to forests where significant negative SPEI–$NDVI_{diff}$ correlations were detected. The inset shows $NDVI_{diff}$ values below the 10th percentile threshold area. The solid lines represent the regression prediction for the main (intercept = 6.12, slope = −0.06; R^2: 0.53) and the inset plots (intercept = 6.05, slope = −0.06; R^2: 0.62). Squares and circles indicate gymnosperms and angiosperms, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

the mean $NDVI_{diff}$ value of the Atlantic bioregion in north-western France did not significantly differ from zero.

In these affected Mediterranean regions, the tree species that experienced the greatest NDVI reductions were mesophilic oak and 'miscellanea' broad-leaved species, while no significant reduction in NDVI value was detected for *Pinus pinaster*, suggesting a high resilience of this species (see Figures S6 and S7). Accordingly, the quantification of the direct impact in terms of NDVI reduction on the forest surface revealed that more than 50% of the total impacted areas were Mediterranean forests dominated by oaks, hornbeam and 'miscellanea' broad-leaved species, which are generally related to mesic sites (Table S1).

Figure 5 shows the species-specific (from pixelwise extraction) temperature and precipitation anomaly thresholds at which the extreme reduction in the $NDVI_{diff}$ was detected. A direct association between the negative NDVI deviations and temperature and precipitation in the summer of 2017 were observed. The most noticeable $NDVI_{diff}$ within the biogeographic regions occurred at temperature and precipitation anomalies ranging from 6.6 ± 0.4 to 8.3 ± 0.6°C and from −12 ± 0.3 to −27 ± 0.5 mm respectively. Among the analysed tree species, the only exception was again *P. pinaster*, with these forests experiencing the lowest temperature and precipitation anomalies. At the other extreme, the temperature related to extremely low $NDVI_{diff}$ values for the 'miscellanea' broad-leaved forests was 8.3 ± 0.4°C, while the precipitation reduction was −29 ± 0.5 mm (Figure 5).

The temporal pattern of August NDVI relative changes for the two sub-periods from 2000 to 2005 and from 2013 to 2017 (Figure 6) showed synchronic and common patterns between the deciduous and conifer tree species. Notably, the relative NDVI changes that occurred in 2017 and 2003 were comparable in terms of both magnitude and agreement among forest types. Interestingly, the 2017 NDVI drop was less pronounced in the *Quercus robur* and *Quercus petraea* among the angiosperms and in *P. pinaster* among the gymnosperms.

Based on the topographic variables, the impact of drought on the NDVI decreased with elevation. The tree species growing at elevations above 1,500 m a. s. l. as well as those growing on east-north-east facing slopes experienced less detrimental effects of drought on their NDVI values (Figure 7; Table S2; Figure S2).

4 | DISCUSSION

The present study provided the first spatially resolved statistical assessment of the impacts of an extreme dry spell, characterized by high temperatures and low precipitation during the summer of 2017, on European forests. By offering a new and robust methodological framework to address how coupled is drought severity and NDVI drops, here, we document how topography and forest type determine the negative responses of NDVI to extreme climate events (droughts, heat waves). As hypothesized, the impacts of the 2017 drought on forest productivity (assessed using the NDVI) were contingent on site factors, such as forest type, tree species, elevation and aspect. During the summer of 2017, record warm temperatures and low soil moisture levels contributed to increasing drought stress and were well correlated with the very low SPEI values detected in Mediterranean regions (Figure 1). Similar heat waves have been linked to an increase in the frequency of extreme droughts across the Mediterranean Basin (Barriopedro et al., 2011; Tebaldi, Hayhoe, Arblaster, & Meehl, 2006). Remote sensing data allowed us to draw a spatially highly resolved picture of the reactions of European forests to heat and drought in the summer of 2017 using the NDVI as an indicator of changes in forest greenness and productivity. To date, consistent results have documented a high correlation of the NDVI with the fraction of photosynthetically active radiation that is intercepted by the photosynthesizing tissue of vegetation (e.g. Zhao, Dai, & Dong, 2018); however, some limitations in the use of the NDVI as a proxy of ecosystem properties have been recognized, including canopy structure and moisture state, since these metrics tend to become saturated in highly multilayered canopies (Glenn, Huete, Nagler, & Nelson, 2008). That's why, alternative remotely sensed vegetation indices like the photochemical reflectance index (He et al., 2016), the sun-induced fluorescence (Li, Xiao, & He, 2018) and the near-infrared reflectance of terrestrial vegetation (Badgley, Field, & Berry, 2017) have recently been proposed because they provide complementary information on drought impacts on gross primary production.

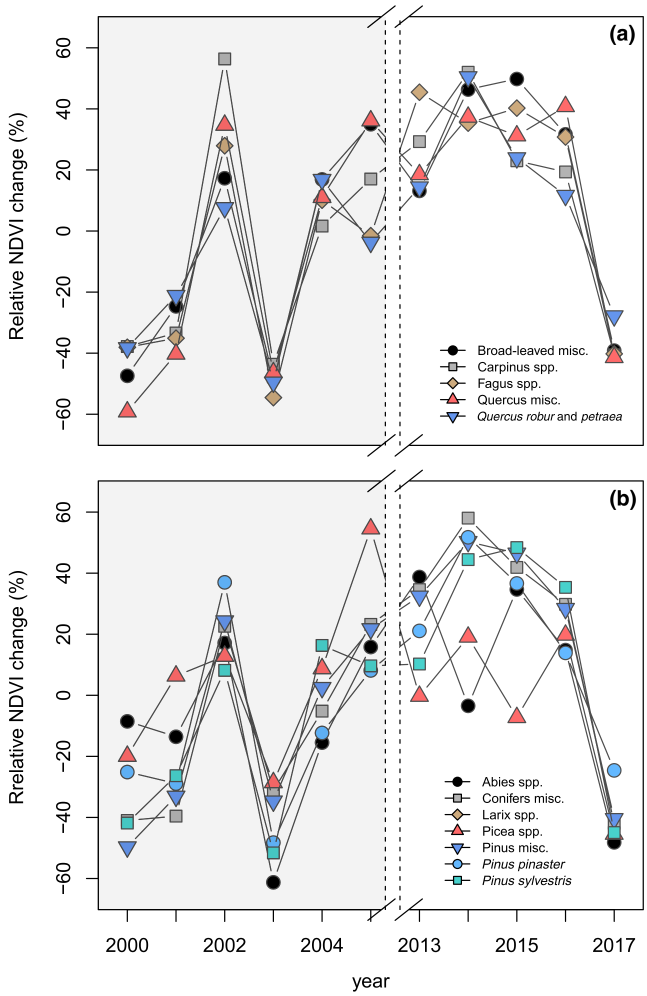

FIGURE 6 Temporal dynamics of the relative change in August normalized difference vegetation index (NDVI) values for angiosperm (a) and gymnosperm (b) tree species considering the sub-periods 2000–2005 and 2013–2017 [Colour figure can be viewed at wileyonlinelibrary.com]

Our results suggest that much of the Mediterranean forest vegetation experienced NDVI reductions, and some forests possibly presented canopy dieback in response to the 2017 drought (Figure 2). High temperature anomalies together with low SPEI values negatively affected the forest canopy, as highlighted by the $\mathrm{NDVI}_{\mathrm{diff}}$, because of the reduced amount of water available for plant development (Mueller & Seneviratne, 2012). This finding indicates that

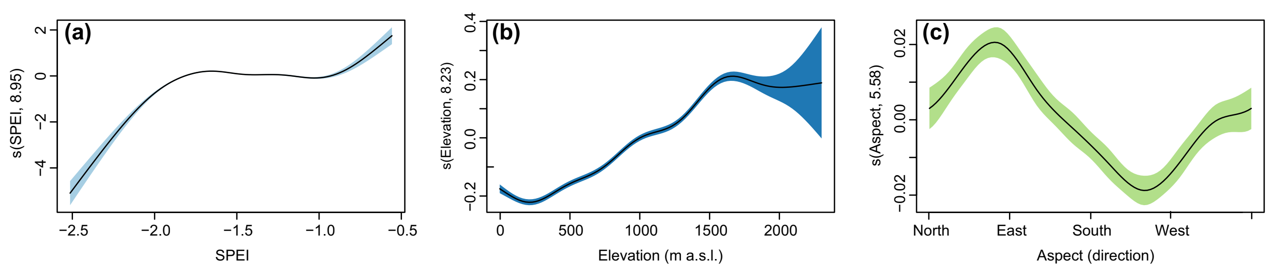

FIGURE 7 Predicted smoothing curve of $\mathrm{NDVI}_{\mathrm{diff}}$ as a function of the standardized precipitation evapotranspiration index (a), elevation (b) and aspect (c) assessed using a generalized additive model (GAM). The *y*-axis values indicate the *x*-axis covariate effect on the anatomical features deviation from the mean predicted by the model (continuous line). The shaded areas indicate the 95% confidence intervals. In these plots, a positive slope of the continuous line indicates a positive effect of the *x*-variable on the $\mathrm{NDVI}_{\mathrm{diff}}$, and a negative slope of the line indicates a negative effect. NDVI, normalized difference vegetation index [Colour figure can be viewed at wileyonlinelibrary.com]

changes in the vegetation response were partly driven by changes in climate anomalies, which is consistent with the high dependency of Mediterranean vegetation on water availability and climate conditions (Vicente-Serrano, 2007).

Clearly, visible symptoms were recorded after the drought event, ranging from leaf yellowing and senescence to leaf curling and shedding in the more drought-prone areas (Michel, Seidling, & Prescher, 2018; see also Figure S4), which contributed to declines in the NDVI and thus the canopy leaf area. Although these symptoms might not be equivalent to tree decay or mortality, they are nevertheless a useful estimator of the drought-induced stress experienced by trees and can be considered early-warning signals of impending die-off (Bréda et al., 2006; Munné-Bosch & Alegre, 2004; Munné-Bosch & Peñuelas, 2004). The observed NDVI decline due to prolonged drought stress may reflect negative responses in terms of photosynthesis, carbon uptake and productivity, as largely reviewed by Chaves et al. (2002) and Teskey et al. (2015). Additionally, drought and extremely warm temperatures are often interconnected and may lead to the lagged dysfunction of whole-tree hydraulic transport (Zweifel, Zimmermann, Zeugin, & Newbery, 2006). As highlighted by Bréda et al. (2006), temperate European forests that were affected by the 2003 extreme drought reduced their overall tree transpiration through a reduction in total leaf area. Then, the insufficient amount of carbohydrate reserves limited the leaf area production and radial growth of temperate oak species the following year (Bréda et al., 2006; Gazol, Camarero, Vicente-Serrano, et al., 2018). Other mechanisms associated with lagged, direct and indirect, impacts of 2003 climate extreme span from changes in carbon allocation patterns (e.g. Granier et al., 2007) to changes in plant species composition (e.g. Kreyling et al., 2011) and tree resistance to pest attacks (e.g. Rouault et al., 2006), which compromised the ability of trees to recover growth and contributed to increase mortality during the following years (He et al., 2018).

As suggested by the common pattern in NDVI relative changes, the 2017 extreme event might be compared in terms of productivity decline to the 2003 heat wave that affected central Europe, although the disturbance spatial pattern differed, as well as the timing of the extreme event within the growing season. Ciais et al. (2005) have estimated a 30% reduction in gross primary productivity over Europe (accompanied by a decrease in both autotrophic and heterotrophic respiration), which resulted in a strong anomalous net source of carbon dioxide (0.5 Pg C/year) to the atmosphere and reversed the effect of roughly 4 years of net ecosystem carbon sequestration (see also Peters et al., 2010; Reichstein et al., 2007; Vetter et al., 2008 for other simulations based on different models and/or reference period). However, the reduction in forest productivity during the European summer 2017 remains to be ascertained through further investigations at more local scales (e.g. retrospectively assessing CO_2 flux measurements and/or tree-ring data).

One of the main findings of this study is that spatial variability or land cover and topography are critical elements in SPEI–$NDVI_{diff}$ relationships. The area of the most severe drought intensity (Figure 3) extended over a large region of the Mediterranean Basin, and several of the very affected areas (Italian peninsula, Balkans, southern France) were highlighted. This distribution over a large fraction of countries agrees with previous studies that confirm largely adverse effects on vegetation throughout Europe, with regionally higher intensities along the Mediterranean coast (Ciais et al., 2005; Fischer & Schär, 2010). Conversely, the areas exhibiting no NDVI reductions were either regions where the climate anomaly was minor (e.g. most of the Iberian Peninsula, Greece) or was favourable for the local forest types (e.g. warm temperatures at high elevations across an alpine range; cf. Jolly et al., 2005). This phenomenon occurred because temperate forests are located in cool-wet sites in central and northern Europe with a positive water balance; in these areas, temperature is the major constraint on plant development, and the control of vegetation activity by drought is low (Vicente-Serrano et al., 2013), as indicated by high–high spatial correlation with the SPEI (Figure 3). However, an exception to this general pattern was observed in semi-arid south-eastern Spain, where a strong local positive effect of the SPEI on the $NDVI_{diff}$ occurred, and in the Atlantic forests of north-western France, where negative responses were detected. In dry south-eastern Spain, this response might be interpreted as an unexpected increase in precipitation (the European Drought Observatory reported extremely wet conditions for this area; Masante et al., 2017) that contributed to alleviating the drought in this area and then affected the positive response of the vegetation NDVI. However, in north-western France, vegetation anomalies might be related to local effects on vegetation cover related to increased crown transparency, as indicated by records from European networks on forest health (Michel et al., 2018). Such enhanced leaf shedding could also be driven by increases in temperature (Sánchez-Salguero, Camarero, Grau, et al., 2017), although a consistent link to date has not been established.

The strongest reduction in NDVI values occurred in Mediterranean biomes, followed by temperate biomes (Figure 4) and the remaining biogeographic regions, which was in accordance with other independent reports (Michel et al., 2018). Several studies found different drought legacy effects on vegetation growth between forest biomes or across gradients of water availability, particularly for temperate and Mediterranean forests across the Northern Hemisphere (Abrams, Ruffner, & Morgan, 1998; Gazol, Camarero, Vicente-Serrano, et al., 2018; Vicente-Serrano et al., 2013; Wu et al., 2018, among others). The high dependence of Mediterranean forests on water availability (Liu, Liu, & Yin, 2013; Vicente-Serrano et al., 2013) suggests that the vegetation in these regions (especially temperate broad-leaved forests) is highly prone to damage due to extreme climate events such as heat waves and dry spells. Indeed, although the vegetation types in these regions are adapted to tolerate summer droughts, they might still display a high sensitivity to the increasing frequency of severe water deficits, as forecasted by future climate scenarios (IPCC, 2014). For instance, as a result of the high frequency of severe droughts affecting Spain (i.e. 1994–1995, 2005 and 2012), there was extensive damage to Mediterranean tree and shrub species, and the damage and recovery responses of different woody taxa varied (Camarero, Gazol, Sangüesa-Barreda, et al., 2015; Camarero, Gazol, Tardif, et al., 2015; Gazol, Camarero, Vicente-Serrano, et al., 2018; Gazol, Sangüesa-Barreda, Granda, & Camarero, 2017; Peñuelas et al., 2001).

The decoupling or uncoupling between (dry–warm) climate conditions and NDVI reductions in several Mediterranean areas or even among tree genera (Figure 4) was likely attributable not only to differences in drought severity but also to species-specific physiological and morphological responses to drought (McDowell et al., 2008), biotic interactions between tree species (Galiano, Martínez-Vilalta, & Lloret, 2010) and heterogeneity in topographic conditions (Vicente-Serrano, Zouber, Lasanta, & Pueyo, 2012), which raises interesting questions regarding the underlying mechanisms providing resilience to trees (Serra-Maluquer, Mencuccini, & Martínez-Vilalta, 2018). For instance, very negative NDVI anomaly values were found in southern Italy and north-eastern Spain, but climate anomalies (dry–warm conditions) were not as extreme in those areas as they were elsewhere (e.g. southern and central Spain). The climate is more continental and drier over most of the Iberian peninsula than over the Italian peninsula, and the proportion of drought-tolerant species within the community, such as conifers (pines, junipers), is more abundant in Iberian forests than in the more humid Italian forests, where mesophilic angiosperms (mainly oak and beech species) are more important. Thus, it is reasonable to assume that differences between functional groups in the ability to face and tolerate drought may drive community responses to dry spells. These differences may depend on different rooting systems or hydraulic responses to drought (e.g. differences in stomatal responses to high water deficits; Forner, Aranda, Granier, & Valladares, 2014; Sanginés de Cárcer et al., 2018).

Not all tree species experienced the same climatic conditions in the summer of 2017; in fact, the ranges in temperature and precipitation anomalies that caused the decrease in NDVI values were very broad (Figure 5). An example is *P. pinaster*, which experienced fewer temperature and precipitation anomalies compared to other species and did not show an NDVI decrease that was as high as those seen in the other tree species (Figure 6; Figure S6). This result may appear quite surprising considering that *P. pinaster* at low elevations is very sensitive to spring–summer drought and experiences diebacks if water shortages are severe (Camarero, Gazol, Sangüesa-Barreda, et al., 2015). However, this phenomenon can be explained both by geographical and topographical factors because this species mainly grows in sites located at low altitudes and therefore experiences, on average, high temperature and low rainfall conditions (Figure S8). In addition, *P. pinaster* has a high phenotypic plasticity to drought tolerance, although the variation across the species distribution range depends on the provenance, which allows some forests to recover after severe droughts (Sánchez-Salguero et al., 2018). Examples of uncoupled responses to climate have also been reported in studies on the Iberian Peninsula, where tree populations in xeric sites exposed to drought experienced significant reductions in growth and productivity compared to populations in mesic sites (Camarero, Manzanedo, Sanchez-Salguero, & Navarro-Cerrillo, 2013; Pasho, Camarero, Luis, & Vicente-Serrano, 2011). In this regard, a clear relationship arises between extreme drought effects and local topography, as was observed with increasing $NDVI_{diff}$ values that were strongly linked to elevation. In particular, those sites were less water-limited and experienced more moderate temperatures during the extreme summer of 2017 than low-elevation sites. Similar observations were made by Lobo and Maisongrande (2006) and Lloret et al. (2007). In some cases, a positive effect of extreme temperature on tree growth has been recorded for high-elevation forests associated with a longer growing season and enhanced photosynthetic activity (Jolly et al., 2005). In addition, the effect of the exposure may be due to the heat wave propagation across the Mediterranean area, from west-southwest to east-north-east. Finally, the temporal concordance of the NDVI variability among different Mediterranean functional tree species confirms that in drought-prone forest ecosystems, NDVI fluctuations are both temporally and spatially coherent (Vicente-Serrano, 2007).

5 | CONCLUSIONS

The present study provided a spatially resolved statistical assessment of the impacts of an extreme dry spell, characterized by high temperatures and low precipitation during the summer of 2017, on European forests. Satellite remote sensing data (i.e. MODIS-based NDVI records) allowed us to quantify the vulnerability of European forests to the 2017 dry spell. The severe drought in the summer of 2017 significantly reduced the NDVI in southern Europe, particularly on the Italian and Balkan Peninsulas. However, a high degree of spatial heterogeneity in the response of forest vegetation to drought, assessed by the SPEI drought index, was also observed. Different biogeographic regions responded differently to severe drought, where the Mediterranean region was the most affected area. A fair degree of variability in the response to drought was also observed among the dominant tree species, where 'miscellanea' broad-leaved and oak species from mesic sites presented the most pronounced drop in NDVI values. In the other extreme, *P. pinaster* was the least-affected tree species. Topographic conditions buffered the negative impacts of the 2017 drought, but other factors, such as interactions between tree species or local climate conditions, might also explain the observed patterns.

Therefore, based on our results, we highlight how a stronger integration of fine-scale spatial heterogeneity across a climate gradient could improve estimates of climate event-induced damage on forest productivity, and may provide insight into how site-specific conditions might mediate species responses to drought and climate change.

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SUPPORTING INFORMATION

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