Forest Systems
26 (3), e014, 13 pages (2017)
eISSN: 2171-9845
https://doi.org/10.5424/fs/2017263-11298
Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria O. A., M. P. (INIA)

RESEARCH ARTICLE

OPEN ACCESS

Site factors and stand conditions associated with Persian oak decline in Zagros mountain forests

Ahmad Hosseini[1], Seyed M. Hosseini[2] and Juan C. Linares[3]

[1]Ilam Agricultural and Natural Resources Research and Education Center, Dept. Natural Resources, 69317-73835, AREEO, Ilam, Iran. [2]Tarbiat Modares University, Faculty of Natural Resources & Marine Sciences, 46417-76489 Noor, Mazandaran, Iran. [3]University Pablo de Olavide, Department of Physical, Chemical and Natural Systems. Carretera de Utrera, Km 1. 41013 Seville. Spain.

Abstract

Aim of study: Drought and stand structure are major and interconnected drivers of forest dynamics. Water shortage and tree-to-tree competition may interact under the current climate change scenario, increasing tree mortality. In this study, we aimed to investigate climate trends, site and stand structure effects on tree mortality, with the main hypothesis that drought-induced mortality is higher as competition increases.

Area of study: Persian oak forests from Zagros Range, western Iran.

Material and methods: We split the study area into 20 topographical units (TUs), based on aspect, slope and elevation. In each TU, three 0.1 ha plots were established to quantify site and stand characteristics, namely the diameter of all trees and shrubs, stand density and basal area, canopy dieback and mortality. In addition, soil profiles were analyzed to obtain physical and chemical soil properties. Six transects 100 m length were established per TU to measure tree-to-tree competition for alive and dead trees.

Main results: The highest mortality rates and crown dieback were found at higher elevations and southern and western aspects. Our findings confirm increasing rates of tree mortality in stands with higher tree density and shallow soils. As regard links between climate change and forest decline, our results suggest that changing forest structure may have a significant impact on dust emission.

Research highlights: Despite severe dry years occurred recently the study area, they are not significantly different than those recorded in the past. Stand structure appears as a modulating factor of climate change effects, linked to competition-related tree vulnerability to drought.

Additional keywords: competition index; coppice; climate change; dieback; drought; oak decline; *Quercus*; tree mortality.

Abbreviations used: CI (competition intensity); DBH (diameter at 1.3 m from the ground); PDSI (Palmer drought severity index); TU (topographical unit).

Authors´ contributions: Conceived and designed the study, analyzed the data and wrote the paper: AH, SMH and JCL. Performed the field sampling: AH.

Citation: Hosseini, A.; Hosseini, S. M.; Linares, J. C. (2017). Site factors and stand conditions associated with Persian oak decline in Zagros mountain forests. Forest Systems, Volume 26, Issue 3, e014. https://doi.org/10.5424/fs/2017263-11298

Supplementary material (Tables S1 to S6; Figs. S1 and S2) accompanies the paper on FS's website.

Received: 24 Feb 2017. **Accepted:** 10 Nov 2017.

Funding: Ministerio de Economía y Competitividad, Spain (CGL2013-48843-C2-2-R); European Union FEDER 0087 (TRANSHABITAT); Tarbiat Modares University (Doctorate support to AH).

Competing interests: The authors have declared that no competing interests exist.

Correspondence should be addressed to Ahmad Hosseini: Ahmad.phd@gmail.com

Introduction

Episodes of drought-induced tree mortality have been recently observed worldwide (Allen *et al.*, 2010). Under a climate change scenario, those effects may boost potential vegetation changes over large geographical areas, with major impacts on forests diversity and ecosystem function (Carnicer *et al.*, 2011). Declination has also been reported in oak forests (Haavik *et al.*, 2015), including the Persian oak forests (*Quercus brantii* Lindl. var. *persica* (Jaub & Spach) Zohary) in Zagros Mountains (Fatahi, 1995). Persian oak covers more than half of the Zagros forest area (west Iran), representing the most important tree species of this region (Bordbar *et al.*, 2010; Hassanzad-Navroodi *et al.*, 2015). These forests support valuable ecological and economic resources, as for instance the use of seeds in traditional medicine, fuel wood, charcoal, and timber hardwood (Fatahi, 1995). As a consequence, conservation of Persian oak forests is an impending management concern, currently challenged by drought-induced tree mortality and insect outbreaks.

Oak decline is a disease complex that involves the interaction of several biotic and abiotic factors (see

Manion, 1991). The effects of decline on oak forests represent one of the most serious forest disease issues, with impacts that range from partial crown dieback to tree death (Starkey & Oak, 1989; Brasier, 1996; Rizzo & Garbelotto, 2003; Lloret *et al.*, 2004; Heitzman *et al.*, 2007; Fan *et al.*, 2008). Due to the increasing risks (beetles attacks, root fungi, drought events, etc.,), forest owners and stakeholders require new adaptation guidelines to increase the resilience of those oak forests subjected to potential decline (Cescatti & Piutti, 1998; McEwan *et al.*, 2011; Haavik *et al.*, 2015).

Tree mortality drives the functional and structural dynamics of forest ecosystems, both as a sink/source of carbon and nutrients, and as a mechanism of forest structure and diversity change (Franklin *et al.*, 1987; Allen & Breshears, 1998). Understanding tree mortality patterns is crucial to understand current forest community composition and to predict changes in stand structure and species composition (Chapman *et al.*, 2006; Heitzman *et al.*, 2007; Galiano *et al.*, 2010; Carnicer *et al.*, 2011; Lechuga *et al.*, 2017). At a regional scale, tree mortality may be mainly influenced by climate, for instance extreme events, such as drought and high temperatures (Anderegg *et al.*, 2012). Tree mortality can occur across a wide range of spatial and temporal scales, from the gradual death of individual trees (Ogaya & Peñuelas, 2007; Camarero *et al.*, 2016) to the abrupt mortality of thousands of trees over large areas due to severe disturbance events (Allen *et al.*, 2010).

As regards the need to improve our understanding of forest response to the current climate change, it might be of great importance to investigate site and stand structure effects, buffering or enhancing decline process of forests decline (Heitzman *et al.*, 2007; Camarero *et al.*, 2016; Colangelo *et al.*, 2017a). As regards the specific case of oak trees, water deficit is the most common stressing factor related to physiological weakness (Jenkins & Pallardy, 1995; Lloret *et al.*, 2004; Ogaya & Peñuelas, 2007; Fan *et al.*, 2008; Haavik *et al.*, 2015), triggering episodic tree declines and mortality (Fan *et al.*, 2012; Keyser & Brown, 2016; Sánchez-Salguero *et al.*, 2017). Furthermore, following drought, other events, such as beetle outbreaks, affect mortality of oak trees or increase its severity (Kabrick *et al.*, 2008; Fan *et al.*, 2008; Hosseini, 2012). As a result, mortality events are usually associated with complex interactions among endogenous factors, such as human use-related stand characteristics and genetics, and exogenous factors that include site conditions, insects and pathogens (Heitzman *et al.*, 2007; Urbieta *et al.*, 2008; McEwan *et al.*, 2011; Haavik *et al.*, 2015).

The effects of drought are more common visualized at the regional-scale (Keyser & Brown, 2016; Sánchez-Salguero *et al.*, 2017), but its influence on crown dieback and tree death will be modulated at the local-scale, where factors such as topography, soil and stand structure might be as important as regional climate to understand oak forests dynamics (Jenkins & Pallardy, 1995; Chapman *et al.*, 2006; Gea-Izquierdo *et al.*, 2009; Galiano *et al.*, 2010). Topographic characteristics such as slope and aspect also strongly influence soil moisture, and therefore drought-induced tree mortality may vary accordingly (Das *et al.*, 2008). Consequently, spatial and temporal variation in site moisture conditions may influence the spatial pattern and severity of drought-induced forest decline, while tree mortality patterns at local scale are very difficult to forecast (Das *et al.*, 2008; Anderegg *et al.*, 2012).

Tree decline has been related to stand structure, otherwise supporting that tree response to water stress also relies on tree-to-tree competition (Das *et al.*, 2011; Lechuga *et al.*, 2017). Episodic tree mortality is usually related to dry site conditions and high stand density (Chapman *et al.*, 2006; Gea-Izquierdo *et al.*, 2009). Specifically, trees subjected to higher competition show lower radial growth and they are more prone to die following extreme drought events (Das *et al.*, 2008; Galiano *et al.*, 2010; Linares *et al.*, 2010; Colangelo *et al.*, 2017b). As a result, contrasting stand structure may act modulating the individual tree responses to drought (Lechuga *et al.*, 2017). Persian oak forests display a wide range of stand structural heterogeneity (Erfanifard *et al.*, 2009), which might be, at least in part, due to contrasting land use practices (Fatahi, 1995; Urbieta *et al.*, 2008). Hence, understanding the effects of drought and tree mortality must take into account stand structure in a spatially explicit context (Das *et al.*, 2008).

Extensive oak mortality is a significant threat to Zagros forests health and economic value of their inhabitant. In this study, we attempt to investigate recent climate trends and the effect of topography, soil, stand structure and tree-to-tree competition on widespread tree mortality in Zagros forests in west of Iran. Specifically we aim to (1) quantify the extent to that recent drought events support a long-term increasing aridity at regional scale; (2) identify stands that are at high risk for oak decline, as regards site conditions (elevation, aspect, slope, soil); and (3) identify the mortality pattern for individual trees within declining stands, according to individual characteristics (size, coppice, standard, etc.) and tree-to-tree competition.

Material and methods

Study area

The study area is located in the Zagros Range, southwestern Iran; 36°.31´ N, 51°.45´ E (Fig. 1). The region is mainly affected by westerly disturbances and the Azores High during the cold (November–March) and warm (May–September) season, respectively, resulting in a clear distinction between a wet winter and a dry summer (Asakereh, 2007; Azizi *et al.*, 2013). Precipitation occurs during an eight month period from previous October to current May with a maximum during December to March. During June to September, almost no effective precipitation occurs. The mean annual temperature of the region is 16 °C, and the mean annual precipitation is 509 mm (Azizi *et al.*, 2013). Meteorological data for our study were available from the climate station of Ilam (33°38′N, 46°26′E; 1337 m a.s.l., about 10 km apart from the study area), covering the time span 1986–2010. Total annual precipitation and dust events (number of days with dust) were investigated. In addition of this local climate dataset, to obtain a long-term regional climate dataset, we analyzed mean annual temperature, total annual precipitation and Palmer Drought Severity Index (PDSI), obtained from the KNMI Climate Explorer web site for the period 1901-2015. We used CRU TS3.24 dataset (http://climexp.knmi.nl/select.cgi?id=someone@somewhere). Annual trends were statistically tested by regression analysis.

Field sampling methods

The study area is mainly comprised by forests dominated by *Quercus brantii* var. *persica* Lindl., *Pistacia atlantica* Desf., *Acer monspessulanum* subsp. *cinerascens* (Boiss.) Yalt., *Crataegus pontica* C. Koch, *Amygdalus orientalis* L., and *Cerasus microcarpa* C.A. Mey. Boiss. These mixed oak forests grow on contrasting aspects, slopes, and elevations, ranging from 1500 to 2000 m a.s.l. (Fatahi, 1995). The limits of the study area were determined on a topographic map with a scale 1:50000, to account for a wide range of environmental variables, and contrasting forest stand structures and mortality. Geographic information system analyses were performed by using ArcGIS 9 ArcMap version 9.2 (ESRI, 2006) to investigate digital layers of slope, aspect and elevation. Aspect data were grouped within four categorical factors: N, north; S, south; W, west; and E, east aspect, respectively. Slope data were

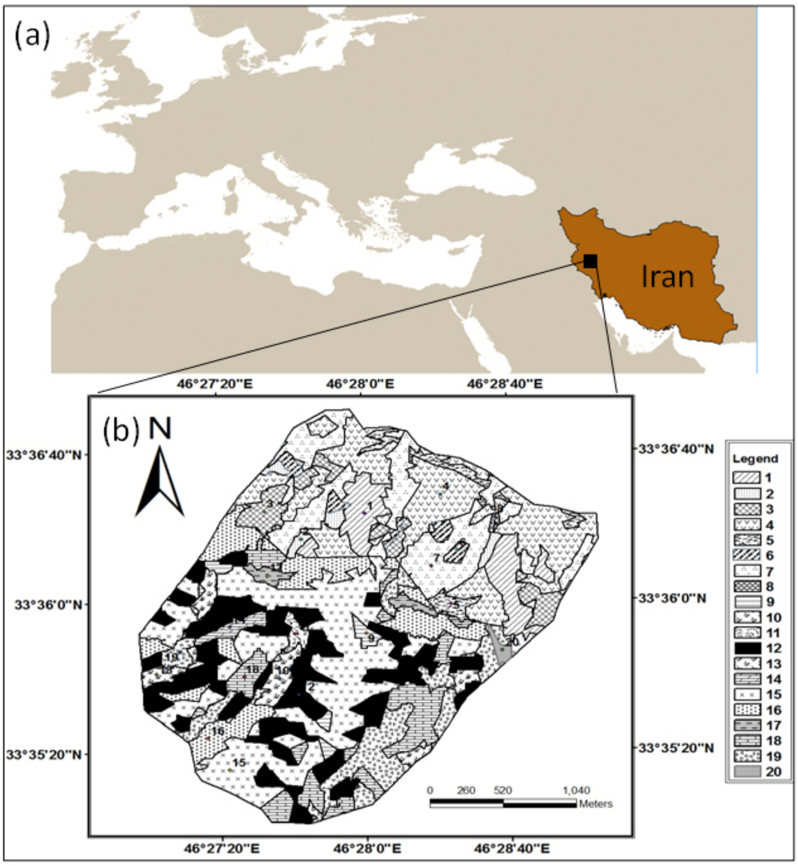

Figure 1. Location of the study area in the central Zagros range, SW Iran (a). Spatial distribution of the topographic units (b) obtained by overlapping digital layers of aspect, slope, and elevation (see also Table S1 [suppl.]).

grouped within three categorical factors: 0-30%, 30-60%, > 60%. Elevation data were grouped within two categorical factors: 1500-1700 and 1700-2000 m a.s.l. The obtained categorical factors were overlapped, accounting for 24 combinations of topographic units (TUs; 3 slopes × 4 aspects × 2 elevation categories, respectively), however only 20 combinations of TUs were suitable for further field sampling (Fig. 1; Table S1 [suppl.]).

Each TU was sampled in the field by mean of three circular plots, 1000 m^2 surface, randomly established (Fig. 2). Within each plot, site characteristics (slope, aspect, elevation) were measured. We performed a soil profile per TU to measure soil properties. Soil depth was measured in the field, while physical and chemical soil properties were measured in the laboratory using a soil sample per TU (Sparks *et al.*, 1996). We determined texture and soil moisture, total nitrogen percentage (N), organic carbon percentage (OC), organic matter percentage (OM), and total neutralizable material percentage (TNV, $CaCO_3$).

In each plot, we recorded all tree and shrub species and measured its diameter at 1.3 m from the ground (DBH) for all trees above 5 cm DBH, maximum and minimum crown diameter, crown dieback percentage, and mortality density. Tree habit (coppice or standard) was also noted (coppice trees are considered those originated by new growth from the stump or roots after cutting), using for coppices equivalent diameter estimation (Grier *et al.*, 1992):

$$\text{Equivalent diameter} = \sqrt{\sum_{i=1}^{n} RCD_i^2} \qquad [1]$$

where *RCDi* is the root collar diameter of each of the individual *i* stems.

Tree-to-tree competition and crown dieback were assessed in each TU by sampling six transects 100 m length (Fig. 2). We sampled five points at 25 m intervals on each transect. In each point, the closest live and dead trees (focal trees), as well as their neighborhoods trees, were characterized as indicated in Fig. 2. We estimated the tree-to-tree competition intensity (CI, Fig. 2) that each focal tree was subjected to by calculating a distance-dependent competition index, which takes into account the number, size and distance to the neighbouring competitors (Hegyi, 1974). The degree of competition experienced by the focal *i* tree was calculated as the sum of the quotients, for all *j* neighbouring trees surrounding it within a radius *R* of 8 m, between the ratio DBH*j*/DBH*i* and the distance between the *i* and the corresponding *j* trees (dist*ij*) (see also Fig. 2):

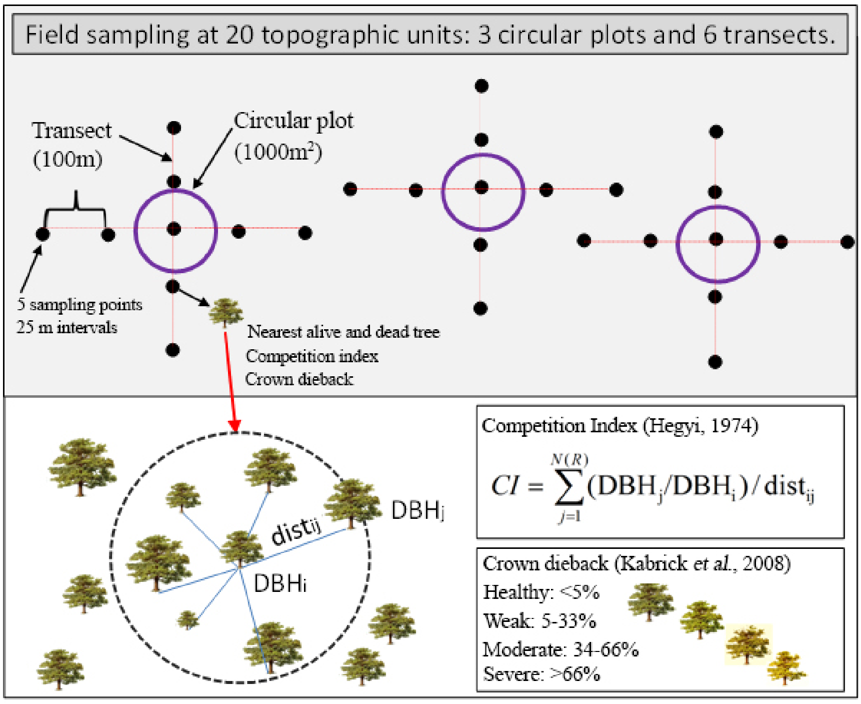

Figure 2. Field sampling design at each topographic unit. The competition intensity (CI) experienced by the focal *i* tree was calculated as the sum of the quotients between the ratio of the diameter at 1.3 m from the ground (DBH_j/DBH_i) for all *j* neighbouring trees surrounding the focal *i* tree, and the distance between the *i* and the corresponding *j* trees ($dist_{ij}$).

$$CI = \sum_{j=1}^{N(R)} (\mathrm{DBH}_j/\mathrm{DBH}_i)/\mathrm{dist}_{ij} \qquad [2]$$

The condition of tree crowns is also an important indicator of tree and forest health (Kabrick *et al.*, 2008). Thus, crown conditions were evaluated using a crown dieback classification for each tree, conducted as follows (Fig. 2): (i) healthy, if the canopy defoliation and browning were less than 5% of the crown length; (ii) weak, if the canopy damage were between 5 to 33% of the crown length; (iii) moderate, if canopy damage symptoms were between 34-66% crown length; and (iv) severe, if canopy damage symptoms were more than 66% crown length (Kabrick *et al.*, 2008; see also Fig. 2).

Data analysis

The Kolmogorov-Smirnov and Levene tests were used to assess normality and homoscedasticity, respectively. Univariate relationships were modelled by linear, polynomial and exponential regressions. We used one-way ANOVA, Duncan and paired t-tests to perform multiple and paired means comparisons. Finally, a backward multiple regression models were performed to investigate the relationships between mortality and site (topography and soil variables) and stands structure characteristics. Total variance explained (R^2 adjusted) and coefficients were computed separately for topographical, soil-related, and stand structure variables. Statistical analyses were carried out with the package Minitab Stat. Softw. v. 15 (Minitab, PA, USA).

Results

Climate trends

Long-term regional climate dataset showed a significant rise trend in mean annual temperature (R^2 = 0.49, p<0.0001; Fig. 3a), while total annual precipitation (Fig. 3a), and PDSI (Fig. 3b) showed no significant trends for the period 1901-2015. Meteorological data obtained from the climate station of Ilam (about 10 km apart from the study area; time span 1986–2010) showed a significant decline in total annual precipitation (R^2 = 0.30, p<0.01; Fig. 3c), with extreme drought events in 1999, 2007 and 2008. Moreover, dust events showed a significant exponential trends (R^2 = 0.62, p<0.0001; Fig. 3c), with increasing number of days with dust mainly from the year 2000 onward.

Forest structure and decline patterns

The study area ranges from 1510 to 1880 m elevation. Soil samples texture was mainly clay (Fig. S1 [suppl.]), with mean values of total organic carbon and nitrogen percentages of 1.66% and 0.17%, respectively, while neutralizable material percentage was on average 43.6%. Persian oak is the dominant species within the study area, accounting for 95.3% of the total tree density and 93.6% of the total basal area (Table S2 [suppl.]). *Crataegus pontica* and *Pistacia atlantica* were the second and third most abundant tree species; the relative contribution of *P. atlantica* to stand basal area was higher, than that of *C. pontica*. *Acer cinerascens* showed the lowest stand density and basal area among trees as well as the highest mortality rate (48%), while *Amygdalus orientalis* and *Cerasus microcarpa* were minor components among the shrub strata (Table S3 [suppl.]). The average stand canopy cover was 32.5%, the majority of which belongs to *Q. persica* (31.5%). Many trees in the study area (especially *Q. persica*) are

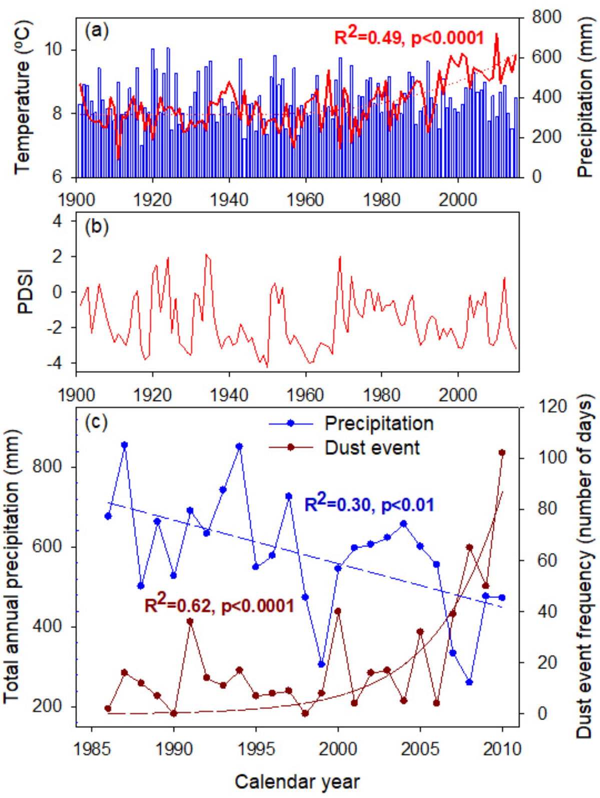

Figure 3. Long-term regional mean annual temperature (a, line), total annual precipitation (a, vertical bars), and Palmer Drought Severity Index (b, PDSI), obtained from CRU TS3.24. Mean annual temperature rises significantly during the time span investigated (1901-2015). The dotted line and the inset in (a) show the results of a cubic polynomial regression. Local data obtained from the Ilam city meteorological station (c). Total annual precipitation (linear regression, upper inset) and dust events (exponential regression, bottom inset) of the local dataset showed significant trends during the time span investigated (1986-2010).

Table 1. Stand density, basal area and canopy cover of coppices and standard grow forms.

Variable		Standard			Coppice		
		Total	Dead	Mortality (%)	Total	Dead	Mortality (%)
Density (trees/ha)	Stand	60.0	11.5	19.2	165.0	23.8	14.4
	Oak	51.7	10.8	21.0	162.7	23.7	14.6
Basal area (m^2/ha)	Stand	4.2	0.8	19.0	9.3	1.1	12.1
	Oak	3.4	0.7	21.0	9.2	1.1	12.1
Canopy cover (%)	Stand	8.0	1.5	18.8	24.5	2.7	11.0
	Oak	7.1	1.4	19.6	24.4	2.7	11.0

sprouts of coppices. Mortality was significantly higher for coppices, expressed as tree density: 23.83 trees/ha *vs*. 11.5 trees/ha, for coppices and standard respectively (t-test, p=0.002; Table 1). Nonetheless, given that total density of coppices was also higher, expressed as percentage, mortality rate was higher among the standard growth form (Table 1), however, this difference on mortality percentage was not significant (t-test, p=0.106).

The most frequent tree diameters were those among 15-25 cm DBH classes (Fig. 4a), as well as the most frequents tree sizes of dead trees (Fig. 4b), nonetheless, basal area percentage of dead trees was higher among tree diameters belonging to 25 and 30 cm DBH classes (Fig. 4c). The mean DBH decreased, while stand mortality increased, as stand density becomes higher (Fig. 5a; Table S4 [suppl.]). The competition index (CI) of alive trees increased significantly according to stand density (Fig. 5b; p<0.02), while the CI of the dead trees was significantly higher than that of the alive trees (within plots) but was not related to stand density (among plots; Fig. 5b, see also Tables S5 and S6 [suppl.]).

Crown dieback was also significantly related to stand density, similar to mortality did; thus, moderate and severely defoliated trees increasing as stand density was higher. As regard environmental variables, total stand density was positively correlated to elevation (Fig. S2 [suppl.]). Nonetheless, expressed as percentage, higher elevation stands showed the lower fraction of healthy trees, as well as the higher fraction of trees with crown damages (Fig. 6). However, mortality rate (*i.e.*, expressed as percentage) was only marginally significant regarding elevation, supporting that the main effect relies on stand density (Fig. 6; Fig. S2 [suppl.]). This result was also supported by multiple regression analyses (Table 2), where mortality percentage was significantly related to aspect (higher mortality percentage at southern and western aspects), but did not showed significant relationship with elevation or slope. According to soil variables, mortality percentage

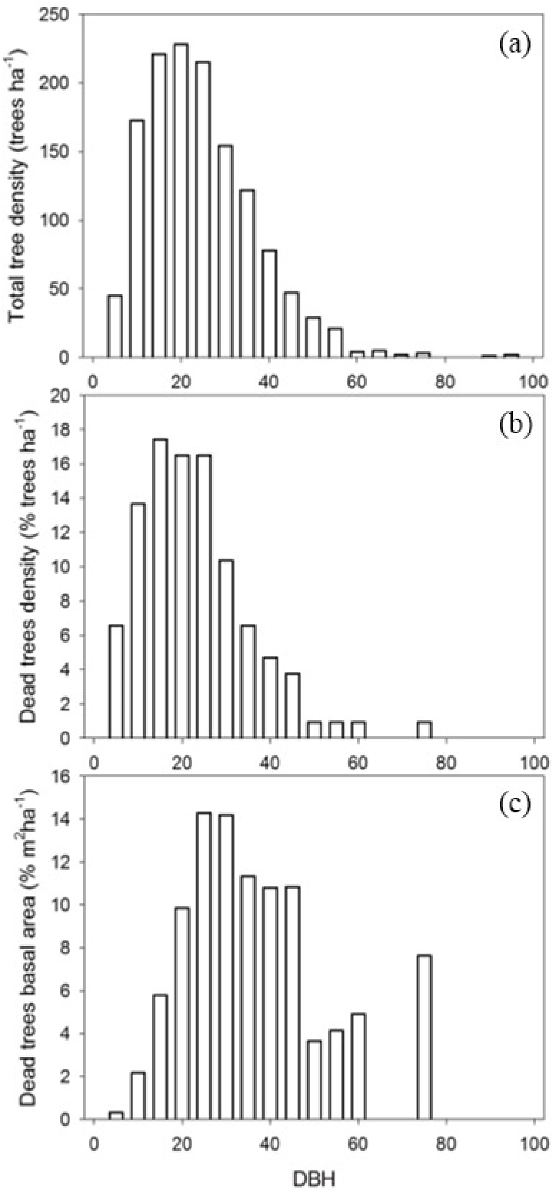

Figure 4. Summary of total and dead trees distribution sizes (DBH): Total density of trees per hectare (a). Density percentage per hectare of dead trees by diameter classes (b). Basal area percentage per hectare of dead trees by diameter classes (c).

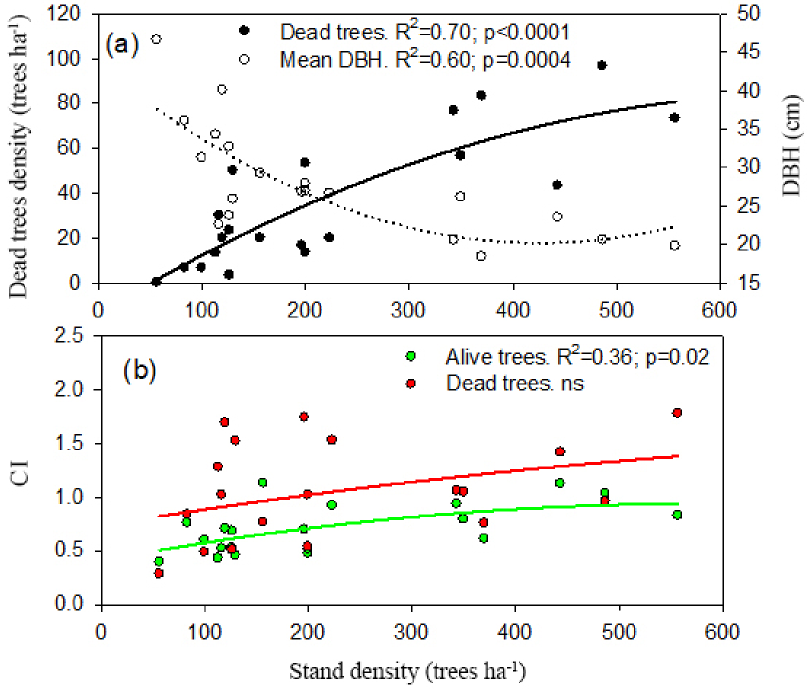

Figure 5. Relationships obtained among total stand density, dead tree density and mean stand DBH (a). Distance-dependent competition index (CI) is also related to total stand density, showing separately the mean values of alive and dead trees (b). The lines and the insets show the results of polynomial regressions; n=20 topographic units.

was higher on shallower soils, while regarding stand structural variables, total basal area showed a positive relationship (and negative for mean DBH), indicating that mature stands, with higher mean DBH and lower basal area, show lower mortality rates. On the other hand, canopy cover showed a negative relationships, *i.e.* higher canopy cover is related to lower mortality percentage, likely reflecting the covariance of defoliation and mortality (Table 2).

Discussion

Climate trends and likely influence on Persian oak decline and mortality

Rising temperatures are amplifying drought-induced stress and mortality in forests globally (Allen *et al.*, 2010). For the Zagros range, precipitation indices have fewer significant trends in the decrease of amount, frequency, and intensity of precipitation when compared with temperature (Fig. 3). Based on tree-rings width linear regression model, October–May precipitation has been reconstructed for the central Zagros region over the last 170 (1840–2010) years (Rahimzadeh *et al.*, 2009). This study revealed that severe dry years occurred in 1847, 1853–55, 1870–71, 1904, 1910, 1918, 1929, 1932, 1944, 1948, 1951, 1960, 1964–65, 1984, 1999 and 2008–2009. Anyway, the number and the intensity of dry periods seem to have increased during the last 170 years (Azizi *et al.*, 2013). Despite the limitation of instrumental records and the low number of meteorological stations in our study area, available information supports that precipitation has reduced significantly at regional scale during recent decades (Asakereh, 2007; Rahimzadeh *et al.*, 2009).

At regional scale, the spatial and temporal patterns of climate extreme indices in the Zagros range support a warming trend over the period 1975–2010 (Soltani *et al.*, 2015). Over the last 15 years (1995–2010), the annual frequency of warm days and nights has increased by 12 and 14 days/decade, respectively. The number of cold days and nights has decreased by 4 and 3 days/decade, respectively. The annual mean maximum and minimum temperatures averaged across Iran both increased by 0.031 and 0.059 °C/decade. The probability of cold nights has decreased from more than 20% in 1975–1986 to less than 15% in 1999–2010, whereas the mean frequency of warm days has increased between the first 12-year period (1975–1986)

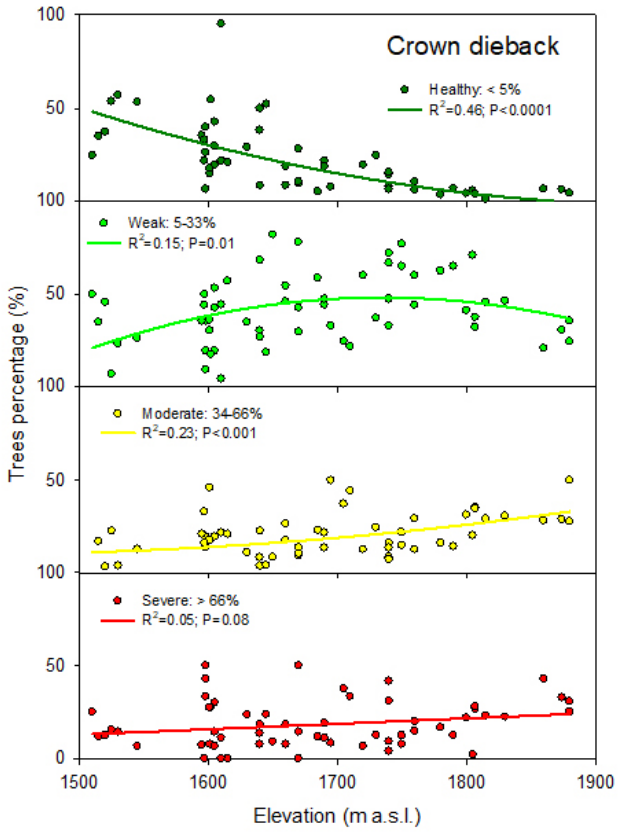

Figure 6. Relationships obtained among different classes of crown dieback and elevation. Data are expressed as the number of tree, within a given crown dieback class, divided by the total number of trees (*i.e.*, percentage). The lines and the insets show the results of polynomial regressions; n=60 plots (see also Fig. S2 [suppl.]).

and the recent 12-year period (1999–2010) from 18 to 40%, respectively (Soltani *et al.*, 2015).

Nonetheless, the same spatio-temporal study revealed that there are no systematic regional trends in total precipitation, nor in the frequency and duration of extreme precipitation events (Soltani *et al.*, 2015, and references therein). Indeed, statistically significant trends in extreme precipitation events have been observed at less than 15% of the investigated weather stations, with no spatially coherent pattern of change, whereas statistically significant changes in extreme temperature events have occurred at more than 85% of the investigated weather stations. Notwithstanding, it has been noted an increasing trend of warm extremes with elevation, suggesting a higher impact of the warming trend in the mountains. Specifically, the trend in maximum temperature (see details in Soltani *et al.*, 2015) shows positive correlation with elevation in the Zagros mountain range. This observation may be related to the increasing trend of crown dieback (Fig. 6) and mortality at higher elevation found in our study, although, the relationships between climate extremes and elevation are not quite clear. Furthermore, our understanding of the influence of drought on mortality remains limited as they are the result of multiple years of prolonged drought.

Long-term climate forecasts for the Zagros range indicate warming temperatures (Christensen *et al.*, 2007). Coupled with this, the severe drought years recently occurred and their incidence on tree mortality

Table 2. Results of multiple regression analysis using the percentage of dead trees as response variable. Total variance explained (R^2) and coefficients were computed separately for topographical, soil-related, and stand structure variables. SD indicates the standard deviation. The multiple regression *T* statistic and *p* values are also showed.

	Variable	**Coefficient**	**SD**	***T***	***p***
Topographic variables	Intercept	23.933	2.721	8.795	0.000
R^2(adj)=19.3%; p<0.001	Aspect	-0.455	2.098	-3.888	0.000
Soil variables	Intercept	23.455	4.068	5.766	0.000
R^2(adj)=20.8%; p=0.03	Soil depth	-8.287	3.461	-2.394	0.028
Stand structural variables	Intercept	49.019	8.045	6.093	0.000
R^2(adj)=23.1%; p<0.001	Basal area	0.587	0.448	2.561	0.013
	DBH	-0.759	0.241	-4.533	0.000
	Canopy cover	-0.834	0.183	-3.189	0.002

may have profound implications for carbon storage and ecosystem services (Carnicer *et al.*, 2011). Our results suggest that Persian oak is sensitive in terms of crown defoliation to warm and dry conditions, as well as they have been found for other mediterranean oaks, like *Q. faginea, Q. Ilex* and *Q. suber* (Sánchez-Salguero *et al.*, 2017). Warm spring conditions and severe summer drought have been already recognised as triggers of crown defoliation, whereas growth of oaks in Mediterranean environments is linked to late spring-early summer water availability, at both annual and decadal timescales, suggesting oak growth decline was associated with a delayed response to climate (Di Filippo *et al.*, 2010; Natalini *et al.*, 2016).

The significant trend observed in dust events also suggests a regional forest decline, despite the limited time span of the available dataset (Fig. 3c). Rising levels of dust deflation may be related to tree mortality and subsequent reductions in vegetation density (Engelstaedter *et al.*, 2003). Regional studies support that forest cover and soil moisture are important controls on dust emission, as atmospheric dust frequency is inversely correlated with leaf area index (*i.e.*, vegetation density) and net primary productivity (Tegen *et al.*, 2002). Forest stands supporting relatively high biomass and vegetation cover protect the surface from deflation, while the presence of healthy trees results in a high surface roughness that reduces surface wind energy and therefore also dust emissions. In contrast, extensive tree decline and mortality led to sparser vegetation and more bare soil (Allen & Breshears, 1998; Engelstaedter *et al.*, 2003).

Site factors modulating Persian oak decline and mortality

The extent to which site factors such as topography and aspect influence the severity Persian oak decline is poorly understood. Several researches performed on different oak forests have reported that shallow soils and/or dry aspects account for the greatest amount of oak decline (Starkey & Oak, 1989; Rizzo & Garbelotto, 2003; Heitzman *et al.*, 2007; Fan *et al.*, 2008; Colangelo *et al.*, 2017a). Trees growing in shallower and poorer soils appear to persist close to their limits of climatic tolerance, while populations in wetter and fertile soils sites may have larger physiological buffers (Johnson *et al.*, 2016). Shallow soils are frequent at higher elevations, likely affecting the obtained spatial patterns of tree mortality. Drought effect is enhanced by lower water availability and limited rooting depth, as may occur in clay soils (Fig. S1 [suppl.]), enhancing drought sensitivity of trees (Johnson *et al.*, 2016). Despite in our study area mortality was inversely related to soil deep (Table 2), there were not consistent patterns regarding soil texture or the amount of organic material and nitrogen. These results suggest that factors other than (or perhaps in addition to) soil properties, topography and aspect, such as species composition, tree age and size structure, and competition, are important determinants of oak decline, likely confounding climate- and site-related influences (Ogaya & Peñuelas, 2007; Bordbar *et al.*, 2010; Lechuga *et al.*, 2017).

Persian oak decline likely involves the interaction of multiple biotic and abiotic factors, with impacts that range from partial crown dieback to tree death. Such decline complex may be framed in terms of predisposing factors, inciting factors, and contributing factors (*sensu* Manion, 1991). Some suggested predisposing factors include high density of lower-size DBH classes, shallow and rocky soils (Table 2). As regards the inciting factors, it is likely that regional drought spells are related to oak decline (Jenkins & Pallardy, 1995; Fan *et al.*, 2012; Keyser & Brown, 2016), while contributing factors may include different oak borers and diseases (Haavik *et al.*, 2015).

An important indicator of the health of a tree is the condition of its crown (Rizzo & Garbelotto, 2003; Lloret *et al.*, 2004; Ogaya & Peñuelas, 2007). Declining trees are initially point out by foliage wilt and browning followed by progressive branch dieback (Starkey & Oak, 1989). Trees with vigorous, healthy crowns tend to have higher growthrates. By contrast, trees with damaged crowns have a reduced capacity for photosynthesis (Brasier, 1996). Many stressors have been related with crown dieback including site factors and tree-to-tree competition (Heitzman *et al.*, 2007; Camarero *et al.*, 2016; Colangelo *et al.*, 2017a). In our study, elevation showed a significant relationship with crown dieback (Fig. 6), nonetheless, expressed as percentage, mortality rate was not related to elevation, supporting that the main effect relies on stand density.

Competition increases Persian oak decline and mortality

Forest dynamics encompass changes in stand structure, species composition, and species interactions with disturbance and environment over a range of spatial and temporal scales (Kabrick *et al.*, 2008; McEwan *et al.*, 2011). Forest structure modifies the effect of regional climate on drought-induced forest mortality, as individual trees respond to climate and resource limitation differently depending on their competitive environment (Heitzman *et al.*, 2007; Clark *et al.*, 2016; Lechuga *et al.*, 2017). Higher levels of competition within a forest stand can increase mortality probability, interacting with the effects of drought on mortality, particularly where water is a limiting resource (Voelker *et al.*, 2008; Ruiz-Benito *et al.*, 2013).

Forest structure mediates the effect of drought on oak forest dynamics at several scales (Clark *et al.*, 2016; Colangelo *et al.*, 2017b). Indeed, recruitment patterns and mortality in several oak species seem to be related to canopy closure (Gómez-Aparicio *et al.*, 2008). Oak seedling survival and growth in Mediterranean forests rely significantly on stand structure, providing crucial implications for regeneration in current and future environmental scenarios (Espelta *et al.*, 1995; Pausas *et al.*, 2009; Sheffer *et al.*, 2013; Pérez-Ramos *et al.*, 2013). Furthermore, as regards the effects of pathogens, infestation may be related to structural variables (Sangüesa-Barreda *et al.*, 2015), usually providing support to the hypothesis of increasing mortality in denser stands. Trees subjected to high competition, usually within high density stands, respond to similar climatic factors than those subjected to low competition, but their response is generally weaker (Gea-Izquierdo *et al.*, 2009). Some oak species have shown an increasing sensitivity to climate in recent decades, which might be related to temperature rise (Di Filippo *et al.*, 2010; Carnicer *et al.*, 2011; Natalini *et al.*, 2016). At this regional scale, the influence of average climate, competition, and their interaction on tree mortality during drought was supported by our study, where tree mortality occurred mainly in denser stand and affected significantly to those trees subjected to higher competition (Fig. 5).

Drought events often impact forests across large geographic areas that have substantial spatial variation in average climate and competitive environments (Jenkins & Pallardy, 1995; Chapman *et al.*, 2006; Lechuga *et al.*, 2017). Persian oak forests display a wide range of stand structural heterogeneity (Erfanifard *et al.*, 2009), likely reflecting contrasting land use practices (Urbieta *et al.*, 2008). Dead Persian oak trees occurred over a wide range of tree DBH (Fig. 4b), but they was most conspicuous among trees 15–25 cm. A similar pattern in oak forest decline was observed in North America (Kabrick *et al.*, 2008; Heitzman *et al.*, 2007; Haavik *et al.*, 2015). Although no age data were collected in our study, it is likely that many small Persian oak trees located at higher elevations were about the same age. These high-elevation stands show the higher density, supporting the hypothesis that episodic tree mortality is related to dry site conditions, here likely relate to warming and drought events (Ogaya & Peñuelas, 2007; Soltani *et al.*, 2015), and high stand density (Chapman *et al.*, 2006; Gea-Izquierdo *et al.*, 2009; Linares *et al.*, 2010; Lechuga *et al.*, 2017).

Many Persian oak forests in the Zagros range originated after timber harvests and pruning (Fatahi, 1995), as support the density of coppices. In the resulting even-aged stands, Persian oak can persist for extended periods as small trees in lower canopy positions (Shakeri *et al.*, 2009). Notwithstanding, such suppressed and presumably older stems, growing as coppices, might be particularly vulnerable to decline (Hamzehpour *et al.*, 2011). Specifically, these trees subjected to higher competition show lower radial growth and they are more prone to die following extreme drought events (Franklin *et al.*, 1987; Das *et al.*, 2008, 2011; Colangelo *et al.*, 2017b). Greater mortality in coppice oaks could be related with the abandonment of stems harvest at earlier age, or with the undone reduction of the number of stems of each coppice, both management practices that could reduce stand-level decline and mortality (Di Filippo *et al.*, 2010). Furthermore, stressed, low vigor oaks are especially susceptible to attack by a variety of organisms (Kabrick *et al.*, 2008; Fan *et al.*, 2008; Sangüesa-Barreda *et al.*, 2015).

Concluding remarks

The magnitude and spatial distribution of mortality indicate that Persian oak decline is a landscape phenomenon. Based on previous oak decline events investigated worldwide, it is likely that Persian oak will remain an important forest component of the Zagros range at the regional scale despite extensive mortality. Over time, however, it is unclear how various levels of oak decline will affect forest structure, species composition, and regeneration dynamics at the local scale, particularly in areas exhibiting high levels of mortality. The consequences of climatic change for Persian oak dynamics and distribution need to be closely monitored, particularly in water-limited sites and degraded soils like those found in many locations along the Zagros range.

This study also highlights the importance of monitoring shifts in rainfall patterns and increasing temperatures, associated with climate change. Such changes might likely to cause widespread forest decline in regions where droughts are predicted to increase in duration and severity. Understanding forest responses to this extreme event is useful to adapt forest management, expecting for the impacts of climate change. The identification of stands prone to be affected by high tree mortality allows management efforts to be focused on higher vulnerability areas. Forest decline episodes as reported here may lead to the reordering of dominance between species within communities, which may persist if extreme events become more frequent. Management should adapt to this climatic variability, through stand competition management and promoting the establishment of more adapted species to the expected climatic scenarios, while ahead research is still required to properly address these important issues.

Acknowledgments

We thank the Handling Editor and two anonymous reviewers whose throughout revision and comments greatly helped to improve a previous version of the manuscript.

References

Allen CD, Breshears DD, 1998. Drought-induced shift of a forest-woodland ecotone: rapid landscape to climate variation. PNAS 95: 14839-14842. https://doi.org/10.1073/pnas.95.25.14839

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, Kitzberger T, Rigling A, Breshears DD, Hogg EH, *et al.*, 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecol Manag 259 (4): 660-684. https://doi.org/10.1016/j.foreco.2009.09.00

Anderegg WR, Kane JM, Anderegg LD, 2012. Consequences of widespread tree mortality triggered by drought and temperature stress. Nature Clim Chang 3: 30-36. https://doi.org/10.1038/nclimate1635

Asakereh H, 2007. Temporal and spatial variations of precipitation in Iran during the last decades. Iran J Geogr Devel 10: 145-164.

Azizi G, Arsalani M, Bräuning A, Moghimi E, 2013. Precipitation variations in the central Zagros Mountains (Iran) since A.D. 1840 based on oak tree rings. Paleog Paleoclim Paleoecol 386: 96-103. https://doi.org/10.1016/j.palaeo.2013.05.009

Bordbar K, Sagheb-Talebi KH, Hamzehpour M, Joukar L, Pakparvar M, Abbasi AR, 2010. Impact of environmental factors on distribution and some quantitative characteristics of Manna oak (*Quercus brantii* Lindl.) in Fars province. Iran J For Poplar Res 18: 390-404.

Brasier CM, 1996. *Phytophthora cinnamomi* and oak decline in southern Europe. Environmental constraints including climate change. Ann For Sci 53 (2-3): 347-358. https://doi.org/10.1051/forest:19960217

Camarero JJ, Sanguesa-Barreda G, Vergarechea M, 2016. Prior height, growth, and wood anatomy differently predispose to drought induced dieback in two Mediterranean oak species. Ann For Sci 73: 341-351. https://doi.org/10.1007/s13595-015-0523-4

Carnicer J, Coll M, Ninyerola M, Pons X, Sánchez G, Peñuelas, J. 2011. Widespread crown condition decline, food web disruption, and amplified tree mortality with increased climate change-type drought. PNAS 108: 1474-1478. https://doi.org/10.1073/pnas.1010070108

Cescatti A, Piutti E, 1998. Silvicultural alternatives, competition regime and sensitivity to climate in a European beech forest. For Ecol Manage 102: 213-223.

Chapman RA, Heitzman E, Shelton MG, 2006. Long-term changes in forest structure and species composition of an upland oak forest in Arkansas. For Ecol Manage 236: 85-92.

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, *et al.*, 2007. Regional climate projections. In: Climate change 2007: The physical science bases; Solomon S, *et al.* (eds), pp: 847-943. Cambridge University Press.

Clark JS, Iverson L, Woodall CW, Allen CD, Bell DM, Bragg DC, *et al.*, 2016. The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States. Glob Change Biol 22 (7): 2329-2352. https://doi.org/10.1111/gcb.13160

Colangelo M, Camarero JJ, Battipaglia G, Borghetti M, De Micco V, Gentilesca T, Ripullone F, 2017a. A multi-proxy assessment of dieback causes in a Mediterranean oak. Tree Physiol 37: 617-631. https://doi.org/10.1093/treephys/tpx002

Colangelo M, Camarero JJ, Borghetti M, Gazol A, Ripullone F, 2017b. Size matters a lot: drought-affected Italian oaks are smaller and show lower growth prior to tree death. Front Plant Sci 8: 135. https://doi.org/10.3389/fpls.2017.00135

Das AJ, Battles JJ, van Mantgem PJ, Stephenson NL, 2008. Spatial elements of mortality risk in old-growth forests. Ecology 89: 1744-1756. https://doi.org/10.1890/07-0524.1

Das A, Battles J, Stephenson NL, van Mantgem PJ, 2011. The contribution of competition to tree mortality in old-growth coniferous forests. Forest Ecol Manage 261: 1203-1213. https://doi.org/10.1016/j.foreco.2010.12.035

Di Filippo A, Alessandrini A, Biondi F, Blasi S, Portoghesi L, Piovesan G, 2010. Climate change and oak growth decline: dendroecology and stand productivity of a Turkey oak (*Quercus cerris* L.) old stored coppice in Central Italy. Ann ForSci 67 (7): 706. https://doi.org/10.1051/forest/2010031

Engelstaedter S, Kohfeld KE, Tegen I, Harrison SP, 2003. Controls of dust emissions by vegetation and topographic depressions: An evaluation using dust storm frequency data. Geophys Res Lett 30 (6): 1294. https://doi.org/10.1029/2002GL016471

Erfanifard Y, Feghhi J, Zobeiri M, Namiranian M, 2009. Spatial pattern analysis in Persian oak (*Quercus brantii* var. *persica*) forests on B&W aerial photographs. Environ Monit Assess 150: 251-259. https://doi.org/10.1007/s10661-008-0227-4

Espelta JM, Riba M, Retana J, 1995. Patterns of seedling recruitment in West-Mediterranean *Quercus ilex* forests influenced by canopy development. J Veg Sci 6: 465-472. https://doi.org/10.2307/3236344

ESRI, 2006. ArcGIS: Release 9.2, Environmental Systems Research Institute, 1999-2006, Redlands, CA, USA. https://www.esri.com

Fan Z, Kabrick JM, Spetich MA, Shifley SR, Jensen RG, 2008. Oak mortality associated with crown dieback and oak borer attack in the Ozark Highlands. Forest Ecol Manage 255: 2297-2305. https://doi.org/10.1016/j.foreco.2007.12.041

Fan Z, Fan X, Crosby MK, Moser WK, He H, Spetich MA, Shifley SR, 2012. Spatio-temporal trends of oak decline and mortality under periodic region drought in the Ozark Highlands of Arkansas and Missouri. Forests 3: 614-631. https://doi.org/10.3390/f3030614

Fatahi M, 1995. The study of Zagros' oak forests and the most important factors of its destruction. Forests and Pastures Research Institute, Tehran, Iran.

Franklin JF, Shugart HH, Harmon ME, 1987. Tree death as an ecological process. Bioscience 27: 259-288. https://doi.org/10.2307/1310665

Galiano L, Martínez-Vilalta J, Lloret F, 2010. Drought-induced multifactor decline of Scots pine in the Pyrenees and potential vegetation change by the expansion of co-occurring oak species. Ecosystems 13 (7): 978-991. https://doi.org/10.1007/s10021-010-9368-8

Gea-Izquierdo G, Martín-Benito D, Cherubini P, Isabel C, 2009. Climate-growth variability in *Quercus ilex* L. west Iberian open woodlands of different stand density. Ann For Sci 66 (8): 802. https://doi.org/10.1051/forest/2009080

Gómez-Aparicio L, Pérez-Ramos IM, Mendoza I, Matías L, Quero JL, Castro J, Zamora R, Marañón T, 2008. Oak seedling survival and growth along resource gradients in Mediterranean forests: implications for regeneration in current and future environmental scenarios. Oikos 117: 1683-1699. https://doi.org/10.1111/j.1600-0706.2008.16814.x

Grier CC, Elliott KJ, McCullough DG, 1992. Biomass distribution and productivity of *Pinus edulis-Juniperus monosperma* woodlands of north-central Arizona. Forest Ecol Manage 50: 331-350. https://doi.org/10.1016/0378-1127(92)90346-B

Haavik LJ, Billings SA, Guldin JM, Stephen FM, 2015. Emergent insects, pathogens and drought shape changing patterns in oak decline in North America and Europe. Forest Ecol Manage 354: 190-205. https://doi.org/10.1016/j.foreco.2015.06.019

Hamzehpour M, Kia-Daliri H, Bordbar K, 2011. Preliminary study of manna oak (*Quercus brantii* Lindl.) tree decline in Dashte-Barm of Kazeroon, Fars province. Iran J For Poplar Res 19 (2): 352-363.

Hassanzad-Navroodi I, Zarkami R, Basati M, Mohammadi-Limaei S, 2015. Quantitative and qualitative characteristics of Persian oak along altitudinal gradation and gradient (Case study: Ilam province, Iran). J Forest Sci 61 (7): 297-305. https://doi.org/10.17221/13/2015-JFS

Heitzman E, Grell A, Spetich M, Starkey D, 2007. Changes in forest structure associated with oak decline in severely impacted areas of northern Arkansas. South J Appl For 31: 17-22.

Hegyi F, 1974. A simulation model for managing jack-pine stands. In: Growth models for tree and stand simulation; Fries J (ed.), pp: 74-90. Royal College of Forestry, Stockholm.

Hosseini A, 2012. Infestation of forest trees to the borer beetle and its relation to habitat conditions in the Persian oak (*Quercus brantii*) forests in Ilam Province. J Forest Range Prot Res 9 (1): 53-67.

Jenkins MA, Pallardy SG, 1995. The influence of drought on red oak group species growth and mortality in the Missouri Ozarks. Can J For Res 25: 1119-1127. https://doi.org/10.1139/x95-124

Johnson DW, Trettin CC, Todd DE, 2016. Changes in forest floor and soil nutrients in a mixed oak forest 33 years after stem only and whole-tree harvest. Forest Ecol Manage 361: 56-68. https://doi.org/10.1016/j.foreco.2015.11.012

Kabrick JM, Dey DC, Jensen RG, Wallendorf M, 2008. The role of environmental factors in oak decline and mortality in the Ozark Highlands. Forest Ecol Manage 255 (5-6): 1409-1417. https://doi.org/10.1016/j.foreco.2007.10.054

Keyser TL, Brown PM, 2016. Drought response of upland oak (*Quercus* L.) species in Appalachian hardwood forests of the southeastern USA. Ann For Sci 73: 971. https://doi.org/10.1007/s13595-016-0575-0

Lechuga V, Carraro V, Viñegla B, Carreira JA, Linares JC, 2017. Managing drought-sensitive forests under global change. Low competition enhances long-term growth and water uptake in *Abies pinsapo*. Forest Ecol Manage 406: 72-82. https://doi.org/10.1016/j.foreco.2017.10.017

Linares JC, Camarero JJ, Carreira JA, 2010. Competition modulates the adaptation capacity of forests to climatic stress: insights from recent growth decline and death in relict stands of the Mediterranean fir *Abies pinsapo*. J Ecol 98: 592-603. https://doi.org/10.1111/j.1365-2745.2010.01645.x

Lloret F, Siscart D, Dalmases C, 2004. Canopy recovery after drought dieback in holm-oak Mediterranean forests of Catalonia (NE Spain). Glob Change Biol 10: 2092-2099. https://doi.org/10.1111/j.1365-2486.2004.00870.x

Manion PD, 1991. Tree disease concepts, 2nd Ed. Prentice-Hall, Englewood Cliffs, NJ, USA. 402 pp.

McEwan RW, Dyer JM, Pederson N, 2011. Multiple interacting ecosystem drivers: toward an encompassing hypothesis of oak forest dynamics across eastern North America. Ecography 34: 244-256. https://doi.org/10.1111/j.1600-0587.2010.06390.x

Natalini F, Alejano R, Vázquez-Piqué J, Cañellas I, Gea-Izquierdo G, 2016. The role of climate change in the widespread mortality of holm oak in open woodlands of Southwestern Spain. Dendrochronologia 38: 51-60. https://doi.org/10.1016/j.dendro.2016.03.003

Ogaya R, Peñuelas J, 2007. Tree growth, mortality, and above-ground biomass accumulation in a holm oak forest under a five year experimental field drought. Plant Ecol 189: 291-299. https://doi.org/10.1007/s11258-006-9184-6

Pausas J, Marañón T, Caldeira MC, Pons J, 2009. Natural regeneration. In: Cork oak woodlands on the edge: Ecology, adaptive management and restoration; Aronson J, Pereira JS & Pausas JG (eds), pp: 115-124. Island Press, Washington.

Pérez-Ramos IM, Rodríguez-Calcerrada J, Ourcival JM, Rambal S, 2013. *Quercus ilex* recruitment in a drier world: a multi-stage demographic approach. Perspec Plant Ecol Evol Syst 15 (2): 106-117. https://doi.org/10.1016/j.ppees.2012.12.005

Rahimzadeh F, Asgari A, Fattahi E, 2009. Variability of extreme temperature and precipitation in Iran during recent decades. Int J Climatol 29: 329-343. https://doi.org/10.1002/joc.1739

Rizzo DM, Garbelotto M, 2003. Sudden oak death: endangering California and Oregon forest ecosystems. Front Ecol Envir 1: 197-204. https://doi.org/10.1890/1540-9295(2003)001[0197:SODECA]2.0.CO;2

Ruiz-Benito P, Lines ER, Gómez-Aparicio L, Zavala MA, Coomes DA, 2013. Patterns and drivers of tree mortality in Iberian forests: climatic effects are modified by competition. Plos One 8 (2): e56843. https://doi.org/10.1371/journal.pone.0056843

Sánchez-Salguero R, Camarero JJ, Grau JM, de la Cruz AC, Gil PM, Minaya M, Fernández-Cancio A, 2017. Analysing atmospheric processes and climatic drivers of tree defoliation to determine forest vulnerability to climate warming. Forests 8: 13. https://doi.org/10.3390/f8010013

Sangüesa-Barreda G, Linares JC, Camarero JJ, 2015. Reduced growth sensitivity to climate in bark-beetle infested Aleppo pines: Connecting climatic and biotic drivers of forest dieback. Forest Ecol Manage 357: 126-137. https://doi.org/10.1016/j.foreco.2015.08.017

Shakeri Z, Marvi Mohajer MR, Namiraninan M, Etemad V, 2009. Comparison of seedling and coppice regeneration in pruned and undisturbed oak forests of Northern Zagros (Case study: Baneh, Kurdistan province). Iran J For Poplar Res 17: 73-84.

Sheffer E, Canham CD, Kigel J, Perevolotsky A, 2013. Landscape-scale density-dependent recruitment of oaks in planted forests: More is not always better. Ecology 94: 1718-1728. https://doi.org/10.1890/12-2121.1

Soltani M, Laux P, Kunstmann H, Stan K, Sohrabi MM, Molanejad M, Sabziparvar AA, Ranjbar SaadatAbadi A, Ranjbar F, Rousta I *et al.*, 2015. Assessment of climate variations in temperature and precipitation extreme events over Iran. Theor Appl Climatol 126 (3-4): 775-795. https://doi.org/10.1007/s00704-015-1609-5

Sparks DL, Page AL, Helmke PA, Loeppert RH (Eds.), 1996. Methods of soil analysis, Part 3- Chemical methods. Soil Sci Soc Am, Am Soc Agron, Madison, WI, USA.

Starkey DA, Oak SW, 1989. Site factors and stand conditions associated with oak decline in southern upland hardwood forests. Proc of the 7th Central Hardwood Forest Conf. Gen Tech Rep NC-132. USDA, Forest Service, North Central For Exp Station, St. Paul, MN, USA, pp: 95-102.

Tegen I, Harrison SP, Kohfeld KE, Prentice IC, Coe M, Heimann M, 2002. Impact of vegetation and preferential source areas on global dust aerosol: Results from a model study, J Geophys Res 107 (D21): 4576. https://doi.org/10.1029/2001JD000963

Urbieta IR, Zavala MA, Marañón T, 2008. Human and non-human determinants of forest composition in southern Spain: evidence of shifts towards cork oak dominance as a result of management over the past century. J Biogeo 35: 1688-1700. https://doi.org/10.1111/j.1365-2699.2008.01914.x

Voelker SL, Muzika RM, Guyette RP, 2008. Individual tree and stand level influences on the growth, vigor, and decline of red oaks in the Ozarks. Forest Sci 54 (1): 8-20.