Forest Ecology and Management 502 (2021) 119745

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Spatiotemporal dynamics and risk factors of oak decline and Mortality in the Missouri Ozarks of the United States based on repeatedly measured FIA data

Shaoyang Yang [a], Martin A. Spetich [b], Zhaofei Fan [a,*]

[a] School of Forestry and Wildlife Sciences, Auburn University, AL 36849, United States

[b] USDA Forest Service Southern Research Station, 100 Reserve Street, Hot Springs, AR 71902, United States

ARTICLE INFO

Keywords:
Oak risk groups
Kernel smoothing
Logistic regression
Classification and regression tree
Survival
Drought

ABSTRACT

During recent decades there has been widespread oak decline and mortality in the Missouri Ozarks, USA. We extracted data of 18,403 oak trees measured during 1999–2019 from the US Forest Service's Forest Inventory and Analysis (FIA) database to examine the spatiotemporal patterns of oak decline and mortality and associated risk factors. The Missouri Ozarks were classified into three spatial clusters with low (<1.0%), moderate (1.0–1.5%) and high (>1.5%) annual oak mortality rates using kernel smoothing and the Jenks natural breaks method. Oaks within each spatial cluster were further divided into four, five and three risk groups respectively with differentiated annual mortalities (0.35%–3.05%) using a classification and regression tree model. The Kaplan-Meier survival analyses showed that oak trees from individual spatial clusters and risk groups responded differently to droughts, a major regional or sub-regional inciting factor of oak decline. Droughts could have a three to nine year lagged impact on tree mortality in the high risk groups, whereas had little effect on oak mortality in the low risk groups. Tree species, crown class, and stand age were the regionwide predisposing factors of oak decline. However, localized disturbances and geographic/vegetation conditions (e.g., drought, fire, insects, aspect, elevation, ecoregions, historical forest types) could either incite or alleviate the decline process and the fate of declining trees depending on the differentiated spatial clusters or risk groups. Resource managers can base associated risk factors and spatial clusters to rank risk levels to prioritize and plan management activities to mitigate oak decline and mortality.

1. Introduction

An investigation by Allen et al. (2010) indicated that the impacts of increasing drought and heat stress have influenced tree mortality worldwide and that many of these forests are expected to become increasingly vulnerable to drought induced tree mortality. Over the past century oak decline has been reported in the United States, Europe and Asia (Gottschalk and Wargo, 1997; Brasier and Scott, 1994). Oak decline and mortality incidences have been reported since the early 1900s (Beal, 1926; Balch, 1927) in the southeastern United States. In the early 1980s, a large increase of visible oak decline and mortality events was seen in mixed hardwood forests in the eastern United States (Bechtold et al., 1987; Brown, 1993). Since the 1990s, large-scale oak decline episodes have been observed, becoming increasingly severe as numerous fully stocked and over-stocked oak and/or oak-dominated forests approach physiological maturity in the Ozark Highlands of Arkansas and Missouri (Bruhn et al., 2000; Spetich, 2004; Fan et al., 2011; Wood et al., 2018) and elsewhere in the southeastern United States (Starkey et al., 1989; Oak et al., 1996; Wang et al., 2013; Bendixsen et al., 2015). Oak decline has dramatically changed species composition and stand structure, decreased timber value, reduced wildlife habitat quality, and increased fuel loads (Wang et al., 2013), resulting in a serious concern regarding the sustainability of oak forests.

Mortality following recent droughts accounted for 15% − 28% of red oaks (*Quercus rubra* L., *Q. velutina* Lam., *Q. coccinea* Muenchh. and *Q. falcate* Michx.) basal area loss in the Ozark Highlands (Starkey et al., 2004; Voelker et al., 2008). Besides droughts, oak mortality is closely associated with tree characteristics, site, and stand conditions as well as human activities, insects and diseases (Oak et al., 1996; Haavik et al., 2011; Fan et al., 2012a; Wang et al., 2013; Spetich et al., 2016; Wood

* Corresponding author.
E-mail addresses: szy0048@auburn.edu (S. Yang), Martin.Spetich@usda.gov (M.A. Spetich), zzf0008@auburn.edu (Z. Fan).

https://doi.org/10.1016/j.foreco.2021.119745
Received 13 August 2021; Received in revised form 23 September 2021; Accepted 26 September 2021
Available online 5 October 2021

et al., 2018). Due to rising temperature and global warming in the southeastern United States, the effects of extreme drought on oak decline and mortality are expected to increase in the Ozark Highlands (Dai, 2011; Fan et al., 2012a; Spetich et al., 2016) and across the fourteen-state central hardwood forest region of the eastern United States (Vose et al., 2015; Oak et al., 2016). Oak decline analysis based on 10 years of inventory data (1999–2010) indicated that the red oak decline reached its peak in 2008–2009, two years after the end of the 2006 drought (Spetich et al., 2016).

Previous studies of oak decline have examined and quantified risk factors, hazard indices, regeneration dynamics, spatiotemporal patterns, and the effect of alternate harvesting techniques on oak decline and mortality (Spetich and He, 2008; Fan et al., 2012a; Spetich et al., 2016). Fan et al (2006, 2011) classified oaks into different risk groups based on repeatedly measured tree and stand data from a landscape-level study and modeled stand hazards by using tree characteristics and site/stand conditions. Similar statistical procedures or models developed may be applicable to the entire Ozark Highlands and over a longer time period. However, differentiation in landscape and regional variables as well as historical forest conditions may limit their applicability to other areas due to variations in disturbance regimes (e.g., drought, fire, insect, disease) and temporal changes of vegetation cover (Heitzman et al., 2007; Kabrick et al., 2008; Hanberry et al., 2014). Our models may also have applicability outside of the U.S. as "red oaks from the eastern USA have been introduced in Europe, and *Q. rubra* is currently used throughout western Europe, not only as an ornamental tree but also as a plantation species for veneer or timber production" (Kremer et al. 2004).

Starkey et al (2004) proposed a conceptual model of oak decline syndrome in red oaks (*Quercus rubra* L., *Q. velutina* Lam., *Q. coccinea* Muenchh. and *Q. falcate* Michx.) by dividing the risk factors based on their function into three categories: predisposing factors (e.g., tree and stand conditions), inciting factors (drought, defoliating insects, frost, stand disturbance), and contributing factors (boring insects, canker fungi, root disease). Spatially, oak trees across landscapes and ecoregions may grow in similar stand and site conditions (predisposing factors), but experience distinct disturbance regimes (inciting and contributing factors), resulting in great variations in oak decline and mortality (e.g., Oak et al. 2016). It is imperative to develop a new model that examines oak decline and mortality by landscape variables, site/stand conditions, disturbances, historical forests, and physiography to help forest managers mitigate oak decline at the landscape and regional level. In this study a modeling approach that includes the above factors was developed to evaluate oak decline and mortality in the Ozark Highlands of Missouri. The primary objective of this study is to examine recent oak mortality and develop multilevel oak mortality models. Specifically, this study addressed the following objectives: 1) Mapping the spatial variations of oak decline and mortality across the entire Missouri Ozarks; 2) Identifying risk groups and quantifying their long-term survival patterns under recurrent droughts for mapped risk regions; and 3) examining risk factors that affect oak decline and mortality by mapped risk regions and/or groups. The multilevel modeling results and findings will provide useful information for prioritizing treated areas and developing management guides and recommendations for restoring and managing oak forests.

2. Methodology

2.1. Study area

The Ozark Highlands, located in the central USA, extends across the states of Missouri, Arkansas, Oklahoma, and Kansas. A significant portion of the Ozarks is located in southern Missouri (Fig. 1). The Ozark Highlands is a section under the central interior broadleaf forest province and contains 17 (13 in Missouri) subsections (Cleland et al., 2007).

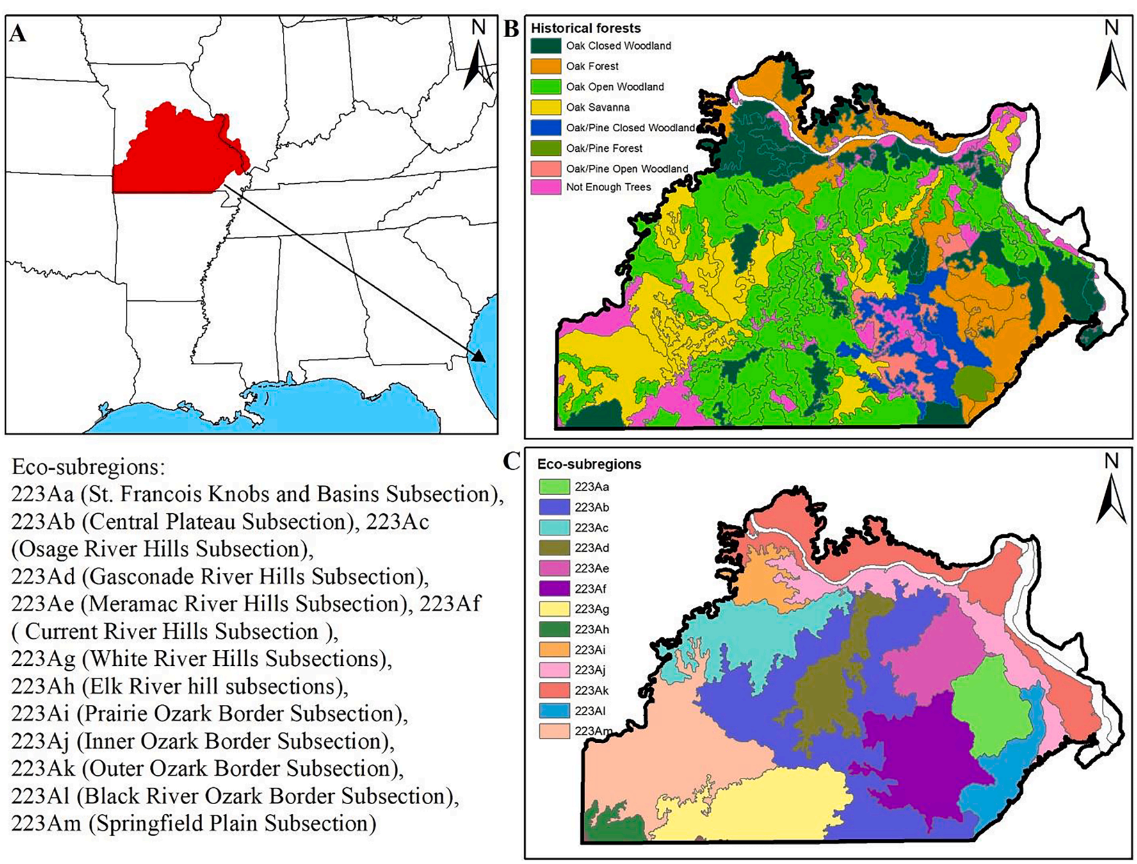

Fig. 1. Map of the Ozark highlands of Missouri (A), seven historical forest types (B) and thirteen ecological sub-regions (C) in the study area.

The highlands include high plateaus of steep hills and low rolling hills. It is dominated by oak-hickory and oak-pine forest types (Mcnab et al., 2007) including oak (*Quercus* spp.), hickory (*Carya*), shortleaf pine (*Pinus echinata*), elm (*Ulmus*), ash (*Fraxinus*), and maple (*Acer*) (Oak et al., 1996; Wood et al., 2018). Historically, seven forest types occurred in the Ozark Highlands, with oak open woodland as the most dominant component (Hanberry et al., 2014). The Climate in the Ozark Highlands is temperate, having mild winters with a mean January temperature of 4 °C and hot summers with a mean August temperature of 27 °C (Haavik et al., 2011). The formations of rock in this area are limestone, sandstone, and shale. The landform and topography are characterized by deep valleys, steep ledges, and cliffs with elevations up to 750 m with slopes facing all cardinal directions (Adamski, 1995).

2.2. The FIA data

In this study, we used only Missouri Ozarks FIA data. In Missouri, the USDA Forest Service's FIA program started the annual measurement scheme in 1999 with a goal of measuring 20% of the entire FIA plots every year, but this target is not always met due to funding and other limitations. From 1999 to 2019, there were four inventory cycles for each FIA plot: cycle 5 (1999–2003), cycle 6 (2004–2008), cycle 7 (2009–2013), and cycle 8 (2014–2019). As of the date of data compilation, data measurements for the last cycle were not completed; therefore, we had partial data for that portion of the study. All trees (i.e. >12.7-cm diameter at breast height) in each plot were used from the four-time period remeasurement with survival status (live or dead). A total of 31,037 trees, all live in cycle 5, were followed in this analysis. Among those trees, there were 18,403 individual remeasured oak trees including ten major oak species in the Ozark Highlands (Table 1). Individual tree data and associated stand level and landscape level information were gathered and merged from the FIA database. These variables were classified into three categories: tree/site/stand variables, landscape/regional variables, and disturbances and management variables based on their potential roles in oak decline (Starkey et al., 2004; Table 1). Tree/site/stand variables are the direct factors that predispose oaks to decline and subsequently determine the levels of risk (Fan et al., 2006), whereas landscape/regional variables may affect or incite oak decline and control the large-scale spatial patterns of oak decline and mortality by regulating biotic and abiotic factors and disturbance regimes (Fan et al., 2012a). Disturbances and management variables measured at microscales are important inciting and/or contributing factors and can either alleviate or exaggerate the decline process and affect the dynamics of oak decline conditions (Fan et al., 2011). These data were downloaded and/or calculated from either the FIA database or other data sources. The monthly Palmer Drought Severity Index

Table 1
Potential risk variables used to evaluate oak decline and mortality. Risk variables are divided into three groups: tree, stand and site variables, landscape and geographic variables, and disturbance/management variables based on the spatial scale on which they were measured and/or the role they played.

Data *Type	Variables	Classification	Time	Sources
Tree, stand, and site variables	Tree status	1: live; 0: dead	1999–2019	Forest Inventory and Analysis data mart
	Oak species	*White oak (*Q. alba*, a)		
		#Scarlet oak (*Q. coccinea*, b)		
		#Shingle oak (Q. imbricaria, c)		
		#Blackjack oak (*Q. marilandica*, d)		
		*Chinkapin oak (*Q. muehlenbergii*, e)		
		#Northern red oak (*Q. rubra*, f)		
		#Shumard oak (*Q. shumardii*, g)		
		*Post oak (*Q. stellata*, h)		
		#Black oak (*Q. velutina*, i)		
		#Southern red oak (*Q. falcata*, j)		
	Crown class			
		1: Dominant		
		2: Codominant		
		3: Intermediate		
		4: Overtopped		
	Diameter at breast height (DBH)	Continuous (cm)		
	Basal area in larger trees (BAL)	Continuous (m^2/ha)		
	Basal area of live trees	Continuous (m^2/ha)		
	Site productivity	Low (<3.5 m^3/ha/yr.)		
		Medium (≥3.5 & < 8.4 m^3/ha/yr.)		
		High (≥8.4 m^3/ha/yr.)		
	Physiographic class	Xeric sites		
		Mesic sites		
	Growing stock	Continuous (%)		
	Stand age	Integer (years)		
	Stand origin	1: artificial; 0: natural		
Data Type	**Variables**	**Classification**	**Time**	**Sources**
Landscape/Geographic Variables	Elevation	Continuous (m)	2019	Extracting from FIA plot data
	Slope	Continuous (degree)		
	Aspect	North-facing vs. south-facing		
	Coordinate (latitude, longitude)	Continuous		
	Historical forest type	Categorical variables (shapefile)		Hanberry et al.2014
	Ecoregion	Categorical variables (shapefile)		
				Environmental Protection Agency
Disturbances/management Variables		Insect and disease: 1=yes, 0=no	1999–2019	Forest Inventory and Analysis data mart
		Weather (storms, ice): 1=yes, 0=no		
		Fire: 1=yes, 0=no		
		Treatment (cutting, site preparation, harvest): 1=yes, 0=no		
		Ownership: public=0, private=1		

*white oak group; # red oak group based on by the United State Forest Service's classifications

(PDSI) for each of the four climate divisions in the Missouri Ozarks was downloaded from the National Climatic Data Center (https://www.ncdc.noaa.gov/). A year was divided into growing season (May-October) and dormant season (November-April), and the drought severity in a single growing season is represented by the cumulative monthly PDSI, a sum of PDSIs from May to October. The cumulative yearly PDSI was calculated as the sum of cumulative growing season PDSIs for the previous n (n = 0, 1, 2,…) years.

2.3. Data analysis

We extracted all live oak trees (n = 18,403) in cycle 5 (1999–2003) from the 1470 FIA plots and tracked each tree's status (live vs. dead) during the following three consecutive inventory cycles (6, 7 and 8). The cumulative oak mortality in terms of percent of dead oak trees among all oak trees in each FIA plot was calculated for cycles 6, 7 and 8 as an indirect measure of oak decline. Considering the weak trend of spatial continuity in mean annual oak mortality (the cumulative oak mortality in the measurement cycle divided by the number of years between cycle 5 and the following measurement cycles) of FIA plots (Fan et al., 2011), the nonparametric "kernel smoothing" (Wand and Jones, 1995) was applied to map the spatial variation of oak decline severity (the % of mean annual oak mortality in cycle 8) using the approach described by Fan et al. (2011). With the unimodal distribution of smoothed annual oak mortalities, the Jenks natural breaks method (Jenks, 1967) was used to classify the Missouri Ozarks into disjoint sub-regions (spatial clusters) showing differentiated oak decline and mortality classes (objective 1).

Within each of the identified sub-regions, the nonparametric classification and regression tree (CART) (Breiman et al., 1984) was used to classify oak trees into different risk groups (objective 2) by using tree status (live versus dead) in the most recent cycle (cycle 8) as the response variable and tree, site and stand variables (Table 1) as the predictors. To obtain an honest estimate of oak mortality, we set the minimum node size of n = 250 trees (the product of tree number and cumulative oak mortality > 10) and used the cross-validation to remove nonsignificant or superficial partitions to develop the best CART model using the R package: rpart (Therneau et al., 2013). We then followed Fan et al. (2006) to apply the Kaplan–Meier (product limit) method (Kaplan and Meier 1958), coupled with the log-rank method, to analyze the survival patterns of individual risk groups. Analysis of covariance (ANCOVA) and multiple comparisons (Habib et al., 2017) were used to analyze the mean annual trend of cumulative oak survival rate that was calculated by using annual mortality of oak trees from 1999 to 2019. The mean cumulative mortality (the proportion of dead oak trees) and standard error of each risk group by measurement year was estimated by using the bootstrapping method (n = 500) (Arellano, 2019) and tree mortality (transformed using the arc sine square root function for normality correction) between different risk groups was compared via Tukey's HSD test (Althouse, 2016). Recurrent droughts are a major inciter of large-scale oak decline episodes and great temporal variations (e.g., Fan et al. 2012a). But, oak trees may respond differently to droughts depending the tree's health condition, and the timing, magnitude and duration of drought events (Oak et al., 1996). To evaluate the lag effects of recurrent droughts on oak mortality, the cross-correlation coefficient (r(d), equation (1)) at delay d ($0 \leq d < N$ years) between annual mortality and cumulative yearly PDSI series was calculated for each risk group (Fan et al., 2012a),

$$r(d) = \frac{\sum_{i=0}^{N-1} (x(i) - \bar{x})(y(i-d) - \bar{y})}{\sqrt{\sum_{i=0}^{N-1} (x(i) - \bar{x})^2} \times \sqrt{\sum_{i=0}^{N-1} (y(i-d) - \bar{y})^2}} \quad (1)$$

where series $x(i)$ and $y(i)$ ($i = 0, 1, 2, \ldots, N-1$) represent the annual mortality and PDSI series, respectively.

To quantify the effect of stand factors and management activities and disturbances on tree mortality (objective 3), tree status (a binary variable: live or dead) in the last inventory cycle was regressed against all predictor variables measured at the first inventory cycle (Table 1) through the logistic regression model (Hilbe, 2009; Fan et al., 2012b). Among the predictor variables, BAL was significantly correlated with tree stocking, and thus the BAL/stocking ratio, a new measure of competition, was used in the logistic regression to replace both variables. We did not find any significant correlation (multicollinearity) among other predictor variables. A stepwise method with the significance level of 0.05 was chosen to select the significant factors associated with the mortality of the remeasured oak trees for each of the three mortality clusters. The Hosmer-Lemeshow test was conducted to measure the goodness of fit of the selected models. All statistical analyses were conducted using the statistical R software (R development Core Team 2011).

3. Results

3.1. Spatiotemporal patterns of oak decline and mortality

Across the Ozark Highlands of Missouri, oak decline and mortality varied spatially with ecoregions (Chi-squared = 464.51, df = 24, p-value < 0.001) and historical forest types (Chi-squared = 278.02, df = 14, p-value < 0.001), and three spatial clusters (sub-regions) with differentiated annual oak mortality rates of ≤1%, 1–1.5%, and >1.5% were identified (Fig. 2). Higher mortality mostly occurred in the following eco-subregions: St. Francois Knobs and Basins Subsection (223Aa), Current River Hills Subsection (223Af), Elk River hill subsections (223Ah), and Prairie Ozark Border Subsection (223Ai), or in the historical forest types including Oak Forests and Oak/Pine Open Woodlands (Figs. 1 and 2).

3.2. Oak risk groups and the effect of PDSI on oak survival patterns

Within each oak decline and mortality class (sub-region), oak mortality varied significantly with species, crown class, and basal area in larger trees (BAL $\geq 9.6\ m^2\ ha^{-1}$ versus BAL $< 9.6\ m^2\ ha^{-1}$) (Fig. 3). Four, five and three risk groups were classified for the low (annual mortality ≤ 1%), moderate (annual mortality > 1% but ≤ 1.5%) and high (annual mortality > 1.5%) risk sub-regions, respectively (Fig. 3, Table 2). The cumulative survival (1-mortality) rate decreased with time either linearly or nonlinearly and varied by risk group (Fig. 3). Within each sub-region, the cumulative survival rates were significantly different among risk groups except for risk groups B, C and D in the sub-region of moderate mortality based on Tukey's HSD (honestly significant difference) test ($P < 0.05$). Oaks experienced high mortality before 2007 and around 2012 following recurrent droughts as shown by steep slopes in the Kaplan-Meier survival curves (Fig. 3). Cross-correlation between the growing season PDSI and mortality showed that the cumulative impact of droughts might last as long as nine years for the high risk intermediate and suppressed red oak groups (group D in the sub-region of low severity and group E in the sub-region of moderate mortality) (Fig. 3, Table 3). No significant correlations were found between oak mortality and PDSI for the remaining risk groups.

3.3. Risk factors that affect oak decline and mortality

For all three risk classes (spatial clusters), logistic regression fits the data well based on the Hosmer-Lemeshow tests ($P > 0.05$) (Table 4). Tree and stand characteristics including species, crown class and stand age appeared in all three models, reflecting their universal significance in predisposing oak decline and mortality- a phenomenon largely attributed to competition and senescence as oaks approach physiological maturity. In addition, BAL/stocking was found to be significant in the low and moderate risk classes, historical forest types were significant in the moderate and high risk classes, and aspect was significant for the

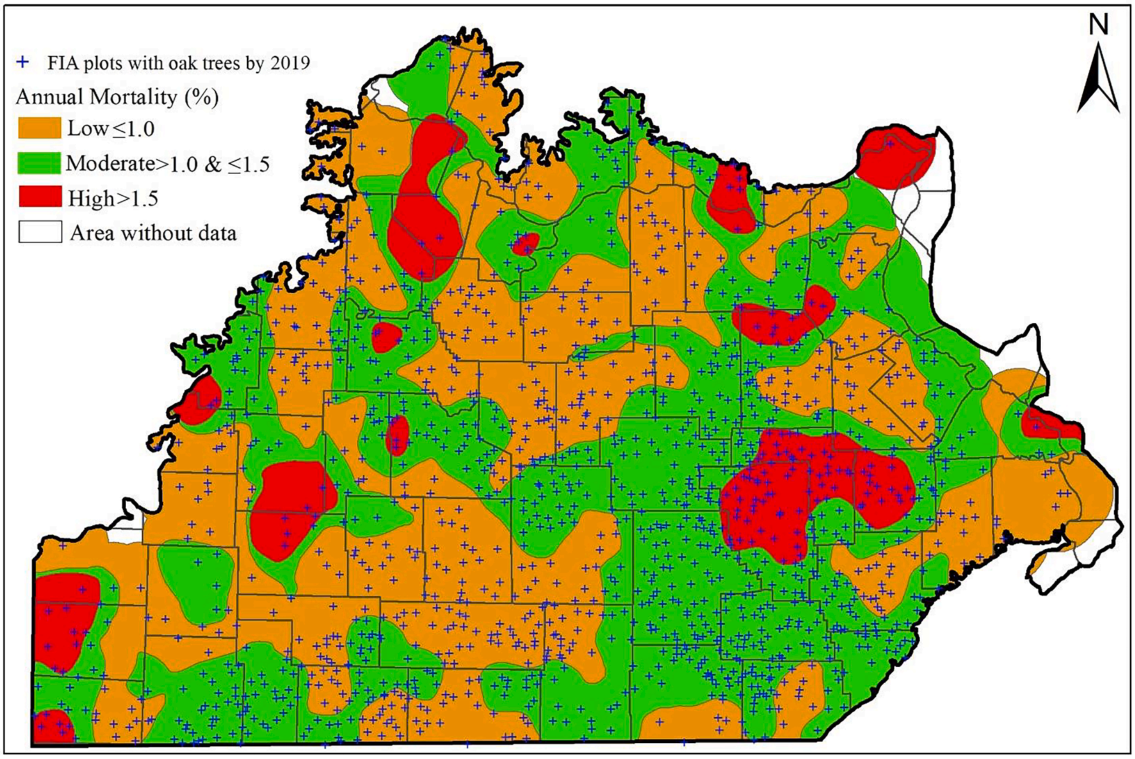

Fig. 2. Kernel-smoothed annual oak mortality showing the three oak decline and mortality classes (low: ≤1%, moderate: 1–1.5%, and high: >1.5%) in the Ozark Highlands of Missouri.

low and high risk classes. Further, physiographic class and ownership were significant in the low risk class, fire disturbance was significant in the moderate risk class, and elevation and weather and insect disturbances were significant in the high risk class (Table 4).

4. Discussion

4.1. Spatial variations of oak decline and mortality

Forests around the world are susceptible to drought and heat associated tree mortality (Allen et al., 2010), and oaks (*Quercus* spp.) are the most widely distributed genus of forest trees worldwide (Kremer et al. 2004). There have been at least five major drought induced oak mortality events across Europe from 1892 to 1961 (Delatour, 1983). Gottschalk and Wargo (1997) reported drought influenced oak decline across more than 20 countries. In the United States, oaks are keystone species and a dominant component of the forest ecosystems of the central highland mountain area (Greenberg and Collins, 2015). Sporadic symptoms of oak decline and mortality had been reported since the 1960s or earlier (Dwyer et al., 1995; Fan et al., 2008; Spetich and He, 2008; Fan et al., 2012a). Understanding the mechanisms and dynamics of oak mortality and decline and the effects of natural and human disturbances has been the focus of many studies (Fan et al., 2011; Fan et al., 2012c; Greenberg and Collins, 2015; Spetich et al., 2016; Kinkead et al., 2017). In this study, similar methods from Fan et al., 2006 and 2011 were extended and applied to the entire Ozark Highlands of Missouri to study the mechanisms and associated factors of oak decline and mortality such as distribution patterns, risk groups, and impacts of disturbances at the regional level. The distribution of oak decline and mortality followed a spatially heterogeneous (non-stationary) pattern that was related to ecoregions and historical forest conditions across the Ozark Highlands (Fan et al., 2012a; Fan et al., 2012b). Ecoregions such as basins and river hills located in the Mark Twain National Forest and historically dominated by oak forests and oak/pine open woodlands (Wang et al., 2007) had higher mortalities. Most forest stands in this area were fully stocked or over-stocked and had reached their physiological maturity, thus suffered recurrent oak decline and mortality incidences as part of the natural process of tree senescence (Wang et al., 2013). In a western Mediterranean region study with a focus on Italy and Spain (Gentilesca et al., 2017) reported that reducing tree density could lead to deeper root systems of remaining trees enabling heightened water use of these trees resulting in greater drought resistance.

Compared to environmental factors (e.g., Kabrick et al., 2008), studies on the effects of historical land use and vegetation change on oak decline have been largely overlooked. However, such studies are of paramount importance and may shed light on historical disturbance regimes and vegetation dynamics. Historically, the dominant vegetation in the Ozarks consisted of oak woodlands and oak savannahs maintained by frequent, low-intensity fires. However, oak forests covered only a small portion of the Ozarks (Spetich et al., 2004; Heitzman et al. 2007; Hanberry et al. 2014). A century of fire suppression has significantly changed the vegetation structure and composition, which was believed to be the major cause of widespread oak decline and mortality in the Ozarks. Restoring open oak woodlands and oak savannas to areas dominated by high-density oak forests is a practical approach to alleviate oak decline and mortality (Dey and Fan, 2009; Oak et al., 2016).

4.2. Oak risk groups and temporal changes of oak mortality

The red oak group species were plagued by decline with consistently higher mortality than the white oak group species. The risk groups further differentiated oak decline and mortality among oak trees based on tree species, crown class and BAL. Even though multiple factors might contribute to oak decline and mortality, recurrent droughts had been proven to be a major inciting factor (Starkey et al., 2004), affecting the spatiotemporal patterns at large spatial scales (e.g., a landscape or ecological sub-region). Recurrent droughts can trigger and exaggerate oak decline and mortality; therefore, the footprint of droughts could be

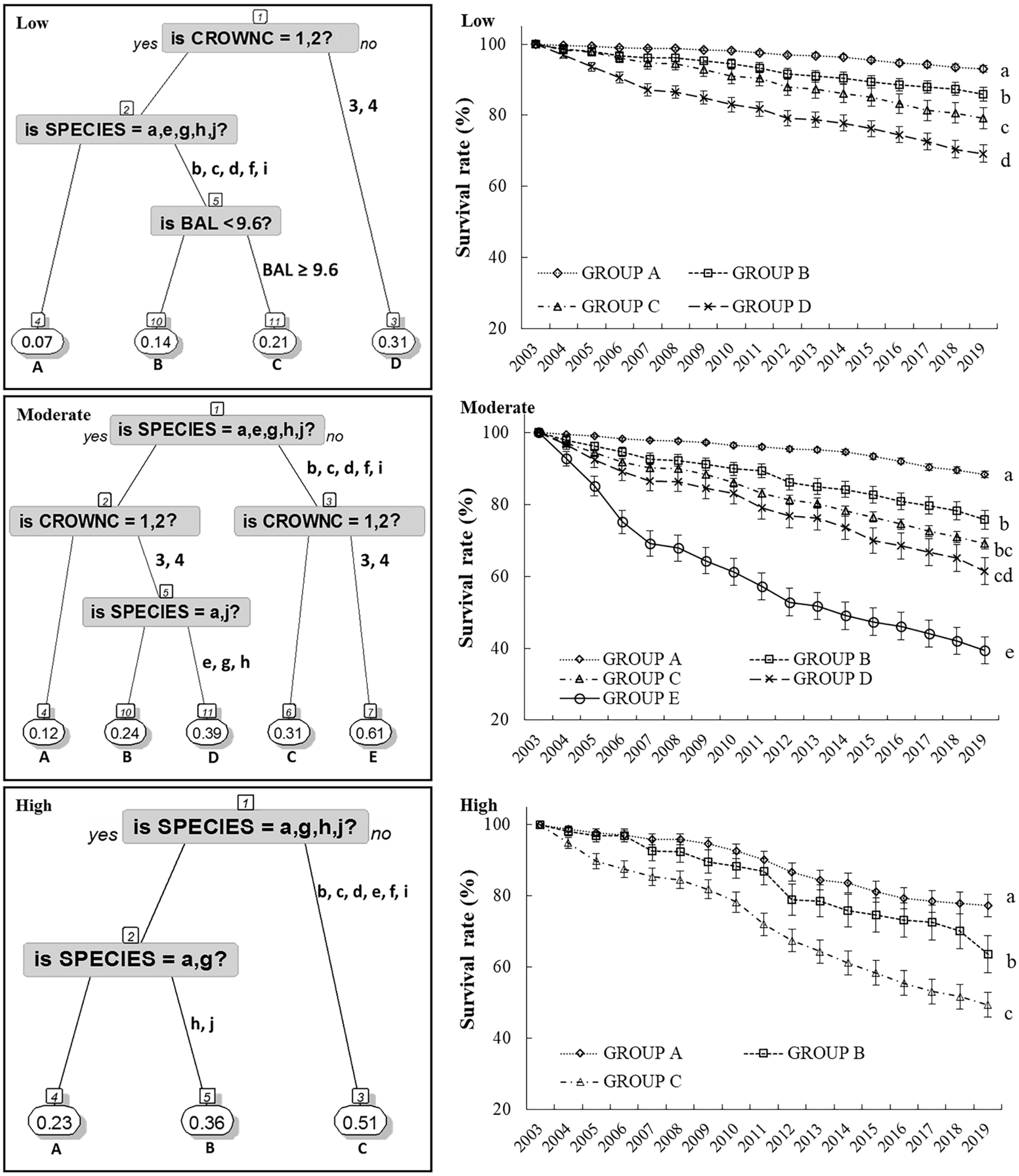

Fig. 3. Oak risk groups (terminal nodes A-E of the CART models) and survival curves for the low, moderate and high oak decline and mortality classes (spatial clusters) in the Ozark Highlands of Missouri. The number in the terminal nodes is the cumulative mortality rate (0–1). Oak species codes (a-j) and crown class codes (1–4) are defined in Table 1, and BAL is basal area in larger trees (m^2 ha^{-1}). Lower case letters to the right of survival curves showed the trend differences (with same letters representing statistically non-significant differences) between risk groups (multiple comparisons, Tukey test); vertical bars showed the 95% confidence intervals.

evaluated based on concordant or lagged temporal patterns in tree mortality and the shift of hot spots of oak decline episodes across the stricken landscape or region (Fan et al., 2012a; Haavik et al., 2015).

Individual trees, however, may respond to drought differently by tree and stand characteristics (predisposing factors), the time (season), duration and severity of droughts (inciting factors), and post-drought disturbances such as outbreak of red oak borers (Enaphalodes rufulus), and *Armillaria* root disease (contributing factors, Starkey et al., 2004). The CART models and the Kaplan-Meier survival curves developed for individual risk groups provided a practical, visual tool to unfold drought effects. Following the recurrent droughts in early- or mid-2000s (2000, 2005–2007), severe oak decline and mortality as shown by a steep slope in the survival curve in the drought year or following the drought were observed among the risk groups composed of predominantly intermediate and suppressed red oak group species (group D in the low severity cluster, group E in the moderate severity cluster, and group C in the high severity cluster) (Fig. 3, Table 2). The increasing mortality following droughts was also pinpointed, to a less

Table 2
Oak risk groups identified by CART in the Ozark Highlands of Missouri.

Severity region	Oak risk group	Tree characteristics	Accumulative mortality (%) (1999–2019)
Low	A	dominant and codominant white oak, chinkapin oak, Shumard oak, post oak, and southern red oak	7
	B	scarlet oak, shingle oak, blackjack oak, northern red oak, and black oak with BAL < 9.6 m^2 ha^{-1}	14
	C	scarlet oak, shingle oak, blackjack oak, northern red oak, and black oak with BAL ≥ 9.6 m^2 ha^{-1}	21
	D	intermediate and suppressed oak trees	31
Moderate	A	dominant and codominant white oak, chinkapin oak, Shumard oak, post oak, and southern red oak	12
	B	intermediate and suppressed white oak and southern red oak	24
	C	intermediate and suppressed chinkapin oak, Shumard oak, and post oak	39
	D	dominant and codominant scarlet oak, shingle oak, blackjack oak, and black oak	31
	E	intermediate and suppressed scarlet oak, shingle oak, blackjack oak, and black oak	61
High	A	white oak and Shumard oak	23
	B	post oak and southern red oak	36
	C	scarlet oak, shingle oak, blackjack oak, Chinkapin oak, and black oak	51

Table 3
Cross-correlations between cumulative growing season PDSI and annual oak mortality in susceptible risk groups showing the significant lagged effect of recurrent droughts.

Delay Years	Low subregion Group D			Moderate subregion Group E		
	R	*P*		*r*	*p*	
0	−0.65	0.006	*	−0.60	0.015	*
1	−0.49	0.056		−0.52	0.037	*
2	−0.35	0.185		−0.46	0.072	
3	−0.31	0.243		−0.40	0.126	
4	−0.44	0.084		−0.50	0.047	*
5	−0.69	0.003	*	−0.68	0.003	*
6	−0.75	0.001	*	−0.76	0.001	*
7	−0.69	0.003	*	−0.79	0.000	*
8	−0.49	0.055		−0.67	0.004	*
9	−0.35	0.178		−0.59	0.016	*
10	−0.29	0.273		−0.50	0.049	*

*Significance level ≤ 0.05.

degree, in other risk groups (groups A and B). In addition, a concordant increase in mortality following one recent severe drought in 2012 was observed in the survival curves of most risk groups (Fig. 3, Table 2). Cross correlations between the cumulative growing season PDSI and mortality showed that the drought impacts might perpetuate for three to nine years among the high risk groups (group D in the low severity region and group E in the moderate severity region) (Table 4, Fan et al., 2012a). Drought was also reported as the main influence activating oak decline in the Mediterranean Basin (Gentilesca et al., 2017).

There were great variations in mortality among different risk groups (Table 2). For instance, the cumulative mortality of some intermediate and suppressed red oak group species (group E in the moderate severity region) could reach as high as 61% within a period of 16 years (from 2003 to 2019) with a mean annual mortality of 3.8%. In contrast, the risk groups composed of dominant and codominant white oak group species (group A in the low and moderate severity regions) had the lowest annual mortality of <1% among all risk groups (Table 2). Existing projections of tree mortality are mostly based on empirical statistical models that lack quantifications of functionally mortality mechanisms and processes, and thus are difficult to predict long-term realistic mortality, especially under frequent environmental stresses (Thomas et al., 2002; Allen et al., 2010; Gentilesca et al., 2017). Unlike those tree-level and stand-level mortality models, in this study we attempted to project oak mortality by individual risk groups which were derived based on the conceptual model of red oak decline syndrome (Starkey et al., 2004). The development of mortality models inherently considered the functional roles and spatiotemporal scales of involved risk factors and thus could more accurately project long-term oak decline and mortality. Fan et al (2011) estimated stand hazards based on the relative proportion of different risk groups. This allows proactive managements and treatments to be prioritized by risk groups, helping mitigate and reduce the hazard of oak decline and mortality. In this way oak trees highly prone to decline could be prioritized to be salvaged prior to widespread mortality.

4.3. Risk factors associated with oak decline and mortality

Tree- and stand-level variables including tree species, crown class, and stand age are the most important predisposing determinants of oak decline and mortality (Starkey et al., 2004; Fan et al., 2011; Wang et al., 2013). In addition, site variables such as aspect, elevation and physiographic condition are indirectly related to oak decline and mortality for some sub-regions with higher mortalities found on mesic sites or sites of low elevations, or north-facing aspects. One explanation to these patterns of oak mortality by site variables was that large proportions of red oak group species occurred on some sites rather than the presumed constraints of resources (e.g., moisture, nutrients) (Kabrick et al., 2008). However, localized disturbances such as drought, wind, flood, frost, ice, and insect damage could stress resource and/or declining tree conditions and incite oak decline compared to non-disturbed forests, contributing to differentiated spatial variations of oak decline and mortality across the Ozarks (Starkey and Oak, 1989; Starkey et al., 2004; Wang et al., 2013).

Oak decline and mortality is a natural process which is largely predisposed by tree and stand characteristics even though geographic factors, natural and anthropogenic disturbances may influence this process. The local or sub-regional significance of these variables reflect the complexity of the oak decline and mortality syndrome across the Ozark Highlands, suggesting that management priorities and guidelines should be tailored by individual mortality or risk classes. For instance, fire as an integral process of oak ecosystems could be an effective tool to mitigate oak decline and mortality, especially in the moderate mortality classes risk class (Dey and Fan, 2009; Fan et al., 2012c), whereas weather (e.g., frost, drought) and insect incidences exaggerated oak decline and mortality in the high risk class (Fig. 3), likely due to the combination of the hazard of being in the high risk group which was primarily associated with tree and stand conditions and additional stresses causing further trauma. Related findings derived from this study were solely based on analyses of repeatedly measured FIA data and could be viewed as tentative guidelines for management decision making. Field experimental studies are needed regarding effects of natural and human disturbances on oak decline and mortality. A precision strike strategy combining prescribed fire and harvest treatments can be developed and prescribed for the mitigation of oak decline and mortality and to create resilient oak forest ecosystems in the Ozark Highlands.

In the meantime, there are a number of treatments that have been recommended to reduce the impacts of oak decline and may have utility.

Table 4
Estimated regression coefficients of logistic regressions to evaluate the effect of risk factors on oak decline and mortality by kernel-smoothed severity (low, moderate, high) regions of oak decline and mortality.

Variables	Estimated coefficients	Standard Error	Odds ratio	*P* value
Low mortality (983/6706; *P**= 0.139)				
Intercept	−3.229	0.224	0.040	< 0.001
BAL/Stocking	0.001	0.000	1.001	0.007
Stand age	0.007	0.002	1.007	< 0.001
Aspect				
North	Reference			
South	−0.182	0.076	0.834	0.017
Physiographic				
Mesic sites	Reference			
Xeric sites	−0.209	0.076	0.811	0.006
Crown classes				
Dominant	Reference			
Codominant	0.255	0.161	1.290	0.114
Intermediate	1.500	0.173	4.483	< 0.001
Overtopped	1.857	0.303	6.404	< 0.001
Species				
White oak (a)	Reference			
Scarlet oak (b)	1.149	0.227	3.153	< 0.001
Shingle oak (c)	1.223	0.393	3.397	0.002
Blackjack oak (d)	2.295	0.175	9.926	< 0.001
Chinkapin oak (e)	0.150	0.211	1.162	0.476
Northern red oak (f)	0.792	0.162	2.207	< 0.001
Shumard oak (g)	0.657	0.499	1.929	0.188
Post oak (h)	0.432	0.107	1.540	< 0.001
Black oak (i)	1.356	0.109	3.883	< 0.001
Southern red oak (j)	0.538	0.630	1.712	0.393
Ownership				
Public	Reference			
Private	−0.200	0.089	0.818	0.024
Moderate mortality (2431/9890; *P**= 0.100)				
Intercept	−3.043	0.163	0.048	<0.001
BAL/Stocking	0.001	0.000	1.001	0.016
Stand age	0.009	0.001	1.009	<0.001
Crown classes				
Dominant	Reference			
Codominant	0.061	0.107	1.062	0.570
Intermediate	1.065	0.118	2.902	<0.001
Overtopped	1.479	0.250	4.390	<0.001
Historical forests				
Oak closed woodland	Reference			
Oak forest	0.320	0.097	1.378	0.001
Oak open woodland	0.046	0.084	1.047	0.587
Oak savanna	0.166	0.114	1.180	0.144
Oak/pine closed woodland	0.090	0.095	1.094	0.343
Oak/pine forest	0.183	0.167	1.201	0.273
Oak/pine open woodland	0.371	0.122	1.450	0.002
None forest	0.043	0.103	1.044	0.673
Species				
White oak (a)	Reference			
Scarlet oak (b)	1.556	0.094	4.737	<0.001
Shingle oak (c)	1.514	0.342	4.544	<0.001
Blackjack oak (d)	2.409	0.134	11.122	<0.001
Chinkapin oak (e)	0.554	0.152	1.740	<0.001
Northern red oak (f)	1.070	0.121	2.916	<0.001
Shumard oak (g)	0.405	0.318	1.500	0.202
Post oak (h)	0.510	0.081	1.666	<0.001
Black oak (i)	1.551	0.072	4.715	<0.001
Southern red oak (j)	0.541	0.359	1.718	0.132
Disturbances				
No fire disturbance	Reference			
With fire disturbance	−0.144	0.066	0.866	0.029
High mortality (679/1807; *P**= 0.685)				
Intercept	−2.279	0.446	0.102	<0.001
Elevation	−0.001	0.000	0.999	0.024
Stand age	0.015	0.003	0.000	
Aspect				
North	Reference			
South	−0.268	0.114	0.765	0.019
Crown classes				
Dominant	Reference			
Codominant	−0.115	0.207	0.892	0.581

(*continued on next page*)

Table 4 (*continued*)

High mortality (679/1807; P^*= 0.685)				
Intermediate	0.414	0.235	1.513	0.078
Overtopped	1.236	0.347	3.442	<0.001
Historical forests				
Oak closed woodland	Reference			
Oak forest	0.507	0.224	1.660	0.024
Oak open woodland	0.121	0.227	1.128	0.594
Oak savanna	−0.075	0.339	0.928	0.824
Oak/pine closed woodland	0.337	0.265	1.401	0.204
Oak/pine open woodland	0.804	0.310	2.235	0.010
None forest	−0.369	0.601	0.692	0.540
Species				
White oak (a)	Reference			
Scarlet oak (b)	1.903	0.190	6.704	<0.001
Shingle oak (c)	2.197	0.996	9.002	0.027
Blackjack oak (d)	2.295	0.423	9.920	<0.001
Chinkapin oak (e)	1.832	0.374	6.248	<0.001
Northern red oak (f)	1.222	0.199	3.395	<0.001
Post oak (h)	1.063	0.180	2.896	<0.001
Black oak (i)	1.604	0.159	4.972	<0.001
Southern red oak (j)	1.481	1.249	4.398	0.236
Disturbances				
No weather disturbance	Reference			
With weather disturbance	0.364	0.118	1.439	0.002
No insect disturbance	Reference			
With insect disturbance	1.292	0.258	3.639	<0.001

P^* is the p value of the Hosmer and Lemeshow goodness of fit test

For instance, Williams and Dumroese (2013) suggested reducing drought driven mortality by changing species and selective cutting. Johnson et al. (2019) suggests thinning stands through removal of vulnerable trees in intermediate or suppressed crown classes, and removal of drought prone tree species. In central Europe forests Thomas et al. (2002) management suggestions included intensive thinning and maintaining an adequate age class distribution. In the Ozark Highlands Spetich et al. (2016) suggested favoring retention of native decline resistant white oak over red oak, the use of prescribed fire and the use of landscape-scale modeling to help identify potential hot spots for oak decline so that limited forest management funds could be utilized effectively. In a review of decline across the eastern U.S. Oak et al. (2016) suggested managing the susceptibility of stands to oak decline by changing species composition to native decline resistant species and reducing vulnerability of forests by improving overall stand vigor.

5. Conclusions

The three oak decline and mortality classes (spatial clusters) in combination with the nested oak risk groups revealed the spatiotemporal patterns of oak decline and mortality in the Ozark Highlands of Missouri. Ecoregions and historical forest types have been proven to be the major determinant of differentiated mortality patterns at large scales (landscape or ecoregion), and severe decline and high mortality incidences mostly occurred in oak forest and oak/pine open woodland in the St. Francois Knobs and Basins Subsection. In addition, disturbances such as droughts, insects, wind storms, and ice damage were found to be significant contributors of oak mortality in this area, causing more declining trees to die. Even though oak risk groups responded differently to natural disturbances, a consistent difference between risk groups was observed over different inventory cycles. These risk groups can be strategically used with other tree, stand and site variables such as stand age, tree competition status (BAL/stocking), aspect and slope for stand hazard evaluation and for prioritizing proactive silvicultural treatments.

Overall, options to control and mitigate oak decline in the Ozark Highlands include combined management prescriptions and a precision strike strategy: 1) using the risk groups of oak mortality to determine the priority groups to be managed; 2) according to the stand conditions (regeneration or fully and over stocked stands), cutting methods such as thinning, partial harvest, and clearcut could be applied to reduce the competition of overstory trees or release overstory canopy; and 3) prescribed fire could be used to complete site preparation to reduce understory fuel load and undesired vegetation, and promote regeneration and survival of oak seedlings. However, further experimental studies are needed to develop efficient management options such as the fire interval, burning season and fire intensity (Fan et al., 2012c; Kinkead et al., 2017).

Declaration of Competing Interest

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

Acknowledgement

This research was supported by the US Forest Service's National Forest Health Monitoring Program- Evaluation Monitoring through a cooperative agreement (Agreement number: 18-CS-11330134-048) between US Forest Service Southern Research Station and Auburn University. We thank the editor (Dr. María Elena Fernández) and two anonymous reviewers for their constructive comments.

References

Adamski, J.C., Petersen, J.C., Freiwald, D.A., Davis, J.V., 1995. Environmental and hydrologic setting of the Ozark plateaus study unit, Arkansas, Kansas, Missouri, and Oklahoma US Geological Survey. Water-Res. Invest. Rep. 94-4022, Little Rock, AK, p. 58.
Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.H., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S.W., Semerci, A., Cobb, N., 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manag. 259 (4), 660–684.
Althouse, A.D., 2016. Adjust for multiple comparisons? It's not that simple. Ann. Thorac. Surg. 101 (5), 1644–1645. https://doi.org/10.1016/j.athoracsur.2015.11.024.
Arellano, G., 2019. Calculation of narrower confidence intervals for tree mortality rates when we know nothing but the location of the death/survival events. Ecol. Evol. 9 (17), 9644–9653. https://doi.org/10.1002/ece3.v9.1710.1002/ece3.5495.
Balch, R.E., 1927. Dying oaks in the southern Appalachians. For Worker 3, 13.
Beal, J.A., 1926. Frost kills oaks. J. For. 24, 949–950.
Bechtold, W.A., Brown, M.J., and Tansey, J.B., 1987. Virginia's forests. US Department of Agriculture Forest Service, Southeastern Forest Experiment Station, Resource Bulletin SE-95, Asheville, NC, USA, 89 p.

Bendixsen, D.P., Hallgren, S.W., Frazier, A.E., 2015. Stress factors associated with forest decline in xeric oak forests of south-central United States. For. Ecol. Manage. 347, 40–48. https://doi.org/10.1016/j.foreco.2015.03.015.
Brasier, C.M., Scott, J.K., 1994. European oak declines and global warming: a theoretical assessment with special reference to the activity of *Phytophthora cinnamomi*. EPPO Bulletin 24 (1), 221–232. https://doi.org/10.1111/j.1365-2338.1994.tb01063.x.
Breiman, L., Friedman, J.H., Olshen, R.A., Stone, C.J. 1984. Classification and regression trees. Wadsworth and Brooks, Monterey, California.
Brown, M.J., 1993. North Carolina's forests 1990. US Department of Agriculture Forest Service, Southeastern Forest Experiment Station, Resource Bulletin SE-142, Asheville, NC, USA, 101 p.
Bruhn, J.N., Wetteroff, J.J., Mihail, J.D., Kabrick, J.M., Pickens, J.B., 2000. Distribution of *Armillaria* species in upland Ozark Mountain forests with respect to site, overstory species composition and oak decline. For. Pathol. 30 (1), 43–60. https://doi.org/10.1046/j.1439-0329.2000.00185.x.
Cleland, D.T., Freeouf, J.A., Keys, J.E., Nowacki, G.J., Carpenter, C.A., McNab, W.H., 2007. Ecological subregions: sections and subsections for the conterminous United States. General Technical Report WO-76D, 76.
Dai, Aiguo, 2011. Drought under global warming: A review. Wiley Interdiscip. Rev. Clim. Chang. 2 (1), 45–65. https://doi.org/10.1002/wcc.v2.110.1002/wcc.81.
Delatour, C., 1983. Les dépérissements de chenes en Europe (Oak die-back in Europe). Revue forestie' re franc¸aise 35 (4), 265–282.
Dey, D.C., Fan, Z., 2009. A review of fire and oak regeneration and overstory recruitment. 3rd Fire East. Oak For. Conf. 2–19.
Dwyer, J.P., Cutter, B.E., Wetteroff, J.J., 1995. A dendrochronological study of black and scarlet oak decline in the Missouri Ozarks. For. Ecol. Manage. 75, 69–75. https://doi.org/10.1016/0378-1127 (95)03537-K.
Fan, Z., Fan, X., Crosby, M.K., Moser, W.K., He, H., Spetich, M.A., Shifley, S.R., 2012a. Spatio-temporal trends of oak decline and mortality under periodic regional drought in the Ozark Highlands of Arkansas and Missouri. Forests 3, 614–631. https://doi.org/10.3390/f3030614.
Fan, Z., Fan, X., Spetich, M.A., Shifley, S.R., Moser, W.K., Jensen, R.G., Kabrick, J.M., 2011. Developing a stand hazard index for oak decline in upland oak forests of the Ozark Highlands, Missouri. North. J. Appl. For. 28, 19–26. https://doi.org/10.1093/njaf/28.1.19.
Fan, Zhaofei, Kabrick, John M, Shifley, Stephen R, 2006. Classification and regression tree based survival analysis in oak-dominated forests of Missouri's Ozark highlands. Can. J. For. Res. 36 (7), 1740–1748. https://doi.org/10.1139/x06-068.
Fan, Zhaofei, Kabrick, John M., Spetich, Martin A., Shifley, Stephen R., Jensen, Randy G., 2008. Oak mortality associated with crown dieback and oak borer attack in the Ozark Highlands. For. Ecol. Manage. 255 (7), 2297–2305. https://doi.org/10.1016/j.foreco.2007.12.041.
Fan, Z., Ma, Z., Dey, D.C., Roberts, S.D., 2012b. Response of advance reproduction of oaks and associated species to repeated prescribed fires in upland oak-hickory forests, Missouri. For. Ecol. Manage. 266, 160–169. https://doi.org/10.1016/j.foreco.2011.08.034.
Fan, Zhaofei, Tan, Yuan, Crosby, Michael K., 2012c. Factors associated with the spread of Chinese Tallow in East Texas forestlands. Open J. Ecol. 02 (03), 121–130.
Gentilesca, T., Camarero, J.J., Colangelo, M., Nolè, A., Ripullone, F., 2017. Drought-induced oak decline in the western Mediterranean region: an overview on current evidences, mechanisms and management options to improve forest resilience. iForest 10, 796–806. https://doi.org/10.3832/ifor2317-010.
Gottschalk, K.W., Wargo, P.M., 1997. Oak decline around the world. In: Fosbroke, S.L.C., Gottschalk, K.W., (Eds.) Proceedings, U.S. Department of Agriculture interagency gypsy moth research forum 1996; 1996 January 16-19; Annapolis, MD. Gen. Tech. Rep. NE-230. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: 3-13.
Greenberg, C.H., Collins, B.S., 2015. Natural Disturbances and Historic Range of Variation. Springer.
Haavik, L.J., Billings, S.A., Guldin, J.M., Stephen, F.M., 2015. Emergent insects, pathogens and drought shape changing patterns in oak decline in North America and Europe. For. Ecol. Manage. 354, 190–205. https://doi.org/10.1016/j.foreco.2015.06.019.
Haavik, L.J., Stahle, D.W., Stephen, F.M., 2011. Temporal aspects of quercus rubra decline and relationship to climate in the Ozark and Ouachita Mountains, Arkansas. Can. J. For. Res. 41 (4), 773–781. https://doi.org/10.1139/x11-018.
Habib, A., Sorensen, J.P.R., Bloomfield, J.P., Muchan, K., Newell, A.J., Butler, A.P., 2017. Temporal scaling phenomena in groundwater-floodplain systems using robust detrended fluctuation analysis. J. Hydrol. 549, 715–730. https://doi.org/10.1016/j.jhydrol.2017.04.034.
Hanberry, B.B., Jones-Farrand, D.T., Kabrick, J.M., 2014. Historical open forest ecosystems in the Missouri Ozarks: Reconstruction and restoration targets. Ecol. Restor. 32 (4), 407–416. https://doi.org/10.3368/er.32.4.407.
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 (1), 17–22.
Hilbe, J.M., 2009. Logistic Regression Models. CRC Press.
Jenks, G.F., 1967. The data model concept in statistical mapping. Int. Yearbook Cartogr. 7, 186–190.
Johnson, P.S., Shifley, S.R., Rogers, R., Dey, D.C., Kabrick, J.M., 2019. The Ecology and Silviculture of Oaks, third ed. CABI Publishing, Wallingford Oxon, UK, p. 628.
Kabrick, John M., Dey, Daniel C., Jensen, Randy G., Wallendorf, Michael, 2008. The role of environmental factors in oak decline and mortality in the Ozark Highlands. For. Ecol. Manage. 255 (5-6), 1409–1417. https://doi.org/10.1016/j.foreco.2007.10.054.
Kaplan, E.L., Meier, Paul, 1958. Nonparametric estimation from incomplete observations. J. Am. Stat. Assoc. 53 (282), 457–481.
Kinkead, C.S., Stambaugh, M.C., Kabrick, J.M., 2017. Mortality, scarring, and growth in an oak woodland following prescribed fire and commercial thinning in the Ozark Highlands. For. Ecol. Manage. 403, 12–26. https://doi.org/10.1016/j.foreco.2017.07.028.
Kremer, A., Xu, L.A., Ducousso, A., 2004. Genetics of Oaks. In: Burley, Jeffery (Ed.), Encyclopedia of Forest Sciences. Academic Press.
McNab, W.H., Cleland, D.T., Freeouf, J. a, Keys Jr., J.E., Nowacki, G.J., Carpenter, C.A., 2007. Description of "Ecological Subregions: Sections of the Conterminous United States" (First Approximation): 242. Available from https://www.treesearch.fs.fed.us/pubs/48672%0Ahttp://fsgeodata.fs.fed.us/other_resources/ecosubregions.html.
Oak, S., Tainter, F., Williams, J., Starkey, D., 1996. Oak decline risk rating for the southeastern United States. Ann. des Sci. For. 53 (2-3), 721–730. https://doi.org/10.1051/forest:19960248.
Oak, S.W., Spetich, M.A., Morin, R.S., 2016. Oak decline in central hardwood forests: frequency, spatial extent, and scale. In: Natural Disturbances and Historic Range of Variation. Springer, Cham, pp. 49–71.
Spetich, M.A., 2004. Upland oak ecology—a synthesis. In: Spetich, M.A. (Ed.), Proceedings of the Upland Oak Ecology Symposium: History, Current Conditions, and Sustainability. General Technical Report SRS-73. USDA Forest Service, Southern Research Station, Asheville, NC, pp. 3–9.
Spetich, M.A., Fan, Z., He, H.S., Wang, W.J., Crosby, M.K., Shifley, S.R., 2016. Oak Decline across the Ozark Highlands – from stand to landscape and regional scale processes. Proc. 18th Bienn. South. Silvic. Res. Conf. 1, 78–83.
Spetich, Martin A., He, Hong S., 2008. Oak decline in the Boston Mountains, Arkansas, USA: spatial and temporal patterns under two fire regimes. For. Ecol. Manage. 254 (3), 454–462. https://doi.org/10.1016/j.foreco.2007.09.087.
Starkey, D.A., Oak, S.W., 1989. Site factors and stand conditions associated with oak decline in southern upland hardwood forests. In: Rink, G., Budelsky, C.A. (Eds.), Proceedings of the Seventh Central Hardwood Conference, Gen. Tech. Rep. NC-132, Carbondale, IL, March 5–8, 1989, pp. 95–102. USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN, USA.
Starkey, D.A., Oak, S.W., Ryan, G.W., Tainter, F.H., Redmond, C., Brown, H.D., 1989. Evaluation of oak decline areas in the south. Protection Report R8 PR17. USDA Forest Service South Region, Atlanta, GA, USA, p. 36.
Starkey, D.A., Oliveria, F., Mangini, A., Mielke, M., 2004. Oak decline and red oak borer in the Interior Highlands of Arkansas and Missouri: natural phenomena, severe occurrences. In: Spetich, M.A. (Ed.), Proceedings of the Upland Oak Ecology Symposium: History, Current Conditions, and Sus- tainability. General Technical Report SRS-73. USDA Forest Service, South- ern Research Station, Asheville, NC, pp. 217–222.
Therneau, T., Atkinson, B., Ripley, B., 2013. Rpart: Recursive Partitioning. R Package Version 4.1-3. http://CRAN.R-project.org/package=rpart.
Thomas, F.M., Blank, R., Hartmann, G., 2002. Abiotic and biotic factors and their interactions as causes of oak decline in Central Europe. For. Path. 32 (2002), 277–307.
Voelker, S.L., Muzika, R., Guyette, R.P., 2008. Individual tree and stand level influences on the growth, vigor, and decline of red oaks in the Ozarks. For. Sci. 54, 8–20.
Vose, J.M., Clark, J.S., Luce, C.H., Patel-Weynand, T., 2015. Effects of drought on forests and rangelands in the United States: a comprehensive science synthesis. General Technical Report WO-93b. WO-93a (January): 302.
Wand, M.P., Jones, M.C., 1995. Kernel Smoothing. Chapman and Hall/CRC Press, Boca Raton, FL, USA.
Wang, Cuizhen, Lu, Zhenqian, Haithcoat, Timothy L., 2007. Using Landsat images to detect oak decline in the Mark Twain National Forest, Ozark Highlands. For. Ecol. Manage. 240 (1-3), 70–78. https://doi.org/10.1016/j.foreco.2006.12.007.
Wang, Wen J., He, Hong S., Spetich, Martin A., Shifley, Stephen R., Thompson III, Frank R., Fraser, Jacob S., Bond-Lamberty, Ben, 2013. Modeling the effects of harvest alternatives on mitigating oak decline in a central hardwood forest landscape. PLoS One 8 (6), e66713. https://doi.org/10.1371/journal.pone.0066713.
Williams, Mary I., Dumroese, R. Kasten, 2013. Preparing for climate change: forestry and assisted migration. Journal of Forestry 111 (4), 287–297.
Wood, Jeffrey D, Knapp, Benjamin O, Muzika, Rose-Marie, Stambaugh, Michael C, Gu, Lianhong, 2018. The importance of drought-pathogen interactions in driving oak mortality events in the Ozark border region. Environ. Res. Lett. 13 (1), 015004. https://doi.org/10.1088/1748-9326/aa94fa.