Stress factors associated with forest decline in xeric oak forests of south-central United States

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Article info
Article history:
Received 26 December 2014
Received in revised form 4 March 2015
Accepted 7 March 2015
Available online 23 March 2015

Keywords:
Cross Timbers
Stress factors
False spring
Drought

Abstract
Near total canopy mortality occurred over several tens of hectares of post oak-blackjack oak forests in the Cross Timbers of south-central United States in 2008. This event closely followed extreme drought in 2006 and a region-wide late spring frost in 2007. Oak decline could contribute to the vegetation pattern of the Cross Timbers which is characterized as a mosaic of forest, savanna and grassland. We investigated the roles played by various stress factors involved in this oak decline. The suspected long-term predisposing factors, short-term inciting factors, and contributing factors ultimately responsible for oak decline were examined after the decline using Geographic Information Systems (GIS) analysis, binary logistic regression, climate data and by direct observation of trees affected. Analysis of predisposing factors showed areas affected by oak decline tended to be close to water, on low elevation steep slopes facing northeast, east or southeast. Proximity to water possibly led to underdeveloped root systems that made trees more susceptible to drought. The extreme drought of 2006 was the fourth most severe since 1895 and may have played a role in the decline by making trees more susceptible to other stresses. A false spring in 2007 was suspected to be a major inciting factor, as its potential to cause cavitations and permanent damage to important conducting vessels in early wood could have led to significant stress for trees already weakened by drought. Three weak fungal pathogens that may have contributed to oak decline were isolated and identified: Biscogniauxia mediterranea, Botryosphaeria obtusa and Discula quercina. Global climate change projections suggest increases in intensity and frequency of extremes in precipitation and temperature events such as severe drought and late spring frost. These deviations could increase oak decline and thereby contribute to changes in the vegetation patterns in ecotones such as the Cross Timbers where there is a mosaic of forest, savanna and grassland.

1. Introduction

Sudden and unexplained near total canopy mortality was observed over several tens of hectares of xeric oak forests in east-central Oklahoma in late summer 2008. These forests are in the Cross Timbers, an ecotone between eastern deciduous forests and western grasslands, characterized as a mosaic of forest, savanna and grassland (Küchler, 1964; Therrell and Stahle, 1998). Although forest vegetation persists under precarious conditions of shallow soils and drought-prone climate, the dominant oaks form dense, old-growth stands with individual trees reaching 200–400 years (Therrell and Stahle, 1998). That oak decline has never been reported in the Cross Timbers, may reflect lack of interest in these non-commercial forests that were never heavily logged for their timber. It is possible oak decline in these forests have been a mechanism for maintaining the mosaic of forest, savanna and grassland. We conducted a study to learn the potential causes of the oak decline because it is an unstudied event in these forests that could influence the vegetation patterns and become more common due to changing climate.

Worldwide, the health and sustainability of oak forests has been threatened by oak decline (Millers et al., 1989; Starkey and Oak, 1989; Tomiczek, 1993; Gibbs and Greig, 1997) that manifests itself by the progressive decrease in tree vigor without any clear evidence of a single causal factor (Ciesla and Donaubauer, 1994). This is an extremely important problem because oak species (Quercus spp.) are dominant in most of the hardwood forests of the Northern Hemisphere (Harlow and Harrar, 1969). In the Central Hardwood Region of the United States, where mixed oak forests occupy over 50% of forested land, they are extremely...
valuable economically and ecologically (Johnson et al., 2002). Oak trees are a “keystone” to biological diversity because their mast production plays a vital role in the food webs of the forest (Feldhamer, 2002). Oak trees also play a major role in maintaining watershed integrity, as well as providing habitat for numerous wildlife species (Johnson et al., 2002). Oak decline has been recognized and studied in the southeastern United States, in relatively productive mesic forests important for commercial exploitation (Law and Gott, 1987; Kabrick et al., 2004; Heitzman et al., 2007; Haavik et al., 2012).

The complex interactions believed to be responsible for oak decline have been organized as predisposing, inciting, and contributing factors (Sinclair, 1965; Manion, 1991; Houston, 1992; Mueller-Dombois, 1992; Ciesla and Donaubauer, 1994). Predisposing factors are long-term and slow changing site factors such as soil type, slope, aspect and climate. These factors may inhibit the tree’s natural ability to withstand and respond to injury-inducing agents. Inciting factors are usually of short duration and can be either physical or biological in nature; examples are defoliating insects, drought, hail and frost. These factors can produce dieback that will cease when the stress ends, and the tree will recover. However, if sufficiently severe, prolonged or repeated in successive seasons, inciting factors can eventually cause tree death. Contributing factors can further weaken and ultimately kill the trees. Examples of these factors are boring insects, bark beetles and pathogenic fungi.

We conducted a study to determine the role of predisposing, inciting, and contributing factors in oak decline in xeric oak forests in south-central United States. Although it is not known whether the stands with nearly total overstory mortality will remain open, forest decline in patches may contribute to the mosaic pattern of forest, savanna and grassland found in this ectone. The overall goals were: (1) to improve understanding of the role of predisposing, inciting, and contributing stress factors in oak decline. (2) to improve ecological understanding of vegetation distribution in an ectone, and (3) to provide managers improved knowledge to better understand, anticipate and respond to oak decline. Global climate change is projected to result in greater variability, intensity and extremes of temperature and precipitation such as late frosts and droughts. A change in the occurrence of oak decline could have major consequences for vegetation patterns.

2. Methods

2.1. Study area

Okmulgee Game Management Area (OGMA), located in Okmulgee County in eastern Oklahoma, was affected by oak decline in 2008. Of the 3700 hectares in OGMA, approximately 3.5% experienced nearly complete canopy mortality (Fig. 1). OGMA is a portion of the Okmulgee Wildlife Management Area and is managed by the Oklahoma Department of Wildlife Conservation. It is approximately 95% wooded with post oak (Quercus stellata, 77%), Blackjack oak (Q. marilandica, 9%) and black hickory (Carya texana, 8%) dominating the canopy (Karki, 2007).

OGMA has a subtropical climate with a mean annual temperature of 16 °C, and mean daily high of 34 °C in August and mean daily low of −2 °C in January. The area receives an average annual precipitation of 1040 mm, although there is substantial interannual variation (OCS, 2014). OGMA contains 13 different soil types but is dominated by Hector–Endsaw soil complex (HtE), which covers approximately 75% of the OGMA. The taxonomic class for Hector series is loamy, siliceous, subactive, thermic Lithic Dystrudepts and for Endsaw series it is fine, mixed, active, thermic Oxyaquic Hapludalfs. HtE is characterized as well drained, non-arable, shallow, stony fine sandy loam with bedrock at a depth of about 30 cm. It has a hill or mountain topography of 5–30% slopes (Sparwasser et al., 1968).

2.2. Predisposing factors

Six predisposing site factors were selected for analysis: slope, aspect, soil type, elevation, terrain form (concave or convex) and distance to water. Interaction variables between these factors were also analyzed using dummy variables. Satellite images for the entire OGMA were obtained from Google Earth (Google, 2010), and the decline area was digitized. A digital elevation model (DEM) for OGMA was obtained from the United States Geological Survey’s National Elevation Dataset with a 3-meter resolution for elevation and 1/3 arcescond (Gesch, 2007). Slope, aspect, terrain form and hydrology were calculated from this DEM using the Spatial Analyst extension in ArcGIS 10.1 (ESRI, 2011). Slope was measured as percent rise. Aspect was converted to cardinal (north, east, south, west) and intercardinal (northeast, southeast, southwest, northwest) directions for analysis. Using the DEM-derived hydrology raster, Euclidean distance was measured to obtain a continuous raster showing distance from the nearest water source for all randomly generated points in the study area. Elevation was centered by subtracting the minimum elevation found in the OGMA. A soil map obtained from the web soil survey was provided by the USDA (Soil Survey, 2013). The coordinate system used was GCS North American 1983, and the projection system used was NAD 1983 UTM Zone 15 N.

These predisposing factors were analyzed using binary logistic regression in SPSS 21.1 with enter selection of predictors (IBM Corp., 2012). Significance was determined using $p = 0.05$ as a cutoff. Binary logistic regression enabled us to model oak decline outcome where the dependent variable takes the value 1 if oak decline occurred and 0 otherwise. The dependent variable, or outcome, of this model is driven by the independent variables or predisposing factors that are suspected of influencing oak decline. The coefficients of a logit model are not directly compared to each other as a measure of relative importance to explain probability. Instead, the odds ratio is analyzed to determine probability. The exponent of a coefficient is the odds ratio; therefore the probability of oak decline can be determined through Eq. (1):

$$
Pr(Y = 1|X_1, X_2, \ldots X_n) = \frac{1}{1 + e^{-(b_0 + b_1 X_1 + b_2 X_2 + \ldots + b_n X_n)}}
$$

where $Y$ is the dependent variable (oak decline), $X_1, X_2, \ldots X_n$ are the explanatory variables (i.e., predisposing site variables), and $b_0, b_1, \ldots b_n$ are the model coefficients. The logit model requires input cases for both categories of the dependent variable (0 and 1). The input cases were created by randomly locating 53,435 points throughout OGMA with the constraint that points were at least 10 m apart. Of these randomly generated points, 3.5% (1888) were located in areas affected by oak decline and were assigned the binary value 1, the remaining 51,547 points were located in areas not affected by oak decline and were assigned the value 0. All six predisposing factors were extracted from the datasets to these randomly located points as the explanatory variables for logit analysis. Using the odds ratios for the predisposing factors from the model, the probability of oak decline was predicted and mapped for the entire OGMA in ArcGIS using map algebra. A predictive model has been used in the Cross Timbers previously (Therrell and Stahle, 1998); however this model was used to locate ancient forests and a model has never been used to predict areas susceptible to oak decline. Additionally, using data from the extracted points, we also analyzed the percent land coverage of categories of predisposing
factors. This analysis allowed us to compare the relative proportions of the predisposing factors in total OGMA to decline areas.

2.3. Inciting factors

Drought and late spring frosts are widely recognized as being associated with oak decline (Thomas et al., 2002). Anecdotal and published reports indicated a severe drought in Oklahoma in 2006 and a widespread late spring frost in 2007 (Gu et al., 2008). We sought to quantify the severity of these events in the area of oak decline in the OGMA and determine whether other unusual temperature and precipitation events occurred close to the time of the oak decline that was first observed in 2008. We used the annual Palmer Drought Severity Index (PDSI) as the measure of drought for the period 1895–2012 (Palmer, 1965). A PDSI value of 0 indicates normal condition while positive values mean wet conditions and negative values mean drought conditions. PDSI data were retrieved from the National Climatic Data Center (NOAA NCDC, 2013) for the east central climate division of Oklahoma.

Late spring frost events before the 2008 decline were characterized by obtaining daily temperature data for the period 1998–2012 from the Oklahoma Mesonet (OCS, 2014) for the Okmulgee station (OKMU) located 14 km southeast of the research site. We used the minimum criteria for a false spring proposed by Stahle (1990) to characterize a damaging late frost. The criteria were twofold: (1) a frost event $\leq -5.0 ^\circ C$ occurring after March 21, and (2) a preceding 10-day warm period, beginning 13 days before the frost with an average daily minimum temperature $\geq 4.4 ^\circ C$, and with no daily minimum temperature $< -2.8 ^\circ C$. These criteria were developed from observations of thousands of oak tree rings in south-central United States and climate data over a nearly 100-year period. They are the minimum temperature excursions associated with traumatic anatomical effects in tree rings including crushed xylem vessels, disrupted ray cells, and abnormal parenchyma cells. The combination of a warm period during which plants commenced spring growth followed by a severe frost had
the potential to cause severe damage to recently produced xylem cells.

2.4. Contributing factors

Decline stands were assessed in mid-Summer of 2008 for the presence of disease pathogens and insect damage. Five samples of symptomatic twigs and branches were collected from declining trees in two different decline stands and processed by the Plant Disease and Insect Diagnostic Laboratory, Oklahoma State University (Damon Smith, personal communication, 10/6/2008). Samples were examined microscopically to reveal areas that appeared abnormal. Ten to twelve small sections of plant tissue (generally 0.5–0.7 cm circular or square pieces) were removed from each field sample with a razor blade, disinfested in 10% bleach for 30 s, and placed on general media for plant pathogen identification.

After 3–5 days, dishes were examined and fungal isolates were transferred to new media. Isolates were examined and transferred to media several times to ensure colony purity. Isolates that were suspected to be plant pathogens were further examined microscopically to confirm the stacks were pure colonies. Then a representative from each group was selected for DNA sequence analysis. The primers were based on the internal transcribed spacer region of RNA. DNA was extracted from the cultures using Qiagen DNeasy Plant Tissue Kit. Isolated DNA was amplified using PCR and sent to the Recombinant DNA/Protein Core Facility at Oklahoma State University for DNA sequencing. Sequences were compared with known sequences for plant pathogen identification (Jen Olson, personal communication, 02/5/15).

Assessment of insect damage was limited to observations made during the collection of twigs and branches for testing for disease pathogens. A visual assessment was made for evidence of insect damage such as exit holes in the bark and defoliation. We did not systematically collect samples of bark and phloem.

3. Results

3.1. Predisposing factors

Distance to water was strongly inversely related to the occurrence of oak decline (Figs. 1 and 2a). The distance to water for a point affected by oak decline averaged 165 m and had a maximum of 617 m. This is significantly lower than points in non-decline areas, with an average of 385 m, and a maximum of 1051 m. Slope was shown to be higher (15%) for decline points compared to non-decline points (9%, Fig. 2b). Elevation was significantly different in decline areas (Fig. 2c). Average elevation was higher for non-decline points (236 m), than decline points (221 m). Aspect in the OGMA was approximately evenly distributed among all cardinal and intercardinal directions: 12.5 ± 0.37% (Fig. 2d). However, areas affected by oak decline were dominated by northeast (18.7%), east (27.9%) and southeast (14.5%) facing slopes.

The Wald test results from the logistic regression model showed that distance to water \((p < 0.001)\), slope \((p < 0.001)\), elevation \((p = 0.019)\) and aspect \((p < 0.001)\) were all significant.

![Fig. 2. Frequency distribution in terms of percentage of 53,435 randomly located points throughout Okmulgee Game Management Area (OGMA) and in decline areas for predisposing factors distance to water, slope, elevation and aspect. OGMA represents the entire management area including decline and non-decline stands.](image-url)
predictors of oak decline. Terrain form \((p = 0.117)\) and soil types \((p = 0.213)\) were not significant predictors of oak decline. There were significant interactions between slope and aspect \((p < 0.001)\), elevation and slope \((p < 0.001)\), distance to water and elevation \((p < 0.001)\) and distance to water and slope \((p = 0.007)\). However, these interaction terms did not improve the fit of our model. The logistic regression equation was able to relatively accurately predict areas that were at risk or predisposed to oak decline (Fig. 3). The model predictions were correct 96.4% of the time. However the model only predicted decline correctly with a surety 0.4% of the time. In logistic regression, there is no true \(R^2\) value as there is in ordinary least squares regression. Instead, goodness-of-fit can be measured using the chi square difference between the null model and the model containing the predictor variables. The Hosmer and Lemeshow Goodness of Fit Chi Square test suggested that the model was not a perfect fit for the data \((p < 0.001)\). However, this was likely due to the large number of samples and the relatively small amount of decline areas (3.5%). The Nagelkerke \(R^2\), a pseudo-\(R^2\) value, indicated a much improved fit of 0.216 though. Based on the ultimate goal of creating a prediction surface using the individual coefficients, we found the statistical significance of the predictor variables (distance to water, slope, elevation, and aspect) from the Wald test, to support the use of the model for this task. The regression equation for this binary logistic regression was:

\[
\ln \left( \frac{P}{1-P} \right) = 0.060(Slope) - 0.003(Elevation) + 0.840(East) - 0.876(North) + 0.649(Northeast) - 0.971(Northwest) + 0.285(South) + 0.424(Southeast) - 0.006(Distance to water) - 2.008
\]

\( (2) \)

3.2. Inciting factors

Mean annual PDSI for 2006 was \(-3.06\) (Fig. 4), the fourth lowest PDSI during the period 1895–2012. Only 1911 \((-4.68)\), 1936 \((-3.30)\) and 1956 \((-4.11)\) droughts were more severe. The weather was relatively wet in 2007–2008 and dry in 2011–2012.

![Fig. 3. Map of binary logistic regression prediction. Image was predicted using only predisposing factors (aspect, slope, elevation and distance to water). Black outline indicates areas affected by oak decline in 2008.](image-url)
A false spring occurred in OGMA in March 2007. It was the second-warmest March on record, approximately \(\frac{8}{176}^\circ C\) above normal (OCS, 2014). Starting March 19th (DOY 78), the daily minimum temperature greatly increased to between 13 and 18 \(\frac{176}{176}^\circ C\) for the remainder of the month (Fig. 5). There was a 10-day warm period (DOY 85–94) beginning 13 days before the freeze. The daily minimum temperature for this period was 12.6 \(\frac{176}{176}^\circ C\). Daily minimum temperature plunged starting April 4th (DOY 94). April 7–8th (DOY 97–98) had daily minimum temperatures below freezing, with April 8th registering \(-5.0\) \(\frac{176}{176}^\circ C\). This qualified as a false spring event according to Stahle (1990).

3.3. Contributing factors

Three different “dieback” plant pathogens were isolated and identified from decline trees. The most common fungal pathogen was \textit{Botryosphaeria obtusa}, which was found on nine trees. \textit{Biscogniauxia mediterranea} was found on six trees and \textit{Discula quercina} was found on three trees. At least one fungal species was found on each tree. All of these pathogens were considered opportunistic and weak in their ability to cause disease. They are commonly found in forests. There were no obvious indicators of insect damage such as exit holes in the bark or defoliation.

4. Discussion

We found the oak decline occurrence in OGMA in 2008 was likely associated with a complex of stress factors (Fig. 6). Although it may have been impossible to conclusively determine the causes of oak decline, we were able to identify several stress factors that were strongly correlated with decline. The strong inverse relation of decline occurrence to distance from water could be due to trees being predisposed to stress because moist soils prevented them from producing sufficient root systems to withstand severe drought. A severe drought and false spring were strong inciting factors, and the close timing of their occurrences just before the decline may have resulted in a synergistic effect. Plant pathogens, \textit{Biscogniauxia mediterranea}, \textit{Botryosphaeria obtusa} and \textit{Discula quercina}, were found in the decline stands suggesting they may have been the final contributing factors.

4.1. Predisposing factors

That the distance to water was inversely related to occurrence of decline seemed counter-intuitive because the closer to a water source, the more access a tree might have to water, especially during a drought. The optimal partitioning theory may provide a basis for an explanation for this seemingly illogical finding. This theory states that plants preferentially allocate biomass to the organ (root, stem, or leaves) that acquires the most limiting resource (Thornley, 1972; McCarthy and Enquist, 2007). Oak trees have been shown to have approximately 28% biomass belowground in mesic sites and 58% belowground in xeric sites (Canadell et al., 1999). Therefore, trees growing close to water would allocate less carbon to roots and more to stems and leaves than trees far from water and they would be more susceptible to occasional extreme drought stress (Tainter et al., 1983). Another potential explanation for the strong correlation between distance to water and tree death was a water-borne pathogen such as \textit{Phytophthora} which was identified as a major stress factor contributing to oak decline in other studies (Jonsson, 2004; Jung et al., 2000). We did not collect roots to test for the presence of \textit{Phytophthora}.

The finding that steep northeast, east and southeast slopes were prone to decline contradicted earlier studies in the southern U.S. that found that decline did not differ by slope or aspect (Starkey and Oak, 1989; Kabrick et al., 2008). Slope and aspect may have a stronger impact on site conditions in the drought prone forests.
of Oklahoma than the more mesic forests of these earlier studies. The lack of soil influence on oak decline may stem from the overwhelming dominance of one soil type; approximately 75% of OGMA was Hector–Endsaw complex.

The Hosmer and Lemeshow Goodness of Fit test suggested that our model was not a perfect fit for our data. This measurement is sensitive to sample size and in a large sample size, such as ours, few parsimonious models would fit. However, the Nagelkerke pseudo-$R^2$ (0.216) suggested that there is a correlation between our model and oak decline. Although the map generated from the binary logistic regression was able to accurately predict areas that were at risk or predisposed to oak decline, we found that the model did not predict decline areas with a high enough frequency. This suggests that the predisposing factors alone were not sufficient stress factors to cause decline, therefore other factors most likely contributed to the decline.

4.2. Inciting factors

The severe drought in 2006 and false spring in 2007 were likely inciting factors for oak decline that manifested itself in 2008. That the false spring came soon after the drought may have led to a very lethal synergistic effect (Thomas and Ahlers, 1999). Drought is often considered to be the most influential inciting factor in oak decline (Law and Gott, 1987; Starkey et al., 1989; Stringer et al., 1989; Tainter et al., 1983). Although drought is a common stress in south-central North America and oak species that dominate the canopy have developed both morphological and physiological adaptations (Kozlowski, 1975; Johnson et al., 2002; Thomas et al., 2002), severe droughts that occur approximately every 20 years are known to cause mortality in forest stands (Albertson, 1940; Albertson and Weaver, 1945; Rice and Penfound, 1959; Johnson and Risser, 1975). Upland oak forests sustained substantial mortality in the droughts of the 1930s and 1950s (Rice and Penfound, 1959; DeSantis et al., 2011). Although the 2006 drought may not have been as severe as these earlier droughts, it may have been lethal enough to kill or weaken trees growing near water with underdeveloped root systems.

Oklahoma experienced the warmest March on record in 2007 followed by severe cold in early April (NOAA/USDA, 2008). There were strong indications this false spring had the potential to damage trees through the combination of extended warm temperatures that caused spring growth to commence early followed by damaging cold temperatures. The event had widespread effects throughout the Southeast, U.S. (Gu et al., 2008). In Oklahoma it caused complete loss of the pecan crop, 60% loss of the grape harvest and significant losses to the wheat crop (NOAA/USDA, 2008).

We believe damage to newly formed xylem and leaves of forest trees caused by the false spring event could have been significant enough to lead to widespread decline especially following closely a severe drought. The event met the criteria for formation of a frost ring with crushed xylem cells, disrupted rays, and abnormal parenchyma cells (Stahle, 1990). Although we did not sample trees for anatomical growth abnormalities, damage to xylem was likely because the weather criteria for a false spring were developed from observations of hundreds of tree rings and 100 years of weather data for the region of the study. Obviously many trees survive effects of a false spring and we believe the effects could be catastrophic for others. Analysis of predisposing factors showed oak decline mainly at lower elevations, on steep slopes and near water where cold air drainage may have exacerbated the effects of the late freeze. Large earlywood vessels form before leaf expansion and are the major conduit for water transport to the new leaves, very little water is conducted in the vessels of earlier annual rings because they are gas filled (Zimmerman and Brown, 1971; Sperry et al., 1994). When water in the vessels freeze, the air comes out of the solution and if the xylem tension is more than a small critical value, the bubbles will continue to expand and this expansion fully embolized the conduit and therefore makes it dysfunctional (Tyree and Cochard, 1996). The low temperatures in 2007 may have caused water to freeze in remaining conducting vessels leading to further embolisms and blockage of water transport (Sperry et al., 1994; Thomas et al., 2002). Thus embolism of older vessels and damage to developing large earlywood vessels (Woodcock, 1989) may have severely impaired water transport weakening the tree’s capacity to survive further stress.

Trees with damaged xylem faced further stress from loss of new foliage killed by the severe frost. Widespread foliage damage evident in the local forests reduced energy acquisition and storage and would have had impacts on current growth and buds for next year. Damage to the xylem and foliage would have had a cascading effect pushing trees closer to death (Augsburger, 2011). Studies in central Europe suggested spring frost contributed to oak decline and also suggested drought occurrences before frost events made trees even more susceptible to freezing damage (Thomas et al., 2002; Thomas and Ahlers, 1999). Although the relation between frost damage and oak decline has not been well explored in North America, research there has shown false springs can affect tree health (Augsburger, 2011) and that the effects differ by tree species (Hufkens et al., 2012). False springs can be very widespread, sometimes covering the entire southeastern North America (Gu et al., 2008). They can be rather common, occurring nearly every five years from 1650 to 1980 in south-central North America (Stahle, 1990). Given studies have suggested occurrence of frost after leaf-out is projected to become more common due to climate change (Cannell and Smith, 1986; Meehl et al., 2000; Gu et al., 2008).

4.3. Contributing factors

All three disease causing pathogens found in this study were for the most part considered to be opportunistic. *Biscogniauxia mediterranea* causes Hypoxylon dieback of oak. Although considered a weak parasite sometimes existing as an endophyte and causing no disease, it may cause the death of trees suffering from severe drought stress (Nugent et al., 2005; Desprez-Loustau et al., 2006; Capretti and Battisti, 2007; Linaldeddu et al., 2011). This pathogen is in the same genus as *Biscogniauxia atropunctata*, the causal agent of Hypoxylon canker in Oklahoma (Olson, 2013). Hypoxylon has been associated with oak decline in other regions (Haack and Blank, 1991). *Botryosphaeria obtusa* causes black rot most often reported on apple tree cultivars (Briggs and Miller, 2004). While not commonly associated with oak, this fungus can be a common inhabitant of many woody plants. It colonizes the bark and lives as a saprobe unless the tree is predisposed by environmental stress or wounds, at which time it can become pathogenic (van Niekerk et al., 2006). Severe leaf spotting can result in defoliation, which weakens the tree, and limb cankers can girdle and eventually kill entire branches (Linaldeddu et al., 2006). *Discula querina* causes the foliar disease oak anthracnose (Scharl et al., 2004). The fruiting bodies, however, are found on young wood and bark. Twig dieback has been associated with this fungus on oaks in California and Oregon. This fungus frequently occurs on the leaves and twigs of declining oaks. Some fungal endophytes spend all, or nearly all, of their lifetime in the host plant with only limited or no pathogenic effect (Scharl et al., 2004). However the fungus can switch to active growth when the plant is subjected to stress (Carroll, 1986; Moricca and Ragazzi, 2008). Possibly due to the stress of predisposing factors and inciting factors, these fungi appeared to play at least a contributing role in the decline complex. However, the presence of fungus could not be directly linked to tree mortality because these fungi are
commonly found in healthy forests as well (Linaldeddu et al., 2006, 2011; Schardl et al., 2004).

The findings concerning contributing factors were limited by the small sample size. A more thorough assessment of contributing factors including larger sample size and more systematic sampling would have produced more conclusive results about the role of fungal pathogens and insects.

5. Conclusion

Oak decline in 2008 at Okmulgee Game Management Area was explained by a complex of stress factors including, but not limited to: distance to water, slope, elevation, aspect, drought, false spring and three plant pathogens. Because secondary succession in decline stands is not entirely understood in xeric oak forest, the future of the decline areas is not known. Studies have suggested that oak decline favors oak regeneration (Sander et al., 1984) or future of the decline areas is not known. Studies have suggested that oak decline favors oak regeneration (Sander et al., 1984) or an increase in importance of non-oak species (Heitzman, 2003). Frequent fire could keep them open indefinitely and they would become savannas or grassland. With fire suppression they may return to forest in several decades. Climate change may increase the frequency and intensity of drought and false springs leading to increased occurrences of oak decline in ecolonal forests. These changes in species composition and vegetation patterns could have lasting ecological effects on the affected region. Seemingly rare regional-scale disturbance events, such as drought or late spring frosts, have been shown to substantially alter the trajectory and future of old-growth forests for decades or centuries to come (Pederson et al., 2014). Therefore, understanding the causes of near total canopy mortality may lead to a better understanding of the full ecological consequences of oak decline.

Acknowledgements

This study was funded by the Department of Natural Resource Ecology and Management at Oklahoma State University. We would like to thank the Oklahoma Department of Wildlife Conservation for access to the Okmulgee Game Management Area. In addition, we are grateful to Damon Smith, former Oklahoma State University pathologist, and Jen Olson for their work in isolating and identifying plant pathogens in the affected areas.

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