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Oak mortality risk factors and mortality estimation

Stephen R. Shifley [a,*], Zhaofei Fan [b,1], John M. Kabrick [a], Randy G. Jensen [c,2]

[a] USDA Forest Service, North Central Research Station, 202 ANBR Building, University of Missouri, Columbia, MO 65211-7260, USA
[b] School of Natural Resources, University of Missouri, 203 ABNR Building, Columbia, MO 65211-7280, USA
[c] Missouri Department of Conservation, Route 2 Box 198, Ellington, MO 63638, USA

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Abstract

Managers are often concerned about oak mortality in maturing mixed-oak forests, but they often lack explicit information about mortality risk for oaks that differ in species, size, crown class, competitive status, and growth rate. In eastern North America, tree species in the red oak group (*Quercus* Section *Lobatae*) are typically shorter lived than those in the white oak group (Section *Quercus*), and red oak group mortality can be greatly exacerbated during episodes of oak decline. We analyzed factors associated with red oak group mortality for two large data sets from the Ozark Highlands and identified groups of trees that differed significantly in mortality risk. One data set was from a large, upland Ozark forest with more than four decades of uneven-aged management, and the other was representative of relatively undisturbed upland oak forests in the same ecoregion. Neither location experienced significant episodes of oak decline during the period of observation, and our results represent endemic mortality for mature (sawtimber size) forests in the region. We found that mortality rates for trees in the red oak group were four to six times greater than mortality rates for associated trees in the white oak group. We also found that red oak group mortality was significantly related to tree crown class, tree diameter, and basal area of larger competitors. When recent tree dbh growth was known, it significantly increased the ability to predict future mortality for some classes of trees. Annual mortality rates for different classes of trees in the red oak group ranged from 0.4 to 10.7%. Classes of trees in the red oak group that were most likely to die (in rank) were as follows: trees with dbh growth <0.2 cm per year; suppressed trees; trees with intermediate crown class and basal area of larger competitors >14 m^2/ha; dominant and codominant trees >25 cm dbh with basal area of larger competitors <14 m^2/ha; trees with intermediate crown class and basal area of larger competitors <14 m^2/ha; dominant and codominant trees >25 cm dbh with basal area of larger competitors <15 m^2/ha; dominant and codominant trees <25 cm dbh with basal area of larger competitors >15 m^2/ha; dominant and codominant trees <25 cm dbh with basal area of larger competitors <15 m^2/ha; and trees with annual dbh growth greater than 0.6 cm (assuming recent dbh growth is known). This information can be used when preparing silvicultural prescriptions and/or forest management plans to identify and treat classes of trees that are at high risk of mortality.
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Keywords: Mortality model; CART; Oak decline; Ozark

1. Introduction

In the Ozark Highlands of southeast Missouri and northern Arkansas there is considerable concern about oak mortality related to oak decline (Heitzman et al., 2004; Spetich, 2004). Red oak group species (*Quercus* Section *Lobatae*) appear to be particularly susceptible, especially those that are large or physiologically mature and growing on droughty sites (Law and Gott, 1987; Starkey and Oak, 1989; Johnson et al., 2002; Lawrence et al., 2002; Kabrick et al., 2004). The decline complex results from the interrelationships among predisposing factors (e.g., physiological tree age, species composition, and soil characteristics), inciting factors (e.g., drought or defoliation), and biotic agents (e.g., Armillaria root disease or insect pests) (Bruhn et al., 2000; Oak et al., 2004). The red oak borer (*Enaphalodes rufulus* (Haldeman) Coleoptera: Cerambycidae) has been particularly prevalent during recent episodes of oak decline in the Ozark Highlands (Muzika and Guyette, 2004).

Forests of the Ozark Highland ecoregion (Ecological Section 222A) (Keys et al., 1995) are increasingly susceptible to oak decline (Lawrence et al., 2002). This is due in large part to the prevalence of predisposing factors, including a great abundance of mature scarlet, black, and northern red oaks on

* Corresponding author. Tel.: +1 573 875 5341x232; fax: +1 573 882 1977.
E-mail addresses: sshifley@fs.fed.us (S.R. Shifley), fanzha@missouri.edu (Z. Fan), jkabrick@fs.fed.us (J.M. Kabrick), Randy.Jensen@mdc.mo.gov (R.G. Jensen).
[1] Tel.: +1 573 875 5341x230; fax: +1 573 882 1977.
[2] Tel.: +1 573 663 7130.

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Table 1
Volume of timber by species in the Ozark Highlands Section of Missouri (MO) and Arkansas (AR) (Ecological Section 222a) (Bailey et al., 1994; Keys et al., 1995)

Species	Total volume in Ozark Highland Section (million m^3)	Proportion of volume in the Ozark Highland Section (%)	Proportion of all MO and AR volume that occurs in the Ozark Highland Section (%)
White oak (*Quercus alba* L.)	96	22	59
Black oak (*Q. velutina* Lam.)	85	19	83
Post oak (*Q. stellata* Wangenh.)	56	13	67
Northern red oak (*Q. rubra* L.)	27	6	54
Shortleaf pine (*Pinus echinata* Mill.)	27	6	20
Scarlet oak (*Q. coccinea* Muenchh.)	16	4	98
Eastern redcedar (*Juniperus virginiana* L.)	16	3	72
Black hickory (*Carya texana* Buckl.)	15	3	56
105 other species combined	107	24	19
All species	443	100	38

Note: Species are listed from greatest to least total volume; individual species in the composite group each comprised less than 3% of total volume. Black, northern red, scarlet, white, and post oaks in combination comprise 64% of the volume in this ecological section. This ecological section contains more than half (range 54–98%) of the total volume of these four species found in all of Missouri and Arkansas.

droughty sites (Table 1). Approximately 98% of all scarlet oak volume, 83% of all black oak volume, and 54% of all northern red oak volume found in Missouri and Arkansas occur in the Ozark Highlands. Consequently, large increases in oak mortality could have a devastating impact on forest composition, timber value, fire risk, aesthetics, and habitat quality in the Ozark Highlands.

As these Ozark oak forests age, the normal course of events is for the scarlet, black, and northern red oaks to reach their longevity and die. Inciting factors include episodic droughts, scattered in time and location, that contribute to accelerated episodes of scarlet, black, and northern red oak mortality which we recognize as oak decline. These episodes appear to be exacerbated on droughty sites that are marginal for oak growth. As a result, the longer-lived white and post oaks increase in dominance.

Oak decline is a periodic event. Millers et al. (1989) found more than 50 previously reported episodes of oak decline in the eastern United States. Most were in some way related to drought, and Millers noted that oak mortality events tended to repeat in the same areas. Recent oak mortality rates at some locations in the Ozark Highlands are significantly higher than normal (Starkey et al., 2004; USDA Forest Service, 2006), but they are not affecting the entire Ozark highlands. It is unknown how much they differ from typical mortality rates for trees of comparable size and species. A number of analytical and modeling techniques can be used with contemporary and historical inventory data to identify the factors most closely associated with oak mortality and to identify mortality risk for upland oak stands that are not presently experiencing oak decline. Classification and regression tree analysis or CART (Breiman et al., 1984) has been shown to be particularly useful for identifying variables and associated threshold values that indicate a high probability of oak mortality (Kabrick et al., 2004).

In general, trees in the red oak group have lower survival rates and shorter longevity than those in the white oak group (Shifley and Smith, 1982; Burns and Honkala, 1990), although there is substantial variation within those groups. Recent research on oak mortality from the Missouri Ozark Forest Ecosystem Project (MOFEP) (Brookshire and Shifley, 1997; Shifley and Brookshire, 2000; Shifley and Kabrick, 2002) has demonstrated that for the period from 1991 to 2002 tree species, crown class, and diameter are significant indicators of the probability of oak mortality. Red oak species (black, scarlet, and northern red oaks) in the intermediate and overtopped crown classes had mortality rates that ranged from roughly 35 to 55% per decade (Kabrick et al., 2004). Thus, managers often disregard those mortality-prone trees in lower crown classes and focus attention on the dominant and codominant trees of red oak species that are: (a) large in size, (b) valuable for timber and wildlife, (c) often a large portion of a stand's total stocking, and (d) at high risk of mortality relative to common associates such as white and post oak.

The recent diameter growth rate of individual oak trees (e.g., over the previous 1–10 years) may be a particularly useful indicator of future mortality rates. This is a logical relationship and consistent with some previously published models of tree survival (e.g., Monserud, 1976; Buchman et al., 1983; Wyckoff and Clark, 2002). Analyses based on a variety of data sources should be able to identify threshold diameter growth rates that, in conjunction with other tree, plot, and/or climate variables, are indicative of high rates of future oak mortality. Diameter growth rates integrate the impacts of multiple predisposing or inciting factors such as site quality, Armillaria root disease, drought, or insects which are difficult to quantify in a standardized way.

In this paper, we analyze oak mortality rates for two large data sets—one representing a relatively undisturbed forest and the other representing a forest that has been managed by uneven-aged silviculture for the past 50 years (Loewenstein et al., 1995). We explore the principal factors associated with oak mortality, the strength of the relationships, and the interactions among variables. We present statistical models that distinguish categories of oaks that have comparatively high mortality rates from those that have low mortality rates. We use that information to create guidelines that can help managers decide: (a) which inventory variables, if collected, are the best predictors of tree survival and (b) which trees are good candidates for removal or retention when implementing silvicultural practices. The same models can be coupled with large-scale inventory data to identify trees, stands, or geographic regions where high levels of future oak mortality are of particular concern.

2. Methods

2.1. Study sites and data

Data on tree survival came from two sources (Table 2). Both sources are predominantly mature forest (sawtimber size class), and trees in the red oak group are reaching physiological maturity. During the observation period (1991–2002), neither set of data included sites with severe or widespread oak decline, but oak decline occurred on more than 100,000 acres elsewhere in the region (Lawrence et al., 2002).

Data from both sources include tree species, diameter, crown characteristics, and measures of density per hectare (e.g., basal area, number of trees, and stocking) that can be calculated by aggregating tree characteristics. Plots with three or more periodic measurements provided the opportunity to observe how a tree's recent diameter growth rate (observed during the first remeasurement interval) was related to tree mortality (observed during subsequent remeasurement intervals). For analysis trees were grouped into a red oak group (primarily scarlet and black oak with some northern red oak) and a white oak group (white and post oak).

2.2. MOFEP 1991–2002

The Missouri Ozark Forest Ecosystem Project is a replicated long-term, landscape-scale study of the effects of harvest treatments on a suite of ecosystem characteristics (Brookshire and Shifley, 1997; Shifley and Kabrick, 2002). Baseline data include six hundred and forty-eight 0.2-ha inventory plots that have been measured four times since 1991 (Shifley and Brookshire, 2000). Approximately 30% of plots were affected by harvest treatments in 1996, but those plots were excluded from this analysis. The remaining 456 plots were measured four times: 1991, 1995, 1998, and 2002. In general, the MOFEP plots used in

Table 2
Characteristics of study data

Characteristic	MOFEP	Pioneer Forest
Location	Carter, Reynolds, and Shannon Counties in Missouri	Carter, Dent, Reynolds, Ripley, Shannon, and Texas Counties in Missouri
Disturbance	Plots with no recent harvest disturbance	Uneven-aged management has been applied for more than 40 years
Number of plots	456 with no harvest	475
Plot type	Fixed circular 0.2 ha	Fixed circular 0.08 ha
Minimum tree diameter	11 cm	13 cm
Dates of measurement	1991, 1995, 1998, 2002	1992, 1997, 2002
Management treatment	No harvest during the remeasurement period and minimal disturbance in the 20 years prior to initial measurement	A combination of uneven-aged management with individual-tree and group selection practiced for 40 years prior to initial measurement
Additional description	Brookshire and Shifley (1997), Shifley and Brookshire (2000), Shifley and Kabrick (2002)	Loewenstein et al. (1995), Loewenstein (1996), Trammel (1996)
Variables measured	Tree species, dbh, disposition (live dead, cut), crown class, plot-level estimates of density and stocking, prior dbh increment	Tree species, dbh, disposition (live dead, cut), crown class, plot-level estimates of density and stocking, prior dbh increment
Mean number of trees (no./ha)	Red oak group 125 Scarlet oak 62 Black oak 63 Northern Red oak <1 White oak group 114 White oak 91 Post oak 23 All oaks 139 All trees 382	Red oak group 105 Scarlet oak 41 Black oak 49 Northern red oak 15 White oak group 117 White oak 100 Post oak 13 Other oaks 4 All oaks 222 All trees 331
Mean basal area (m^2/ha)	Red oak group 8.8 White oak group 5.1 All oaks 13.9 All trees 18.5	Red oak group 5.7 White oak group 4.9 All oaks 10.6 All trees 15.5
Mean dbh increment (cm/year)	Red oak group 0.31 White oak group 0.21 All oaks 0.26	Red oak group 0.42 White oak group 0.31 All oaks 0.36
Mean site index (m at age 50 years)	22	18

this analysis are representative of undisturbed upland forest in the sawtimber size class. The 1991–1995 interval was used to measure recent tree diameter growth, and the 1995–2002 interval was used to observe survival rates.

2.3. Pioneer Forest, 1992–2002

As part of an ongoing continuous forest inventory system on the private Pioneer Forest near Salem, MO, more than 450 inventory plots have been remeasured at 5-year intervals since 1952. Additional plots have been added with new land acquisitions and today the inventory system includes four hundred and eighty-nine 0.08-ha, circular plots (Pioneer Forest, 2005b) Tree survival, diameter growth, crown position, and numerous other tree and plot characteristics were recorded at each measurement. The Pioneer Forest has been continuously managed for more than 50 years using uneven-aged silviculture that employs a mixture of individual-tree selection harvests and group selection harvests (Loewenstein et al., 1995; Loewenstein, 1996; Pioneer Forest, 2005a). Periodic harvests have provided the opportunity to remove trees that are at risk for mortality, or that have recently died. Harvests on a given tract within the Pioneer Forest occur at intervals of 10–20 years and remove an average of 30–37 trees/ha. Experienced foresters make harvest decisions on which trees to cut or leave based on tree vigor, species, form, current or potential damage and decay, disease, crown position, and age.

In this analysis, we used data from 1992, 1997, and 2002 to examine patterns of oak mortality in a managed, uneven-aged forest. This measurement period is similar to that used for the MOFEP data. The 1992–1997 interval was used to observe recent diameter growth for each tree, and the 1997–2002 interval was used to observe survival. Observations on the Pioneer Forest were restricted to trees $\geq$13 cm dbh. Prior to 1950, the Pioneer Forest, like much of the Missouri Ozarks, was heavily disturbed by timber harvesting. In 1952, the stand density was low on the Pioneer Forest; mean basal area was 9 m^2/ha (Loewenstein et al., 1995).

2.4. Abiotic factors

The MOFEP and Pioneer Forest properties both fall in the Current River Hills ecological subsection and the inventory plots generally fall within three land type associations (Current River Pine-oak Woodland Dissected Plain, Current River Oak Forest Breaks, and Eminence Igneous Glade/Oak Forest Knobs) (Nigh and Schroder, 2002). The MOFEP plots have greater density of red oak species (number of trees and basal area), greater overall basal area, and slower mean diameter growth. These differences are consistent with the differences in past management practices between the two properties. Mean site index is greater on the MOFEP sites than on the Pioneer Forest (Table 2).

Precipitation during the period of observation (1991–2002) was fairly typical and not characterized by significant drought. Precipitation at the centrally located Ellington, MO, weather station was greater than the 30-year normal values for 5 of 12 years and for the entire period from 1991 to 2002. Summer precipitation (June, July, and August) was greater than 30-year normals for 6 of 12 years and for the period from 1991 to 2002. The period prior to 1997 (period when dbh growth was observed) was drier, on average, than the period from 1997 to 2002 (when mortality was observed and related to dbh growth). Mortality of the trees in the red oak group was less than levels associated with severe episodes of oak decline (e.g., Spetich, 2004; Starkey et al., 2004) and characteristic of typical mortality rates for stands that are mature but not undergoing oak decline. Droughts occur periodically in the region. Over the past 55 years summer precipitation is less than half of normal about 1 year in 10 and less than two-thirds of normal about 2 years in 10.

2.5. Analysis

We initially screened all data records for incomplete observations, missing values, and other errors that inevitably occur with databases of this magnitude. We then used graphical summaries and related statistics to summarize univariate and bivariate mortality rates based on location (MOFEP versus Pioneer Forest), site characteristics (slope, aspect, and site index for all plots; plus ecological land type and geo-landform for MOFEP plots), tree species, tree size, tree crown class, stand density, and basal area of larger trees (bal). The basal area of larger trees is computed uniquely for each tree on an inventory plot as the basal area (m^2/ha) of the trees on that plot that are as large or larger in dbh. We also used nonparametric classification and regression tree analysis to examine the hierarchical structure and interdependence among variables (Breiman et al., 1984). The binary response (dependent) variable was whether a tree was dead (0) or alive (1) at the end of a remeasurement period. The CART procedure recursively partitioned the data into paired nodes (subsets) such that one node contained as many dead trees as possible, and the other node contained as few dead trees as possible based on a threshold value of one of the explanatory (independent) variables (e.g., a particular value of dbh or of bal). The CART procedure selects variables and threshold values that maximize the ability to distinguish dead and live trees. This procedure revealed the distribution patterns of dead trees in the data and the factors and factor values associated with these patterns in a hierarchical regression ‘‘tree’’ or diagram showing relationships among variables. For cohorts identified by the CART model, we calculated the mean mortality per decade and ranked cohorts by mortality rate from highest to lowest.

We used the 10-fold cross-validation to find the CART model that minimized the overall misclassification rates (Steinberg and Colla, 2000). With the best CART model for each data set, we calculated the mean and 95% confidence interval (CI) of the probability of dead trees as a measure of mortality rate and variation within that node (risk class). Then we compared the model structure (and associated significant variables) between the two data sets representing different management practices.

Table 3
Observed mean mortality rates (percent) by species group and data source

Species	Annual tree mortality		Annual basal area mortality	
	MOFEP	PIONEER	MOFEP	PIONEER
Red oak group	2.11	2.26	1.87	1.67
White oak group	0.61	0.36	0.50	0.32
Ratio red to white oak	3.5	6.3	3.7	5.2

Because managers generally find it costly and difficult to measure the recent rate of dbh growth for each tree, we limited the explanatory variables in some CART models to easily observed tree and stand characteristics (e.g., species, crown class, and stand density). Then for each subset of observations classified in each terminal node of the final CART model, we used logistic regression to estimate the relationship of mortality to dbh growth. Specifically,

$$\text{Annual mortality rate} = \frac{\exp(\beta_0 + \beta_1 \text{DGR})}{1 + \exp(\beta_0 + \beta_1 \text{DGR})} \qquad (1)$$

where DGR is the current annual dbh growth (cm) and the β_i are coefficients to be determined by regression. This quantified the incremental value of using dbh growth to explain differences in mortality rates after other factors were already included in the model.

CART is a nonparametric and computationally intensive approach to identify and explore complicated patterns and interactions buried in data. Logistic regression is a more traditional approach to mortality estimation that can also be used to identify such relationships, but only if the relationships are specified in advance and if certain assumptions about the distribution of residuals are met. The combination of CART and logistic regression is a powerful approach to analysis of mortality risk that capitalizes on the features of each approach. CART excels at identifying factors associated with different mortality rates and placing them in hierarchical order of importance. It can combine categorical and continuous variables, and it makes no assumptions about normality of the data or of residuals. Multicollinearity may inflate errors and biases of estimated of parameters in the logistic regression framework and complicate evaluation of relative importance of variables. However, the hierarchical structure of CART circumvents this problem. Variables at the top of CART hierarchy are more important than those entering later, and CART models largely depend on the importance of individual variables rather than their correlations. CART is particularly adept at classifying tree species into multi-species groupings that have the similar survival rates. Within each composite group identified in the CART analysis, logistic regression can readily estimate the importance of knowing tree diameter when estimating tree mortality or survival.

3. Results

Simple data summaries indicate that annual mortality rates for trees in the red oak group (i.e., percent of trees dying each year) were four to six times greater than for the white oak group (Table 3). The partial association of risk factors is a measure of a single variable's influence on the survival rate, independent of other factors. The corresponding odds ratios indicate the proportional change in the mortality rate associated with change in the value of a single independent variable (Table 4). For example, a 0.1 cm increase in the red oak diameter growth rate for the MOFEP data results in a mortality rate that decreases by a ratio of 0.45 (i.e., a 0.1 cm increase in annual diameter growth more than halves the mortality rate). Similarly,

Table 4
Partial association of risk factors for oak mortality at the MOFEP and Pioneer Forest sites, MO

Risk factor	MOFEP		Pioneer Forest	
	Odds ratio	95% CI for odds ratio	Odds ratio	95% CI for odds ratio
Red oak group				
Annual diameter increment (0.1 cm)	0.447	0.421–0.473	0.516	0.472–0.561
Diameter (1 cm)	0.972	0.968–0.977	0.935	0.918–0.953
Basal area in larger trees (1 m^2)	1.101	1.091–1.112	1.083	1.062–1.105
Suppressed crown class (reference for MOFEP)	N/A	N/A	N/A	N/A
Intermediate crown class (reference for Pioneer)	0.434	0.352–0.535	N/A	N/A
Codominant crown class	0.145	0.118–0.178	0.294	0.223–0.386
Dominant crown class	0.111	0.088–0.140	0.125	0.089–0.177
White oak group				
Annual diameter increment (0.1 cm)	0.259	0.220–0.303	0.611	0.500–0.738
Diameter (1 cm)	0.963	0.951–0.976	N/A	N/A
Basal area in larger trees (1 m^2)	1.079	1.058–1.100	N/A	N/A
Suppressed crown class (reference for MOFEP)	N/A	N/A	N/A	N/A
Intermediate crown class (reference for Pioneer)	0.353	0.287–0.435	N/A	N/A
Codominant crown class	0.131	0.097–0.177	0.505	0.257–0.993
Dominant crown class	0.144	0.086–0.241	0.298	0.120–0.738

Note: Odds ratios indicate the proportional change in the mortality rate with a specified change in each risk factor (in parentheses). Relative changes in mortality for increasing crown class are referenced against either the suppressed or intermediate crown class, as indicated. Values are not shown for variables where the confidence interval of the odds ratio included 1, indicating no change in mortality rate.

Table 5
Estimated percentage of annual mortality for black and scarlet oaks by various risk classes and diameter increment subclasses for MOFEP sites, based on a 7-year observation period (1995–2002)

<table>
<tr><th rowspan="2">Risk class generated by CART</th><th rowspan="2">Overall</th><th colspan="5">Annual diameter increment (cm)[a]</th></tr>
<tr><th>≤ 0.05</th><th>0.06-0.10</th><th>0.11-0.15</th><th>0.16-0.25</th><th>> 0.25</th></tr>
<tr><td>Suppressed trees (class 1)</td><td>7.3</td><td>10.7</td><td>8.1</td><td colspan="3">3.5</td></tr>
<tr><td>Intermediate trees with bal[b] > 14.1 m^2/ha (class 2)</td><td>4.3</td><td>9.9</td><td>6.7</td><td>3.9</td><td colspan="2">1.6</td></tr>
<tr><td>Intermediate trees with bal ≤ 14.1 m^2/ha (class 3)</td><td>2.0</td><td>9.2</td><td colspan="2">2.6</td><td colspan="2">0.7</td></tr>
<tr><td>Dominant and codominant trees with bal > 15.7 m^2/ha and dbh > 24 cm (class 4)</td><td>3.8</td><td colspan="3">8.1</td><td>3.0</td><td>1.2</td></tr>
<tr><td>Dominant and codominant trees with bal > 15.7 m^2/ha and dbh ≤ 24 cm (class 5)</td><td>1.9</td><td colspan="2">6.6</td><td>3.5</td><td colspan="2">1.4</td></tr>
<tr><td>Dominant and codominant trees with bal ≤ 15.7 m^2/ha and dbh > 30 cm (class 6)</td><td>1.5</td><td colspan="3">4.2</td><td>1.8</td><td>0.9</td></tr>
<tr><td>Dominant and codominant trees with bal ≤ 15.7 m^2/ha and dbh ≤ 30 cm (class 7)</td><td>0.9</td><td colspan="2">4.6</td><td colspan="2">2.3</td><td>0.4</td></tr>
</table>

[a]Analysis of diameter increment effects was conducted after classes 1–7 were determined by CART analysis. For each class (row) the block widths shown under annual diameter increment vary to indicate diameter increment subclasses that have significantly different mortality rates. For example, for suppressed trees (class 1) the annual mortality rate for trees with annual diameter increment from 0.06 to 0.1 cm was 8.1%. The annual mortality rate for all trees with annual diameter increment 0.11 cm and larger was 3.5%. CART did not identify significant differences in mortality rates for finer diameter increment classes.
[b]The basal area of larger trees (bal) is computed uniquely for each tree on an inventory plot as the basal area (m^2/ha) of the trees on that plot that are as large or larger in dbh.

a 1 m^2/ha increase in the basal area of larger trees boosts the mortality rate by a ratio of 1.1 for the MOFEP red oak group (Table 4). Changes in crown class had a large impact on oak survival rates, other things being equal. Changes in the annual diameter growth rate of 0.1 cm also resulted in a large relative change in the survival rate for the red oak group and the white oak group at Pioneer Forest. Location and site variables were not significant predictors of tree mortality.

As an exploratory measure we fitted a CART model using oak mortality as the response variable, and we included tree dbh growth in the suite of independent variables. For both the red oak group and the white oak group and for both the Pioneer Forest and MOFEP data sources, the CART analysis identified the rate of recent dbh growth as the most important indicator of future mortality. For both data sources, white oaks growing slower than 0.05 cm dbh per year had a mortality rate approximately 10 times greater than trees growing at least 0.05 cm dbh per year (2% versus 0.2% annual mortality, respectively). Faster growing white oaks on the MOFEP sites (i.e., those with dbh growth >0.15 cm per year) had an annual mortality rate that was less than 0.1%. Species in the red oak group had a significant increase in mortality rate when dbh growth dropped below 0.15 cm on the MOFEP sites (0.7% versus 6.4% annual mortality). On the Pioneer Forest, mortality for the red oak group jumped from 1% to more than 8% annually when annual dbh growth dropped below 0.25 cm per year.

When annual dbh growth was excluded from the CART analysis, the MOFEP red oak observations fell into seven terminal nodes (classes of trees) that differed significantly ($p = 0.05$) in mortality rates (Fig. 1; Table 5). The significant nodes were distinguished based on tree crown class, basal area in larger trees, and dbh. Crown class and basal area of larger trees were the most important factors for identifying red oak group trees likely to die (i.e., uppermost in the hierarchy). Interactions among variables are indicated by lower levels of

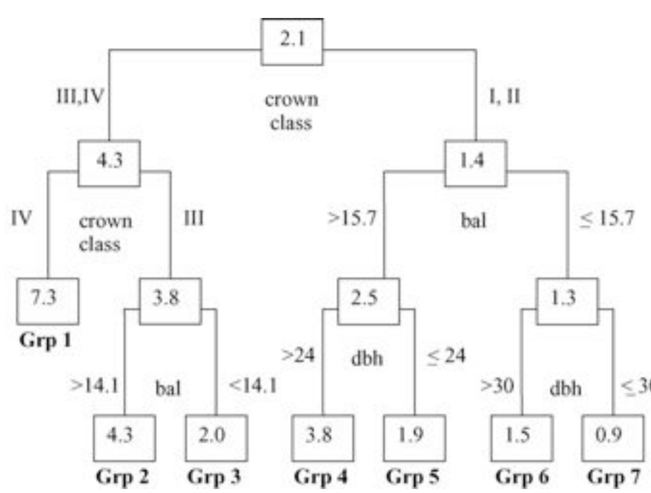

Fig. 1. Annual mortality (%) of red oak group species by risk factors for the MOFEP sites. Crown classes are: (I) dominant, (II) codominant, (III) intermediate, and (IV) suppressed. Basal area in larger trees (bal) is computed uniquely for each tree on an inventory plot as the total basal area (m^2/ha) of the trees on that plot that are as large or larger in dbh. Tree dbh classes are in centimeters.

Table 6
Estimated parameters of model (1) for overall and individual risk classes for MOFEP sites

Risk class	No. of trees	No. of dead trees	Dead trees (% per 7 years)	Mean annual dbh increment (cm)	MLE of parameters in Eq. (1)		Hosmer–Lemeshow Goodness-of-fit test ($p >$ chi-square)[a]
					β_0 (S.E.)	β_1 (S.E.)	
Class 1	474	242	51.1	0.143	1.962 (0.321)	−6.242 (0.879)	0.010
Class 2	2070	622	30.0	0.180	2.239 (0.190)	−8.088 (0.494)	0.022
Class 3	548	75	13.7	0.232	1.066 (0.385)	−7.120 (0.957)	0.092
Class 4	383	103	26.9	0.260	2.282 (0.477)	−7.135 (1.035)	0.361
Class 5	927	126	13.6	0.254	1.403 (0.342)	−7.427 (0.794)	0.024
Class 6	4304	466	10.8	0.365	−0.296 (0.137)	−3.373 (0.257)	<0.0001
Class 7	3582	231	6.4	0.329	0.394 (0.213)	−6.128 (0.443)	0.033
Overall	12288	1865	15.2	0.298	1.084 (0.079)	−6.096 (0.174)	<0.0001

[a] Values ≥0.05 indicate a significant relationship for model (1) based on the observations in each risk class.

the CART hierarchy. For example, the effect of basal area in larger trees (bal) differs by crown class (e.g., group 1 versus groups 2 and 3 in Fig. 1). We found that each of the seven CART classes could be further segregated into three or four additional subclasses based on diameter increment (Table 5). Within each of the seven main classes the mortality rate decreased with increasing dbh growth rate, but the statistically significant thresholds for diameter growth differed among the classes (Table 5).

The seven red oak classes identified by the MOFEP CART analysis varied in size from 383 to more than 4300 observations (Table 6). As an alternative to using CART to determine statistically significant diameter growth subclasses (as in Table 5), we also fit the logistic model (Eq. (1)) to estimate the probability of mortality as a function of diameter growth rate for trees in each of the seven classes identified by the MOFEP CART model. The general trend was one of decreasing mortality with increasing dbh growth (Fig. 2). However, the lack of fit for the model was significant ($p = 0.05$) for most classes; only classes 3 and 4 had significant regression relationships based on dbh growth (Table 6).

Analysis results for the Pioneer Forest inventory data were similar to MOFEP in many respects. The significant predictors (independent variables) for red oak group mortality on Pioneer Forest were similar to the MOFEP sites in the partial associations and the CART analyses (Fig. 3; Tables 4 and 7).

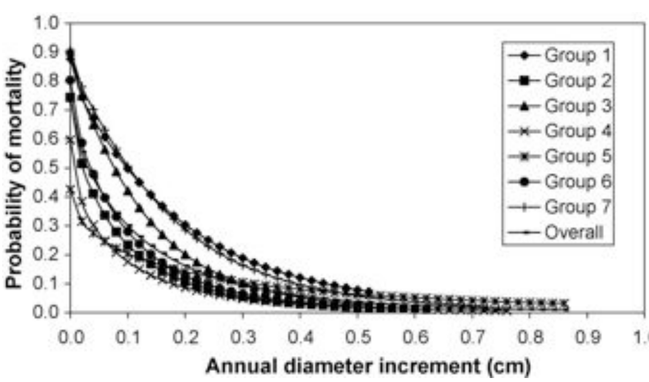

Fig. 2. Mortality by annual diameter increment for red oak group risk classes on the MOFEP sites. Risk groups are defined in Fig. 1.

However, for the Pioneer data tree dbh was not a significant indicator of red oak group mortality, and the resulting CART model with five terminal nodes was simpler than that for the MOFEP data (Fig. 3).

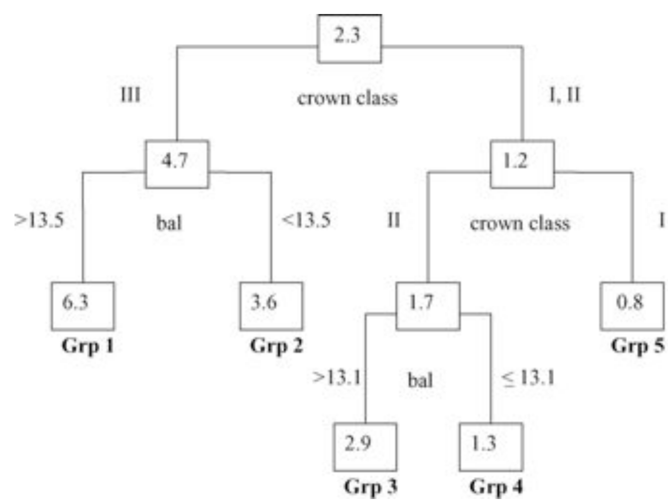

Fig. 3. Annual mortality (%) of red oak group species by risk factors for the Pioneer Forests sites.

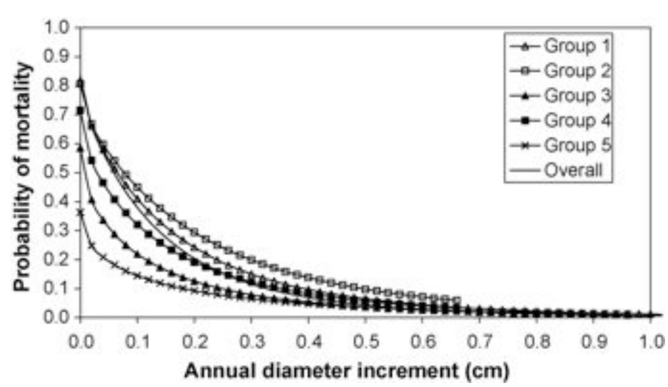

Fig. 4. Mortality by annual diameter increment for red oak group risk classes on the Pioneer Forest. Risk groups are defined in Fig. 3. Crown classes are: (I) dominant, (II) codominant, and (III) intermediate or suppressed. Basal area in larger trees (bal) is computed uniquely for each tree on an inventory plot as the total basal area (m^2/ha) of the trees on that plot that are as large or larger in dbh.

Table 7
Estimated percentage of annual mortality for various risk classes and diameter increments in Pioneer Forest based on a 5-year observation period (1997–2002)

<table>
<tr><th rowspan="2">Risk class</th><th rowspan="2">Overall</th><th colspan="7">Annual diameter increment (cm)[a]</th></tr>
<tr><th>≤ 0.15</th><th>0.16-0.20</th><th>0.21-0.25</th><th>0.26-0.30</th><th>0.31-0.40</th><th>0.41-0.45</th><th>>0.45</th></tr>
<tr><td>Intermediate and suppressed trees with bal[b] > 13.5 m^2/ha (class 1)</td><td>6.3</td><td>9.7</td><td colspan="6">3.8</td></tr>
<tr><td>Intermediate and suppressed. trees with bal[b] ≤ 13.5 m^2/ha (class 2)</td><td>3.6</td><td colspan="3">6.4</td><td colspan="4">1.4</td></tr>
<tr><td>Codominant trees with bal[b] > 13.1 m^2/ha (class 3)</td><td>2.9</td><td>9.3</td><td colspan="6">2.2</td></tr>
<tr><td>Codominant trees with bal[b] ≥ 13.1 m^2/ha (class 4)</td><td>1.3</td><td colspan="5">1.8</td><td colspan="2">0.5</td></tr>
<tr><td>Dominant trees (class 5)</td><td>0.8</td><td colspan="4">2.1</td><td colspan="2">0.9</td><td>0.4</td></tr>
</table>

[a]For each class (row) the block widths shown under annual diameter increment vary to indicate diameter increment subclasses that have significantly different mortality rates. For example, for trees in class 2 the annual mortality rate for trees with annual diameter increment less than 0.26 cm was 6.4%. The annual mortality rate for trees with annual diameter increment 0.26 cm and larger was 1.4%. CART did not identify significant differences in mortality rates for finer diameter increment classes.
[b]The basal area of larger trees (bal) is computed uniquely for each tree on an inventory plot as the basal area (m^2/ha) of the trees on that plot that are as large or larger in dbh.

Table 8
Estimated parameters of model (1) for overall and individual risk classes for Pioneer Forest

Risk class	No. of trees	No. of dead trees	Dead trees (% per 5 years)	Range of annual dbh increment (cm)	MLE of parameters in Eq. (1) β_0 (S.E.)	MLE of parameters in Eq. (1) β_1 (S.E.)	Hosmer–Lemeshow Goodness-of-fit test ($p >$ chi-square)[a]
Class 1	350	110	31.4	0.0–0.7	1.430 (0.415)	−5.155 (0.964)	0.215
Class 2	403	73	18.1	0.0–1.0	1.503 (0.461)	−5.906 (0.936)	0.374
Class 3	297	43	14.5	0.0–0.7	0.920 (0.688)	−5.272 (1.350)	0.290
Class 4	748	47	6.3	0.0–1.0	0.344 (0.673)	−5.106 (1.166)	0.988
Class 5	1112	43	3.9	0.0–1.2	−0.561 (0.742)	−3.843 (1.101)	0.163
Overall	2910	316	10.9	0.0–1.2	1.618 (0.220)	−6.658 (0.417)	0.092

[a] Values ≥0.05 indicate a significant relationship for model (1) based on the observations in each risk class.

For Pioneer Forest the mean dbh growth rates for oaks were 30–50% greater than for MOFEP. The range of dbh growth values was also greater. Each of the five classes that the CART analysis identified for the Pioneer data could be further split into two or three subclasses based on diameter growth rate (Table 7). When the logistic model (Eq. (1)) was used to estimate mortality rate as a function of tree diameter growth rate for each class of trees classified by CART, the general pattern of the relationships (Fig. 4) was similar to that for the MOFEP data (Fig. 2). In contrast to the MOFEP data, the Pioneer Forest logistic regression models were statistically significant for each of the classes (i.e., no significant lack of fit, $p = 0.05$) (Table 8).

4. Discussion

The magnitude of the difference in mortality rates of red oaks relative to white oaks was striking. Mortality rates reported in this study for trees in the red oak group were greater than statewide means reported for the 1960s and 1970s (Shifley and Smith, 1982), and mortality rates reported in this study for white oaks were lower than statewide means for that earlier period. The differences in survival among the red oak group and white oak group were expected based on typically shorter longevity of species in the red oak group (Hicks, 1998) and the fact that most inventory plots fell in mature stands in the sawtimber size class. What we previously did not know was the magnitude of those differences and the extent to which the differences were statistically related to tree and site characteristics.

Suppressed trees in the red oak group had the highest mortality rates. But contrary to general expectations for dominant and codominant trees (e.g., Oliver and Larson, 1990; Johnson et al., 2002), black and scarlet oaks in dominant and codominant crown classes suffered relatively high rates of mortality, particularly when basal area of larger trees was also high (Figs. 1 and 3). Higher mortality rates are not surprising because large trees in the red oak group are: (a) nearing the end of their natural longevity (particularly scarlet oaks) and (b) less tolerant of drought stress (e.g., through low root–shoot ratios as suggested by Jenkins and Pallardy, 1995).

Consistent with previous investigations of tree mortality (e.g., Monserud, 1976; Buchman et al., 1983; Kobe and Coates, 1997; Wyckoff and Clark, 2002) and, more specifically, oak mortality in the Ozarks (e.g., Jenkins and Pallardy, 1995), we found that both the recent rate of dbh growth and tree dbh were important indicators of oak mortality. It was notable in our analyses that red oak group mortality increased significantly when annual dbh growth fell below 0.15 cm (MOFEP) or 0.25 cm (Pioneer Forest). White oaks did not experience a significant increase in mortality until annual dbh growth dropped below 0.05 cm. Wyckoff and Clark (2002) reported for the southern Appalachians that northern red oak mortality remained at low levels for trees with annual dbh growth greater than about 0.05 cm, but it increased sharply as annual dbh growth dropped below that threshold. That threshold growth rate was comparable to what we observed for white oaks, but far below the higher annual dbh growth threshold of 0.15–0.25 cm associated with high mortality for red oak species on our sites. The lower growth rate thresholds reported for northern red oak may reflect interspecific differences in mortality rates within the red oak group. For example, Starkey and Oak (1989) reported that the northern red oak mortality rate associated with oak decline was about one-third that for black oak or scarlet oak and about the same as for white oak.

Based on exceptionally large populations of field observations, we were able to explicitly quantify the probability of oak mortality by species, crown class, tree dbh, stand density, and/or tree dbh growth (Figs. 1 and 2; Tables 3, 5, 6 and 7). Although a tree's recent dbh growth is generally a good integrator of overall vigor and a good predictor of near term mortality, in mature upland oak forests with minimal management (i.e., MOFEP untreated plots) knowledge of dbh growth did not add significant predictive power *after* other easily measured variables such as crown class, dbh, and basal area of larger trees were already in the model. This is not particularly surprising given that crown class and relative tree size have been found to be among the best indicators of future tree dbh growth for oaks and associated species (Trimble, 1969).

Ironically, rapid dbh growth for species in the red oak group favors their survival in the short term but may contribute to their demise in the long term. In a dendrochronological analysis of relationships among dbh growth, drought, and survival for scarlet and black oaks, Jenkins and Pallardy (1995) found that mortality was greater for trees that grew fast for many years prior to a drought than for those that grew more slowly. They suggested that rapid growth during favorable conditions can produce trees with low root–shoot ratios and eventually render those trees more susceptible to mortality during drought.

Based on analyses for both data sets, classes of red oak group trees most likely to die were (in rank order after generalizing across both data sources):

- trees with annual dbh growth less than 0.2 cm (assuming recent dbh growth is known);
- suppressed trees;
- trees with intermediate crown class and basal area of larger trees greater than about 14 m^2/ha;
- dominant and codominant trees larger than about 25 cm dbh with basal area of larger trees greater than about 14 m^2/ha;
- intermediate crown class trees with basal area of larger trees less than about 14 m^2/ha;
- dominant and codominant trees greater than about 25 cm dbh with basal area of larger trees less than about 15 m^2/ha;
- dominant and codominant trees less than about 25 cm dbh with basal area of larger trees greater than about 15 m^2/ha;
- dominant and codominant trees less than about 25 cm dbh with basal area of larger trees less than about 15 m^2/ha;
- trees with annual dbh growth greater than 0.6 cm (assuming recent dbh growth is known).

We anticipated management-related differences between the MOFEP (largely undisturbed forest) and Pioneer Forest (more than four decades of uneven-aged management) data sets. The MOFEP and Pioneer data sets are two case studies of the impact of management practices on oak mortality rates. Although these two sites cannot be used to make broad generalizations about management effects on oak mortality, comparisons of the tracts are interesting due to the large number of plots and the large spatial extent of each data set. On the managed Pioneer Forest the average annual mortality rate for red oak trees was slightly greater than for the MOFEP site, but the average annual basal area of mortality was slightly less (Table 3). This indicates that red oak mortality on the managed Pioneer Forest sites claimed more trees and smaller trees than on the MOFEP sites. White oak mortality on the Pioneer Forest was about half the rate observed on MOFEP. Both of these outcomes are consistent with Pioneer Forest management practices that periodically remove trees that are unlikely to survive (including large trees in the red oak group), reduce stand density, and increase diameter growth of the remaining trees.

Recent tree dbh growth is generally a good predictor of future mortality. But for the MOFEP sites after tree crown class, basal area of larger trees, and dbh were taken into account, knowledge of dbh growth was significantly related to tree morality for only two of the seven CART classes (Table 6). Overall, the mean diameter growth rate for red oak group trees was 0.36 cm per year for the Pioneer data, or 35% greater than for the MOFEP sites. The relatively rapid diameter growth for Pioneer Forest is likely the consequence of long-term management practices that maintain relatively low basal area (e.g., mean base area 14 m^2/ha; Table 2). Recent dbh growth was a significant predictor of red oak group mortality on the managed Pioneer Forest, even after crown class and basal area of larger trees were taken into account (Table 8). Mortality rates for red oak species on the Pioneer Forest were (from greatest to least mortality probability):

- suppressed trees with basal area of larger trees greater than 13 m^2/ha;
- suppressed trees with basal area of larger trees less than 13 m^2/ha;
- codominant trees with basal area of larger trees greater than 13 m^2/ha;
- codominant trees with basal area of larger trees less than 13 m^2/ha;
- dominant trees.

Within each class of trees the rate of dbh growth, if known, can be used to refine the mortality estimate. For all classes the mortality rate increased when dbh growth fell below 0.2 cm (0.08 in.) annually.

From a silvicultural perspective, there is usually little benefit in removing suppressed red oaks unless it is targeted at establishing reproduction. Small trees have low economic value, a high natural mortality rate, and little influence on the growth of trees in the upper canopy layers (Johnson et al., 2002). In stands prone to oak decline, large codominant trees in the red oak species group should be of management concern. They are frequently important economically and ecologically, and are subject to comparatively high rates of mortality, especially when the basal area of larger trees is relatively high (e.g., greater than about 14 m^2/ha) (61 ft^2/ac). Where this occurs, the total stand basal area and stocking percent are usually relatively large as well.

Individual-tree diameter growth rates are not available for most forest management inventories. However, diameter growth rates are regularly observed on the statewide system of Forest Inventory and Analysis (FIA) plots and some private forests. Those data can be readily applied with the models presented here to assess mortality risk at large spatial scales.

5. Conclusions

The recent dbh growth rate is a good predictor of future mortality for oaks in the Missouri Ozarks. However, most management inventories do not collect information on tree dbh growth, so other variables must be used to estimate future mortality rates. Crown class, basal area of larger trees, and tree dbh were significant predictors of future mortality for trees in the red oak group on our study sites in the Missouri Ozarks. We were able to use a combination of CART and logistic regression to identify specific tree sizes and density thresholds that distinguish trees in the red oak group that were most likely to survive from those most likely to die. In most cases, these classifications are easy to apply to management inventory data or to apply ‘‘on-the-fly’’ by foresters or tree marking crews.

Mortality rates for red oaks were three to six times greater than for white oaks on our study sites. White oak did not show a significant increase in the annual mortality rate until annual dbh growth dropped below 0.05 cm. In contrast, mortality rates for red oaks increased significantly when annual dbh growth dropped below 0.25 cm. Thus, diameter increment is significantly related to mortality for both the red oak and the white oak species groups, but the white oak group is better able than the red oak group to tolerate conditions that result in slow growth. Rapid growth of red oak species may decrease their ability to tolerate periodic droughts (e.g., as suggested by Jenkins and Pallardy, 1995), but at this point there is no evidence that purposely managing red oak species for slow growth will improve long-term, net growth per hectare. Nor is there evidence that regular thinning significantly reduces the rate of mortality for the red oak group, but periodic thinning will allow timber recovery from mature red oaks that are likely to perish at a relatively rapid rate.

Our results are typical for mature Ozarks forests where oak decline is not significant. Even in the absence of serious oak decline events, the mortality rate for red oaks is high compared to white oak species. Even codominant trees of the red oak group species can suffer annual mortality approaching 3%. In addition to supporting management guidelines that anticipate future red oak group mortality rates, our findings serve as a baseline against which to compare the relative severity of mortality linked to episodes of oak decline.

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