Developing a Stand Hazard Index for Oak Decline in Upland Oak Forests of the Ozark Highlands, Missouri

Zhaofei Fan, Xiuli Fan, Martin A. Spetich, Stephen R. Shifley, W. Keith Moser, Randy G. Jensen, and John M. Kabrick

ABSTRACT

Black oak (*Quercus velutina* Lam.) and scarlet oak (*Quercus coccinea* Muenchh.)—two major components (44% of total stand basal area) of upland oak forests—are suffering severe decline and mortality in the Ozark Highlands, Missouri. However, factors influencing their survival (mortality) are not well understood. In this study we quantified how stand and tree-level predisposing factors are associated with survival of black and scarlet oaks. Sixteen-year monitoring data from the Missouri Ozark Forest Ecosystem Project (MOFEP) indicated that overall annual mortality of black and scarlet oaks averaged 2.2 and 1.7%, respectively, three to five times higher than expected (around 0.5%) for white oak, a common associate. For the first 8 years of the study (1990–1998), survival rates of black and scarlet oaks were similar. Thereafter, the survival rate of black oak declined relative to scarlet oak. Using the classification and regression tree (CART) method we classified black oak and scarlet oak trees into seven and nine risk groups, respectively, that differed significantly in rates of tree mortality. Groups were distinguished based on tree diameter, crown class, and size relative to competitors. An oak decline and mortality hazard index was thus developed as the weighted means of risk group mortality, which can help managers prescribe species-specific silvicultural treatments to help mitigate oak decline and associated mortality.

Keywords: oak decline, survival, hazard index, Missouri Ozark Highlands

With the maturing of upland oak-hickory forests in the Missouri Ozarks, large-scale oak decline and mortality have increased in extent and severity. Among oaks, black oak (*Quercus velutina* Lam.) and scarlet oak (*Quercus coccinea* Muenchh.) are the two major species that have suffered moderate to severe "oak decline syndrome" and mortality in the upland forests of southeastern Missouri (Fan et al. 2008). A study by Spetich and He (2008) indicated that oak decline is a process associated with forest succession that operates at long temporal scales. Oak decline is therefore a persistent process and results from the interaction of biological and environmental factors including predisposing stress factors (e.g., poor site quality, unfavorable stand condition, and advanced tree age), inciting factors (e.g., drought), and secondary contributing factors (e.g., root disease and insect borers; Law and Gott 1987, Starkey and Oak 1989, Lawrence et al. 2002, Kabrick et al. 2004, Starkey et al. 2004, Fan et al. 2006, Shifley et al. 2006). Decline and subsequent mortality of black and scarlet oaks in Missouri were noted in the late 1970s (Law and Gott 1987) or even earlier (Toole 1960) and is periodically prevalent throughout the entire Ozark Highlands of Missouri, Arkansas, and Oklahoma as upland forests become mature physiologically (Lawrence et al. 2002, Heitzman et al. 2004).

To implement potential management actions that reduce the risk or severity of oak decline (Moser and Melick 2002, Clatterbuck and Kaufmann 2006), it is essential to identify and to quantify potential risk factors associated with oak decline and to predict the likelihood that declining trees will live or die. Periodic droughts and climatic extremes play an important role in triggering oak decline in the Ozark Highlands and elsewhere. Drought years are essentially impossible to predict in advance, but there is high certainty that future droughts will periodically occur and affect oak forests. Consequently, identification of stand and tree-level risk factors and site variables associated with oak decline is essential for the development of prescriptions that help mitigate the negative impacts of future episodes of oak decline. For instance the dead-to-live tree ratio, the forest health quotient, has proven useful in predicting oak decline (Spetich 2006).

As a long-term, landscape-level experiment, the Missouri Ozark Forest Ecosystem Project (MOFEP) has been monitoring changes in forest attributes under various management scenarios since the early 1990s (Brookshire and Shifley 1997, Shifley and Kabrick 2002). More

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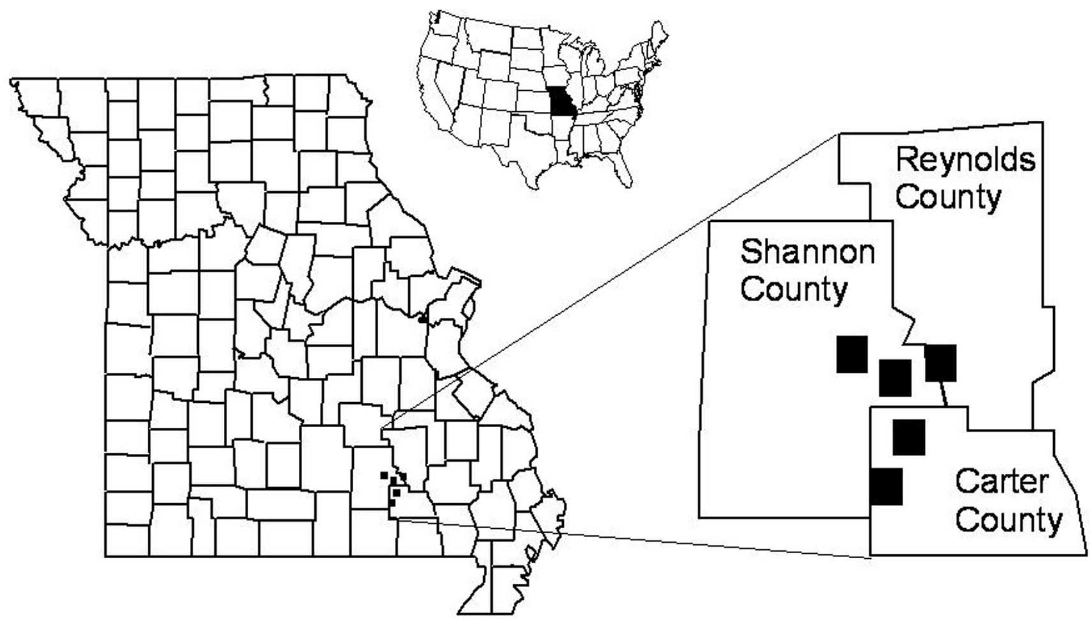

Figure 1. Location of the MOFEP, the source of data used in this study.

than 50,000 overstory trees of >11.5 cm (4.5 in.) dbh (measured 1.4 m [4.5 ft] aboveground level) have been measured and reinventoried approximately every 3 years for species, dbh, crown class, crown condition, and status (live or dead; Shifley and Brookshire 2000). Meanwhile, site and stand variables such as aspect, slope, soil type, landform, ecological land type, stand density, and basal area (BA) of 648 0.2-ha (one-half acre) permanent plots where these trees grow were measured or otherwise derived (Kabrick et al. 2000). This constitutes a unique database for monitoring oak decline.

According to previously published study results (Fan et al. 2006, Shifley et al. 2006, Fan et al. 2008), major tree- and stand-level predisposing factors for oak decline and mortality include tree species, crown class, dbh, and BA in larger trees (competition from above). In those studies site characteristics including aspect, slope, landform and ecological land type had no or at most a marginal impact on tree mortality (Kabrick et al. 2004, 2008). Fan et al. (2006) applied classification and regression tree (CART)–based survival analyses to 12-year monitoring data (1990–2002) with composite species groups (i.e., red oak species group versus white oak species group). Monitoring data collected over a longer period (1990–2006) reveal differences in survival between black and scarlet oaks since 1998.

In this study, we used the CART-based survival analysis (Fan et al. 2006) to separately quantify distinct differences in the long-term survival patterns of declining black and scarlet oaks based on 16-year monitoring data. The major objective of this study was to quantify how stand- and tree-level predisposing factors are associated, individually and in combination, with the survival of two major decline-prone oak species—black oak and scarlet oak and how they affect a stand decline hazard index (HI). Specifically, we classified black oak and scarlet oak into different risk groups based on predisposing factors and quantified black oak and scarlet oak survival by risk groups. We then developed a stand HI based on a linearly weighted means of risk group annual mortality of scarlet oak and black oak. The risk groups for both species and the stand HI of oak decline can help managers prescribe species-specific silvicultural treatments to help mitigate oak decline and mortality.

Methods

Study Sites

MOFEP is a long-term study designed to quantify the effects of forest management on upland oak ecosystems (Brookshire and Shifley 1997, Shifley and Brookshire 2000, Shifley and Kabrick 2002). The study consists of nine sites ranging in size from 314 to 516 ha (776–1,275 ac) located in southeastern Missouri (Figure 1). The study area is within the Current River Oak Forest Breaks and the Current River Oak-Pine Woodland Hills land-type associations of the Ozark Highlands (Nigh and Schroder 2002). The Current River Oak Forest Breaks has narrow ridges and steep sideslopes with relief of 90–140 m (295–460 ft), which exposes three sedimentary bedrock formations: Roubidoux and Gasconade (both Ordivician age) and Eminence (Cambrian age). The Current River Oak-Pine Hills has broad ridges with relief of < 90 m and exposes only the Roubidoux and Gasconade bedrock formations. Soils in this region are primarily classified Ultisols (Typic Paleudults and Typic Hapludults) or Alfisols (Typic Paleudalfs and Typic Hapludalfs; Kabrick et al. 2000, Meinert et al. 1997). Mean January minimum temperature is −7°C (19.4°F) and mean July maximum temperature is 32°C (90°F). Mean annual precipitation is 114 cm with 56% falling between April and October (Nigh and Schroder 2002).

Data

On the nine MOFEP sites, 648 0.2-ha (one-half acre) woody vegetation monitoring plots were established beginning in 1990; all live trees of >11 cm (4.5 in.) dbh within these plots were permanently tagged for repeated measurements in subsequent years. Tree species, dbh, crown class, and status (live or dead) were recorded and remeasured for each tagged tree in inventory years 1995, 1998, 2002, and 2006. Other stand and site factors that are potential contributors to oak decline and mortality (Starkey and Oak 1989) were measured or computed from tree measurement data. These included plot aspect, slope, ecological land type, species composition, and BA. Some plots received harvest treatments during the 16-year monitoring period, so they were excluded. In total, 13,177 black and scarlet oak trees from 445 untreated plots were used for survival analysis and development of a stand HI.

CART-Based Survival Analysis of Decline-Prone Scarlet Oak and Black Oak Trees

In this study the repeated measurement on tree status (live or dead) belongs to a set of right-censored interval data that has ties with observed survival (event) time. Note that mortality rates and survival rates are mathematically related (i.e., mortality = 1 − survival), and discussion of one carries implications for the other. We discuss trends and results in terms of survival and mortality rates, depending on the context; in the context of management it is often more meaningful to express results in terms of mortality rather than survival.

The CART-based survival analysis is a nonparametric method consisting of two steps: risk group identification by CART based on major predisposing factors (e.g., tree size and stand condition) and Kaplan-Meier survival analysis of the identified risk groups. One advantage of CART-based survival analysis lies in its flexibility, dichotomous structure, and independence of assumptions.

Our data analysis and modeling procedures are summarized in the following four steps. First, we conducted a log-rank test on survival data of scarlet and black oaks to evaluate differences based on the approximate chi-square distribution with one degree of freedom,

$$\chi^2 = \frac{(O_1 - E_1)^2}{E_1} + \frac{(O_2 - E_2)^2}{E^2}, \qquad (1)$$

where the O_1 and O_2 are the observed numbers and E_1 and E_2 are the expected numbers of dead trees in the scarlet oak and black oak species groups, respectively. The expected numbers of dead trees for each species and time step were calculated as a proportion of all trees that died with the interval with the proportion computed as the relative number of trees of each species at the start of the period.

$$E_k = \sum_{j=1}^{i} e_{kt_j} = \sum_{j=1}^{i} \frac{n_{kt_j}}{n_{li_j} + n_{2t_j}} * d_{t_j} \quad k = 1, 2, \qquad (2)$$

where n_{1t_j} and n_{2t_j} are the number of remaining live trees at inventory year t_j and d_{t_j} is the total number of dead trees of black and scarlet oaks that occurred over the inventory time interval. Second, based on results in the first step, we conducted CART analyses separately for black oak (6,670 trees) and scarlet oak (6,507 trees) to identify risk groups based on tree and stand variables. We used tree status (live or dead) in 2006 as the response variable and tree dbh (in.), crown class (I, dominant; II, codominant; III, intermediate; and IV, suppressed; Smith et al. 1997), and BA in larger trees (bal, calculated as the total BA [ft^2/ac] of trees larger than the candidate tree) as the splitting (independent) variables. This choice of independent variables was based on exploratory analysis and other studies (Kabrick et al. 2004, Fan et al. 2006, Shifley et al. 2006). The dbh and crown class indicate an individual tree's size and relative crown condition, while bal reflects a tree's competitive position based on the size and density of larger trees growing in proximity. The best CART models were determined using the 10-fold cross-validation method. For accurate estimation of survival, we specified that the tree number in each risk group should not be <200 in the best CART models. Technical details of CART-based survival analysis are described in Fan et al. (2006). Third, we bootstrapped the best CART models for black and scarlet oaks 200 times to quantify the relative risk (confidence interval) of oak mortality between the left (high mortality) and right (low mortality) groups identified by splitting variables in the CART model. Finally, we used the Kaplan-Meier (product limit) method to estimate tree survival rate at inventory time t_i as

$$\hat{S}(t_i) = \prod_{j=1}^{i}\left(1 - \frac{d_j}{n_j}\right), \qquad (3)$$

where t_i ($i = 1, 2, 3, 4$) represents inventory year 1995,1998, 2002, and 2006, respectively; n_i is the number of the surviving trees at inventory year t_i, and d_i is the number of the trees that died during the inventory period ending at t_i. The estimated standard error of $\hat{S}(t_i)$ can be calculated as (Kalbfleish and Prentice 2002)

$$\hat{\sigma}(\hat{S}(t_i)) = \hat{S}(t_i)\sqrt{\sum_{j=1}^{i} \frac{d_j}{n_j(n_j - d_j)}}. \qquad (4)$$

Development of a Stand HI of Oak Decline and Mortality

Oak decline, the precipitous mortality of mature oak trees has been a chronic problem in xeric oak ecosystems and is reaching unprecedented levels in the red oak group (*Quercus* section *Lobatae*) species in the Ozark Highlands. The high rates of mortality are leading to rapid changes in species composition, forest structure, and related changes in fire risk, insect population dynamics, and the belowground ecology of root diseases such as Armillaria. The importance and severity of these changes have caused us to investigate methods for quantifying oak decline hazard based on the factors associated with decline-induced mortality. The CART models classified potentially declining scarlet and black oak trees into nine and seven disjoint risk groups based on three major predisposing factors (dbh, crown class, and bal). The survival analysis (Kaplan-Meier curves) showed that the identified risk groups except for the risk group V of scarlet oak maintained the same order over the 16-year monitoring period, indicating the temporal stability of these risk groups.

As a basic unit of forest management, a stand is composed of trees of different species, sizes, and growing conditions. In the Ozark Highlands of Missouri, the oak decline hazard of a stand is mainly determined by two factors: the abundance and growing condition of two major decline-prone species: scarlet and black oaks. A stand with more scarlet and black oak trees (growing on a south-facing site or in shallow, rocky soil) has a higher risk (hazard) of experiencing oak decline. Moreover, a stand with more scarlet and black trees falling within high risk groups (e.g., I, II, III, and IV in the CART models) is more susceptible to oak decline. Therefore, we use the ratio of the number of dead black and scarlet oak trees versus total tree number (dead standing plus live standing trees) in a stand to express a stand HI of oak decline. As shown in Equation 5, HI is expanded into two parts: relative mortality (M) and relative abundance (A) of black and scarlet oaks to reflect both the decline condition and the abundance of scarlet and black oak trees in a

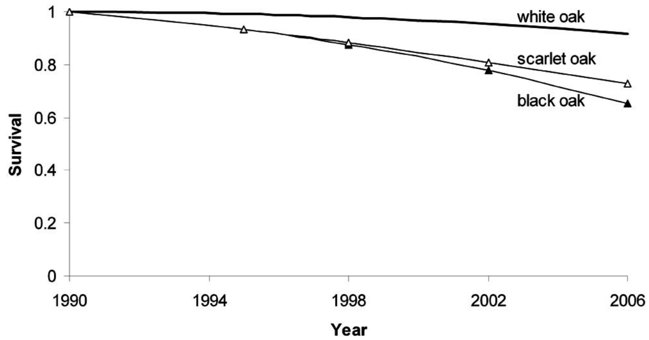

Figure 2. Survival of declining black and scarlet oaks versus white oak (reference).

stand. Note that "abundance" as defined here includes the total of standing dead and live trees,

$$\begin{aligned}
HI &= \frac{\text{dead_tree_number_of_black_oak_and_scarlet_oak}}{\text{total_tree_number_in_a_stand}} \\
&= \frac{\text{dead_tree_number_of_black_oak_and_scarlet_oak}}{\text{total_tree_number_of_black_oak_and_scarlet_oak}} \\
&\quad \times \frac{\text{total_tree_number_of_black_oak_and_scarlet_oak}}{\text{total_tree_number_in_a_stand}} \\
&= M \times A. \qquad (5)
\end{aligned}$$

Based on the CART models of scarlet oak and black oak, the HI in Equation 5 can be quantified as

$$\begin{aligned}
HI &= \sum_{i=1}^{IX} MS_i * AS_i + \sum_{j=1}^{VII} MB_j * AB_j \\
&= \{[4.3AS_{I} + 3.1AS_{II} + 1.9AS_{III} + 2.1AS_{IV} + 2.1AS_{V} \\
&\qquad + 1.7AS_{VI} + 1.2AS_{VII} + 0.9AS_{VIII} + 0.5AS_{IX}] \\
&\quad + [3.9AB_{I} + 2.9AB_{II} + 2.6AB_{III} + 1.9AB_{IV} \\
&\qquad + 1.6AB_{V} + 1.3AB_{VI} + 10AB_{VII}]\}/100 \qquad (6)
\end{aligned}$$

where MS_i and AS_i (i = I, II, …, IX), and MB_j and AB_j (j = I, II, …, VII) are the relative mortality and relative abundance of scarlet and black oaks within each risk group, respectively. The relative mortality for each risk group was replaced by the annual mortality (percent) estimated by the CART models.

The prediction accuracy of HI in Equation 6 is related to sample size (the AS and AB), because the coefficients (weights) are properties of a large sample. HI may either seriously underestimate or overestimate the true value if the ASs and ABs are too small. An independent sample of 27 0.2-ha (one-half acre) plots (about 3,000 trees) from a MOFEP study site was used to test how the predicted HI vary around the observed. The resampling technique (drawing without replacement) was used to draw a set of samples of size = 0.2, 0.4, 0.6, …, 5.4 ha (including all sample plots), respectively. The relative difference (residual) between the predicted and observed HI (1 − predicted/observed) was plotted against sample size to evaluate how the prediction accuracy of HI changes with the sample size. Using the HI to accurately rank forest stands is of practical importance for resource managers and foresters in forest management and planning.

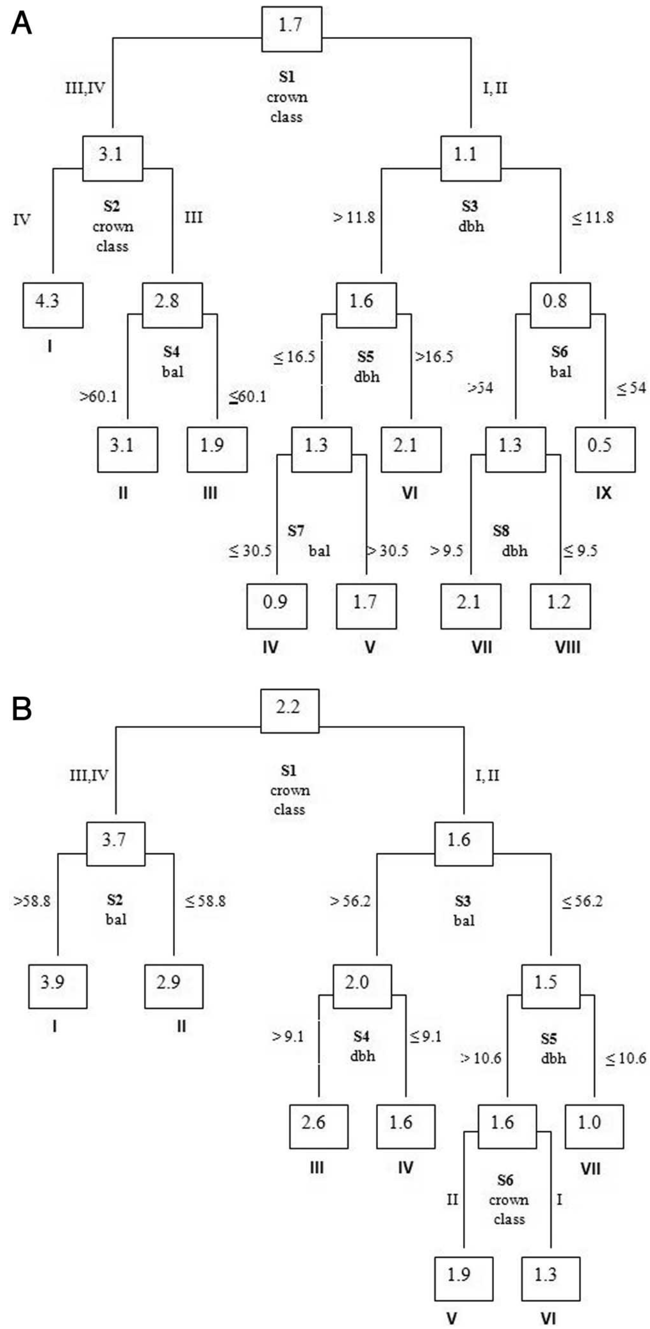

Figure 3. Annual mortality (%) of (A) scarlet oak and (B) black oak by risk groups identified by CART analysis. Annual mortality rates are shown within boxes for each statistically significant category. Each dichotomous split is numbered (S_i) and indicates the variable and values used to identify the subordinate categories. Crown class is a categorical variable (I, dominant; II, codominant; III, intermediate; and IV, suppressed), tree dbh is expressed in inches, and BA in larger trees (bal) is expressed in square feet per acre. Roman numerals indicate terminal categories that are further described in Figure 4. Additional information about each split is presented in Table 2.

Results

Compared with white oak (92% survival rate), only 65 and 73% of black oak and scarlet oak, respectively, survived after 16 years

Table 1. Risk groups for scarlet oak and black oak based on classification and regression tree analysis (listed from high to low mortality).

Risk group number	Description	Annual mortality (%)
Nine risk groups for scarlet oak		
Within intermediate and suppressed trees		
I	Suppressed trees	4.3
II	Intermediate trees with bal > 60.1 ft^2/ac	3.1
III	Intermediate trees with bal ≤ 60.1 ft^2/ac	1.9
Within dominant and codominant trees		
VI	dbh > 16.5 in.	2.1
VII	9.5 in < dbh ≤11.8 in. and bal > 54 ft^2/ac	2.1
V	11.8 in < dbh ≤ 16.5 in. and bal > 30.5 ft^2/ac	1.7
VIII	dbh ≤ 9.5 in. and bal > 54 ft^2/ac	1.2
IV	11.8 in < dbh ≤ 16.5 in. and bal ≤ 30.5 ft^2/ac	0.9
IX	dbh ≤ 11.8 in. and bal ≤ 54 ft^2/ac	0.5
Seven risk groups for black oak		
Within intermediate and suppressed trees		
I	bal > 58.8 ft^2/ac	3.9
II	bal ≤ 58.8 ft^2/ac	2.9
Within dominant and codominant trees		
III	bal > 56.2 ft^2/ac and dbh ≤ 9.1 in.	2.6
V	Codominant trees with bal ≤ 56.2 ft^2/ac and dbh > 10.6 in.	1.9
IV	bal > 56.2 ft^2/ac and dbh ≤ 9.1 in.	1.6
VI	Dominant trees with bal ≤ 56.2 ft^2/ac and dbh > 10.6 in.	1.3
VII	bal ≤ 56.2 ft^2/ac and dbh ≤ 10.6 in.	1.0

Table 2. Relative risks (RR) and 95% CIs for each dichotomous split in the scarlet oak and black oak classification and regression tree models shown in Figure 3.

Split	Annual mortality in node (%)	Sample size (trees no.)	RR (95% CI[a])
Scarlet oak			
S1	1.7	6,507	2.69 (2.39–3.02)
S2	3.1	1,963	1.54 (1.19–1.98)
S3	1.1	4,544	1.85 (1.59–2.16)
S4	2.8	1,633	1.63 (1.29–2.06)
S5	1.6	1,829	1.59 (1.28–1.98)
S6	0.8	2,715	2.68 (2.12–3.39)
S7	1.3	1,229	1.79 (1.35–2.38)
S8	1.3	1,212	2.01 (1.49–2.71)
Black oak			
S1	2.2	6,670	2.26 (2.01–2.54)
S2	3.7	1,637	1.35 (1.04–1.75)
S3	1.6	5,033	1.40 (1.23–1.59)
S4	2.0	1,640	1.57 (1.28–1.94)
S5	1.5	3,393	1.53 (1.25–1.88)
S6	1.6	2,547	1.49 (1.25–1.79)

[a] CI was based on 200 bootstrapped samples.

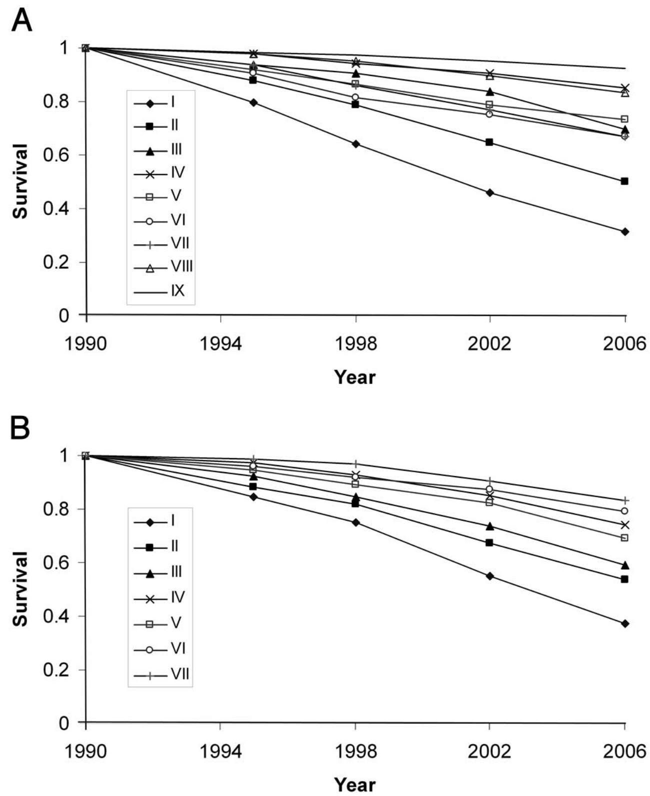

Figure 4. Survival of (A) scarlet oak and (B) black oa by risk groups. Risk groups (identified by Roman numeral) represent terminal CART classifications identified in Figure 3. During the growing season, abnormally dry conditions occurred in 1991, 1996, 2000, and 2005 (Dr. Richard Guyette, pers. comm., University of Missouri, Department of Forestry, Feb. 2008).

(Figure 2). The log-rank test showed that the difference in survival time between black and scarlet oaks is statistically significant by year 2006 ($P < 0.0001$). As shown by the estimated Kaplan-Meier curves, no difference was evident between black and scarlet oaks for the first 8 years (1990–1998). The difference between these two species significantly increased after 1998 as black oak mortality escalated.

Seven and nine terminal risk groups were identified by CART for scarlet oak and black oak, respectively (Figure 3; Table 1). As illustrated by CART, crown class was the most significant determinant of survival for both species. Crown class divided scarlet oaks and black oaks into two internal risk groups: (intermediate + suppressed trees) and (dominant + codominant trees) with respective annual mortality of 3.1% versus 1.1% (scarlet oak), and 3.7% versus 1.6% (black oak). Based on the location in the CART hierarchy, bal was more influential to black oak survival (i.e., appearing in the upper level of the CART model) than was dbh for scarlet oaks (Figure 3). Effects of crown class, bal, dbh, and associated thresholds on mortality were quantified by the relative risk (RR) and its confidence interval (CI). For instance, crown class (split S2 in scarlet oak CART model) was relatively less important among small trees than dbh among large trees (split S3 in scarlet oak model), because split S2 had a lower RR and wider CI than split S3. However, the RR for each split is statistically significant (Table 2; i.e., the bootstrapped CIs do not include zero).

Over the 16-year monitoring period, scarlet oak and black oak plagued by oak decline had annual mortality as high as 1.7 and 2.2%, respectively, in contrast to the 0.5% annual mortality rate of white oak, a longer-lived oak species minimally affected by the decline syndrome. Annual mortality among risk groups ranged from 0.5 to 4.3% for scarlet oak and from 1 to 3.9% for black oak. The Kaplan-Meier curves traced the survival trend of individual risk groups for both species (Figure 4). During the 16-year study period, survival of scarlet oak decreased linearly compared with the curvilinear pattern of black oak.

As Figure 5 illustrates, the HI more closely predicted the real decline-induced mortality as the sample size increased. The widely

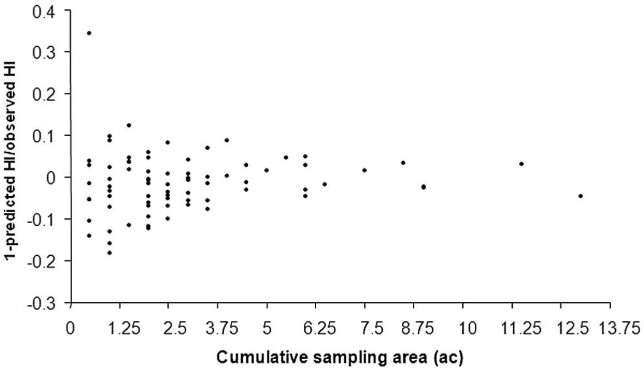

Figure 5. Change of relative residuals of HI with cumulative sampling area (ac).

Table 3. Relative basal area (BA) and mean annual mortality (%) of oaks and associated species on Missouri Ozark Forest Ecosystem Project sites.

Species	Percent of all BA	Mean annual mortality
Black oak (*Q. velutina* Lam.)	23	2.2
Scarlet oak (*Q. coccinea* Muenchh.)	21	1.7
White oak (*Quercus alba* L.)	20	0.5
Post oak (*Quercus stellata* Wangenh.)	6	1.2
Chinkapin oak (*Quercus muehlenbergii* Engelm.)	1	0.8
Blackjack oak (*Quercus marilandica* Muenchh.)	1	4.6
Shumard oak (*Quercus shumardii* Buckl.)	<1	0.8
Northern red oak (*Quercus rubra* L.)	<1	1.0
Shortleaf pine (*Pinus echinata* Mill.)	8	1.0
Pignut hickory (*Carya glabra* [Mill.] Sweet)	4	0.4
Black hickory (*Carya texana* Buckl.)	4	0.8
Mockernut hickory (*C. tomentosa* Poir. Nutt.)	4	0.6
Flowering dogwood (*Cornus florida* L.)	3	1.5
Blackgum (*Nyssa sylvatica* Marsh.)	2	0.3
Thirty-six other tree species combined	3	1.2

Total exceeds 100% due to rounding.

adopted one-plot (one-half acre in size) scheme to evaluate other characteristics of a stand, e.g., species composition and BA per hectare, is not appropriate for oak decline and mortality evaluation. The predicted mortality may overestimate or underestimate the truth by over 30% at this scale (one-half acre.). To achieve accurate prediction (e.g., 10% of relative error), the minimum sample area should be ≥2.5 ac. The relative error fluctuated within 10% as the sample size increased above 6 ac.

Discussion

In the Ozark Highlands oak decline was reported in the 1970s or even earlier (Toole 1960). Regionwide droughts during the early 1980s, late 1990s, and part of this decade exacerbated oak decline, and oak tree mortality associated with decline (dieback) increased drastically (Lawrence et al. 2002). Most of the trees affected by oak decline were in the red oak species group, particularly black oak and scarlet oak, which are prominent species in the Ozark forests (Moser et al. 2007). Based on MOFEP data, black oak and scarlet oak account for approximately 45% of the overall overstory BA, and all other red oak group species represent <5% of that (Table 3). Over the 16-year monitoring period (1990–2006), black oak and scarlet oak annual mortality due to oak decline averaged 2.2 and 1.7%, respectively, which are three to four times higher than observed for white oaks growing in the same communities and higher than previously reported mortality rates for black and scarlet oaks of similar size (Shifley and Smith 1982).

A large portion of dead oak trees occurred on moisture-deficient sites such as south-facing slopes and ridge tops. However, relative oak mortality (calculated as a percentage of the overall oak tree density and BA) did not reveal a significant difference from other sites, indicating effects of site factors (e.g., slope, aspect, and ecological land types) are marginal (Kabrick et al. 2008). The rapid accumulation of dead oak trees on south-facing slopes and ridge tops mainly results from the prevalence of black oak and scarlet oak on these sites. In the early 1900s these two oak species, because of their fast-growing and resprouting characteristics, quickly took the place of shortleaf pine and other hardwood competitors to become major components on dry or nutrient-deficient sites after extensive logging and subsequent burning and grazing (Cunningham and Hauser 1989, Kabrick et al. 2008). However, black oak and scarlet oak are relatively short-lived, so they are extremely vulnerable to oak decline and insect and disease attacks caused by environmental stress such as drought as they mature physiologically (Hicks 1998).

Drought is the major inciting factor triggering the recent decline in the Ozarks (Lawrence et al. 2002). According to the Kaplan-Meier survival curves (Figures 2 and 4), however, black and scarlet oaks responded differently. Black oak was more susceptible to drought than scarlet oak after the severe droughty period from 1998 to 2000. Before that time these two species had a nearly identical mortality rate, but then black oak mortality rate increased quickly and by year 2006, the difference became statistically significant (Figure 4).

Differences in black oak and scarlet oak mortality patterns are reflected in the CART model, where black oak survival seems more closely related to competition from above (bal), and scarlet oak survival is more related to individual tree size (dbh; Figure 3). This means that black oak decline and mortality is more susceptible to high stand density (stocking) than scarlet oak. With regard to relationships among tree survival, drought, and dbh growth, Jenkins and Pallardy (1995) noted that trees that grew fast before drought usually had lower survival than those that grew slowly. One morphological interpretation to explain this is that trees with rapid growth had low root–shoot ratios, and during drought periods they are less able to acquire sufficient moisture to support the relatively large aboveground tree biomass. Mechanistic exploration of oak decline and mortality and explicit quantification of the relationship between black oak survival and the interaction of drought and predisposing factors will be a challenge in future forest health monitoring.

The risk groups for black oak and scarlet oak revealed the relationship of major predisposing (predictive) factors associated with oak decline and mortality (or survival). Separate CART models for black oak and scarlet oak (Figure 3) are similar in some respects to the combined model for the whole red oak group over the first 12 years of observation (Shifley et al. 2006). We separated black oak from scarlet oak in this study primarily because these two species showed statistically significant differences in survival during years 12–16 of observation (2002–2006). The CART models for individual species identified species-specific differences in the interaction of predisposing factors and their association with mortality and survival rates.

We did not further combine risk groups into a set of nonoverlapped survival groups as done by Fan et al. (2006) because our aim was to monitor/trace survival based on risk groups and the CART model. Survival rates of these risk groups were not necessarily different from one another. As shown in Figure 4, the survival curves for certain risk groups intersect, which indicates other factors (e.g., crown dieback condition) may improve the ability of the CART model to distinguish mortality classes (Fan et al. 2006).

Oak decline and mortality is a chronic process and results from many factors. Before the physiological and mechanistic causes of oak decline and mortality are uncovered, both onsite monitoring practices and laboratory tests of potential assumptions, as well as applied monitoring tools and models, are a necessity. Given known facts on oak decline and mortality, integrating drought and other potential inciting factors with well-known predisposing factors should be a focus for future monitoring activities. Risk groups identified by these analyses can be used by managers to favor retention of trees that are most likely to survive and promote early use of trees that are most likely to die.

Developing an HI to evaluate stand decline condition is challenging. The stand-level model itself can not accomplish this task because of the structural and compositional diversity and complicity of natural oak stands and the multiple level characteristics of predisposing, inciting, and contributing factors associated with oak decline. Aggregation of the tree-level decline model provides an appropriate option. Compared with the regression models (e.g., logistic regression), CART seems more appealing and intuitive to aggregate tree-level mortality up to the stand-level hazard estimation. Logistic regression predicts the probability of each individual tree and therefore needs to aggregate each individual tree's mortality in a stand to estimate the HI. However, unlike logistic regression, CART classified the declining trees into a limited number of groups (terminal nodes). As noted, the stand HI is solely estimated as the linearly weighted combination of the terminal nodes of the CART models. Foresters and resource managers can use a set of rules and criteria CART identified and the distribution of declining trees among these groups to evaluate stand hazard. The temporal stability of these risk groups over a relatively long monitoring period (16 years) makes the stand HI a more reliable measure of oak decline condition in the Ozark Highlands.

Conclusions

Among overstory trees (≥4.5-in. dbh) 65 and 73% of live black oaks and scarlet oaks measured in 1990 were still alive by the most recent monitoring year (2006); this contrasts with the 92% survival rate for white oaks. The low survival rate of black oak and scarlet oak caused by oak decline (dieback) will have significant impact on future species composition and forest structure. Using this information, managers can help mitigate decline by encouraging regeneration of more decline-resistant species while optimizing growing conditions for existing decline-prone species.

The seven and nine risk groups identified by the CART model for black oak and scarlet oak quantified the effects of predisposing factors (crown class, dbh, and bal) on tree mortality and survival. The CART models and Kaplan-Meier survival curves, in combination, provided an intuitive but statistically rigorous tool for risk assessment and monitoring of oak decline and mortality in affected forest stands. However, further study is needed to explicitly incorporate important inciting factors (e.g., drought) to the model structure and integrate those with predisposing factors (e.g., dbh, bal, and crown class) in a mechanistic way.

The HI provides a practical measure of oak decline and mortality severity based on the risk groups (terminal nodes) identified by CART. In the Ozark Highlands, a sample area of at least 1 ha (2.5 ac) per stand on average is necessary to obtain 10% relative error. However, based on our test result, a sample area of 2 ha (5 ac.) per stand should be used so that the relative error is <10%. In practice, foresters or resource managers will only need to tally black and scarlet oak trees falling within each group to estimate the HI of a stand.

Both drought and predisposing stand and tree factors including crown class, dbh, and bal are associated with mortality rates for decline-prone black oak and scarlet oak trees. Black oaks exhibited higher rates of mortality, but there were no statistically significant differences among black and scarlet oak survival during the first 12 years. This highlights the important role of long-term monitoring in revealing changes in ecosystem processes.

Application

As shown in Equation 5 the HI of red oak decline was expressed as the ratio of the number of dead black and scarlet oak trees versus total tree number (dead standing trees plus live standing trees) in a stand, which was the product of two components: relative mortality (M) and relative abundance (A) of red oaks. To estimate the HI for a stand or a management unit/tract, foresters and managers need know both M and A, which can be estimated by the CART model (Figure 3 and Table 1) and through sample surveys, respectively. Equation 6 was the expanded form of the CART model for the HI calculation. To calculate an HI, one needs to survey a sample area of 3–5 ac (or three to five 1-ac plots) to obtain a overstory tree (>4.5 in) list with species, dbh, and crown class measured or recorded for each tree in the list. Then, follow these steps to calculate the HI:

1. Sort the tree list based on dbh in a descending order using a spreadsheet.
2. Calculate the BA (BA = $3.14 * (\text{dbh}/2)^2$ [in ft^2]) for each tree.
3. Calculate the bal (BA in larger trees [in ft^2/ac]) for each tree. For instance, the largest tree's bal is equal to zero, the second largest tree's bal is equal to the largest tree's BA divided by the sample area (in ac), the third largest tree's bal is equal to the sum of the first and second largest trees' BA divided by the sample area, the fourth largest tree's bal is equal to the sum of the first, second, and third largest trees' BA divided by the sample area, and so on.
4. Based on the criteria listed in Table 1, group the trees into one of the seven risk groups for black oak and the nine risk groups for scarlet oak, respectively.
5. Calculate the relative abundance (proportion) of black oak and scarlet oak in the seven and nine risk groups, respectively.
6. The HI is the sum of the product of the relative abundance and annual mortality of the 16 risk groups as shown in Equation 6.

We specify the sample area between 3 and 5 ac so that the estimated HI will have a small error (<10%). Statistically, the larger the sample area is, the smaller the error will be. But from a practical standpoint, 3–5 ac should be reasonable. Based on this study, the HI calculation is applicable to mature stands between 70 and 120 years old with little or no intensive management for the past 40 years.

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