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Oak mortality associated with crown dieback and oak borer attack in the Ozark Highlands

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Abstract

Oak decline and related mortality have periodically plagued upland oak–hickory forests, particularly oak species in the red oak group, across the Ozark Highlands of Missouri, Arkansas and Oklahoma since the late 1970s. Advanced tree age and periodic drought, as well as Armillaria root fungi and oak borer attack are believed to contribute to oak decline and mortality. Declining trees first show foliage wilt and browning, followed by progressive branch dieback in the middle and/or upper crown. Many trees eventually die if severe crown dieback continues. In 2002, more than 4000 living oak trees $\geq$11 cm dbh in the relatively undisturbed mature oak forests of the Missouri Ozark Forest Ecosystem Project (MOFEP) were randomly selected and inventoried for tree species, dbh, crown class, crown width, crown dieback condition (healthy: <5% crown dieback, slight: >5–33%, moderate: 33–66%, and severe: >66%) and number of emergence holes created by oak borers on the lower 2.4 m of the tree bole. The same trees were remeasured in 2006 to determine their status (live or dead). In 2002, about 10% of the red oak trees showed moderate or severe crown dieback; this was twice the percentage observed for white oak species. Over 70% of trees in the red oak group had evidence of oak borer damage compared to 35% of trees in the white oak group. There was significant positive correlation between crown dieback and the number of borer emergence holes ($p < 0.01$). Logistic regression showed oak mortality was mainly related to crown width and dieback, and failed to detect any significant link with the number of oak borer emergence holes. Declining red oak group trees had higher mortality (3 or 4 times) than white oaks. The odds ratios of mortality of slightly, moderately, and severely declining trees versus healthy trees were, respectively, 2.0, 6.5, and 29.7 for black oak; 1.8, 3.8, and 8.3 for scarlet oak; and 2.6, 6.5 and 7.1 for white oaks.
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Keywords: Oak decline; Mortality; Oak borer; Logistic regression

1. Introduction

Oak decline is the progressive crown dieback and eventual mortality of oaks over a wide geographic area (Starkey and Oak, 1989). It has been reported in most eastern states since the mid-1800s (Millers et al., 1989). Studies reveal that the chronic process of oak decline syndrome starting with foliage wilt and browning followed by progressive branch dieback and increased probability of tree mortality is a complex interaction of numerous factors often classified as predisposing stress factors (e.g., poor site quality, unfavorable stand condition, advanced tree age), inciting factors (e.g., drought, frost, tree damage) and contributing factors (e.g., disease, root fungi, insect borers) based on their respective roles in the decline process (Law and Gott, 1987; Starkey and Oak, 1989; Lawrence et al., 2002; Kabrick et al., 2004).

In the Interior Highlands of Missouri, Arkansas and Oklahoma, oak decline has remained a chronic problem since the late 1970s (Law and Gott, 1987); it has become increasingly severe as the numerous fully stocked and over-stocked oak forests in this region approach physiologic maturity. The

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likelihood of a tree being susceptible to decline and mortality depends on its species and physiological condition (vigor) and varies with the duration and intensity of inciting factors like drought and secondary insects/diseases (Fan et al., 2006; Kabrick et al., 2004; Shifley et al., 2006). Repeated droughts in the Interior Highlands from 1998 to 2000 exacerbated the decline process and resulted in increased mortality of declining oaks, particularly those of red oak group (Fan et al., 2006; Starkey et al., 2004). However, the species dynamics can be somewhat complex. For instance, in a 14-year monitoring study in the Missouri Ozarks, Dwyer et al. (2007) reported that fewer trees in the white oak species group than in the red oak species group exhibited moderate to severe crown dieback, but white oaks that showed moderate to severe crown dieback were more likely to die than comparable trees in the red oak species group. Insects such as red oak borers (*Enaphalodes rufulus* (Haldeman) Coleoptera: Cerambycidae) may damage oaks and degrade the timber quality due to the galleries they excavate, but rarely do they directly cause tree mortality (Solomon, 1995).

Extensive oak mortality and unprecedented abundance of oak borer populations are significant threats to forest health and economic value of timber. Regionally, there is a need to (a) identify trees and stands that are at high risk for oak decline, (b) forecast the mortality risk for individual trees within declining stands, and (c) select silvicultural treatments to mitigate decline. In this study we examined the relative importance of information about of oak species, tree size, crown dieback class, and the density of oak borer exit wounds for forecasting future mortality of oak trees.

2. Methods

2.1. Study site

We used data from the Missouri Ozark Forest Ecosystem Project (MOFEP), 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 located in southeastern Missouri, USA (centered approximately 37°7′12″N, 91°6′45″W). 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, 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 <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 and mean July maximum temperature is 32 °C. Mean annual precipitation is 114 cm with 56% falling between April and October (Nigh and Schroder, 2002).

2.2. Data

There are 648 permanent 0.2 ha vegetation plots distributed roughly equally among the nine MOFEP sites. Since 1992, these permanent plots have been re-inventoried approximately every 3 years to document the condition of woody vegetation. Characteristics recorded for each tree include species, diameter at breast height (dbh), status (e.g., live, dead, den, cut, down), and crown class (dominant, codominant, intermediate, suppressed) (Jensen, 2000). Trees >11 cm dbh are permanently tagged to ensure proper identification when they are remeasured.

Data from vegetation plots showed that when the study was initiated in 1992, the forests were second growth and fully stocked (Gingrich, 1967) and that 68% of the canopy dominant and codominant trees were 45–65 years old. Oaks were the dominant trees and four oak species – black oak (*Quercus velutina* Lam.), scarlet oak (*Q. coccinea* Muenchh.), white oak (*Quercus alba* L.), and post oak (*Q. stellata* Wangenh.) – comprised 71% of the basal area (Table 1). Other oaks found at MOFEP included chinkapin oak (*Q. muehlenbergii* Engelm.), blackjack oak (*Q. marilandica* Muench.), Shumard oak (*Q. shumardii* Buckl.), and northern red oak (*Q. rubra* L.), but in combination they comprised only 1% of the basal area. Shortleaf pine (*Pinus echinata* Mill.) (8%), pignut hickory [*Carya glabra* (Mill.) Sweet] (4%), black hickory (*C. texana* Buckl.) (4%), mockernut hickory (*C. tomentosa* Poir. Nutt.) (4%), flowering dogwood (*Cornus florida* L.) (3%), and blackgum (*Nyssa sylvatica* Marsh.) (2%) also occurred in the study area.

In the period 1999–2002, the incidence of oak decline was particularly acute at locations in the Missouri Ozarks and the Interior Highlands of Arkansas (Law et al., 2004; Starkey et al., 2004). In 2002, the MOFEP sites appeared to have an especially high incidence of crown dieback (personal observations), so in that year on each of the 448 MOFEP plots that were undisturbed by prior harvesting we examined trees of each of four species: black oak, scarlet oak, white oak, and post oak. Whenever possible we measured five randomly selected trees of each species per plot. However, when fewer than five trees of a species were present on a plot, we measured additional trees of

Table 1
Relative basal area of major oaks and associated species on Missouri Ozark forest ecosystem project sites

Species	Percent of all basal area
White oaks (*Q. alba* L., *Q. stellata* Wangenh.)	26
Black oak (*Quercus velutina* Lam.)	23
Scarlet oak (*Q. coccinea* Muenchh.)	21
Hickories (*Carya glabra* (Mill.) Sweet, *C. texana* Buckl., *C. tomentosa* Poir. Nutt.)	12
Shortleaf pine (*Pinus echinata* Mill.)	8
42 other tree species combined	10

the other oak species. The number of observations per species per plot ranged from 1 to 10. For this subset of 4837 trees >11 cm dbh we recorded crown width, and crown dieback class (none = <5%; slight = 5–33%; moderate = 34–66%; severe = >66%). We also, noted evidence of oak borer damage including bark scars and sap stains and recorded the number of oak borer emergence holes on the first 2.4 m of bole (i.e., the butt log). We attempted to identify the species of oak borers that had caused the damage and we verified our estimates by cutting into borer-damaged trees in nearby stands that were recently harvested. Our verifications confirmed that most of the borer damage was caused by the red oak borer and by the twolined chestnut borer (*Agrilus bilineatus* (Weber) Coleoptera: Buprestidae). The same trees were reexamined in 2006 after 3 complete growing seasons to determine whether they lived or died.

2.3. Statistical analyses

In our analyses we separately examined black oak, scarlet oak, and a white oak group comprised of white and post oaks together; post oak is relatively less abundant (6% of basal area) and similar to white oak with regard to decline condition (Fan et al., 2006; Kabrick et al., 2004; Shifley et al., 2006). We (a) computed proportions of trees by crown dieback classes and number of borer emergence holes (by classes) to describe the trends for each species group, (b) calculated Kendall's tau index to quantify the strength of association between crown dieback class and borer attack class (both are ordinal variables), and (3) used logistic regression to model the relationship of tree mortality with tree and plot variables including crown width, dbh, basal area in larger trees (bal), crown dieback class, and borer attack class.

3. Results

On the MOFEP monitoring sites in 2002, one-fourth of white oaks (white oak and post oak) and over one third of black oaks and scarlet oaks showed signs of crown dieback of varying degree (Fig. 1A). Among them, trees with slight (5–33%) crown dieback were the majority; trees with severe (>66%) crown dieback accounted for only 2% of white, black and scarlet oaks. Compared to white oaks, black and scarlet oak had twice the number of moderately declining trees (crown dieback 34–66%).

Based on emergence holes detected in the lower 2.4 m of the bole, 81% of scarlet oaks and 73% of black oaks were attacked by red oak borers (Fig. 1B). In contrast, only 33% of white oaks showed evidence of borer attacks. Of the trees that were attacked, 28% of scarlet oaks and 25% of black oaks had 11 or more red oak borer wounds. Only 2% of the attacked white oaks had 11 or more emergence holes.

We found that oak borers attacked trees with healthy crowns as well as those with declining crowns (Fig. 2). Over 80% of scarlet oaks and black oaks not exhibiting crown dieback had been attacked by oak borers, while the majority of healthy white oaks were free from borer attacks (Fig. 2). Nevertheless,

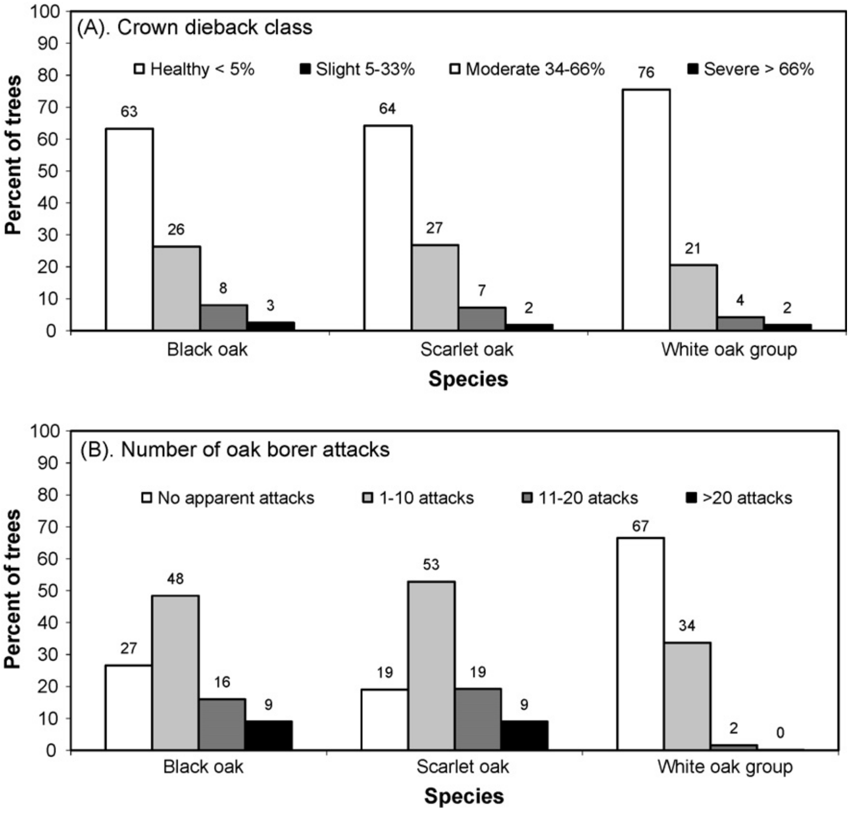

Fig. 1. Proportions of trees showing (A) crown dieback and (B) oak borer attacks in the lower 2.4 m of tree boles.

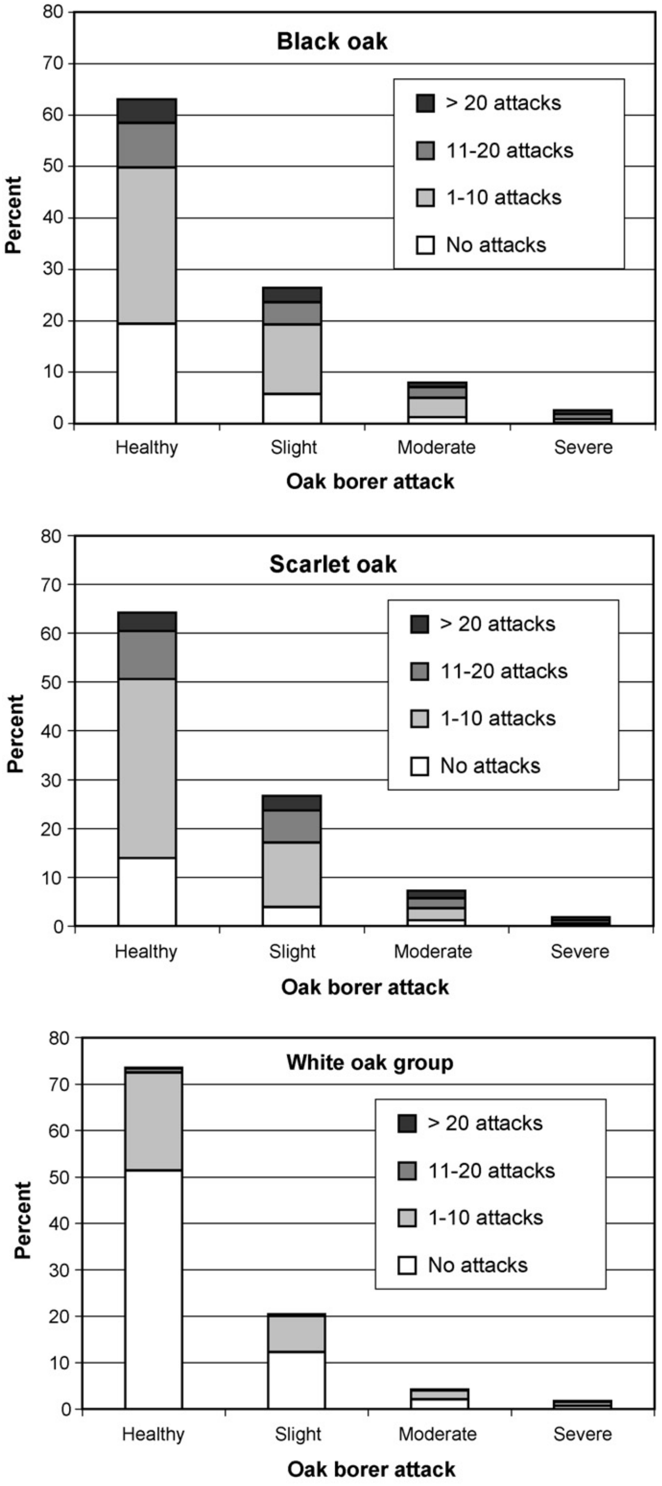

Fig. 2. Association of oak borer attacks with crown dieback among oaks in the study area. The white oak group includes both white and post oak. Crown dieback classes are healthy (<5% dieback), slight (5–33%), moderate (34–66%), and severe (>66%).

the number of oak borer emergence holes (by class) was significantly greater for trees in advance crown dieback classes for all oak species ($p < 0.01$).

Oak mortality increased with increased crown dieback and varied by species. Black oak had the greatest total mortality and greatest mortality for each crown dieback class, followed by scarlet oak, and then the white group (Fig. 3). Logistic regression confirmed that crown width, crown dieback class, dbh and species were the variables most significantly associated with observed tree mortality over the three growing seasons included in the remeasurement period (Table 2 and Figs. 4 and 5). The number of red oak borer attacks (by class) and the basal area in larger trees were not significantly related to oak mortality ($p = 0.58$ and $p = 0.21$, respectively). Within a specific crown dieback class, tree mortality increased dramatically when crown width was less than 4 m or dbh was less than 20 cm (Fig. 4). The odds ratios of tree mortality for slightly, moderately and severely declining trees versus healthy trees when adjusted by crown width were, respectively, 2.0, 6.5, and 29.7 for black oak; 1.8, 3.8, and 8.3 for scarlet oak; and 2.6, 6.5 and 7.1 for white oaks (Table 2, part A). These ratios quantify, compared to healthy trees, the increased likelihood of mortality with increasing crown dieback. For example, black oaks with severely declining crowns were about 30 (29.7) times more likely to die than comparable black oaks with healthy crowns and similar crown widths.

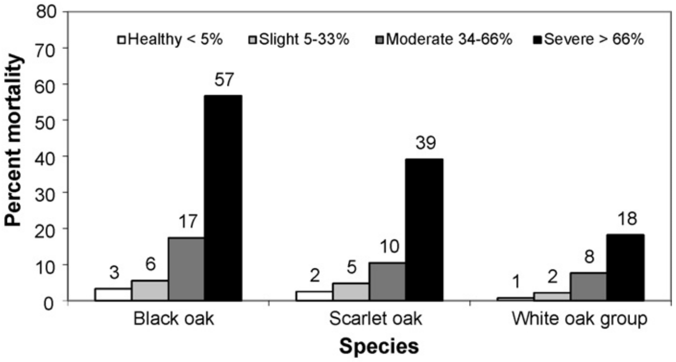

Fig. 3. Oak mortality percent over three growing seasons by species and crown dieback class.

As expected, oak mortality increased as crown class declined from dominant to overtopped. This was true for each of the oak species when all crown dieback classes were combined. Moreover, for each species there was a general trend of increasing mortality with increasing crown dieback within a given crown canopy class (Table 3). Thus, trees in the intermediate and suppressed crown classes with moderate or severe crown dieback generally had high mortality. Notable, however, were the comparatively low mortality rates for suppressed scarlet oaks with severe crown dieback and for codominant black oaks with severe crown dieback.

Oak crown width is known to be related to tree diameter; for this data set we found

$$\mathrm{cw} = 1.358 + 0.205\,\mathrm{dbh} \tag{1}$$

where cw is the crown width in meters and dbh is the tree diameter at breast height in cm. Coefficient of determination was 0.72. Thus, we substituted tree diameter for crown width and refit the logistic model for tree mortality as a function of species, dbh, and crown dieback class for the data (Table 2, part

Table 2
Estimated parameters for logistic regression of tree mortality over three growing seasons (2002–2006) as a function of species, crown dieback class, and (A) crown diameter or (B) bole diameter

Species (groups)	Number of dead/live trees	Model parameters	Estimated coefficients (S.E.)	Odds ratio and (95% CI)[a]	Hosmer–Lemeshow goodness-of-fit ($p >$ Chi-square)[b]
(A) Logistic mortality model: $p = \frac{1}{1+e^{-(a+b\log(\mathrm{CW})+c\mathrm{CD})}}$, where p is the probability of mortality over 3 growing seasons, CW is the crown width (m), and CD is 1 for the selected crown dieback class with associated coefficient					
White oaks	40/2455	*a*	4.911 (1.34)		
		b	−3.033 (0.52)	<0.1 (0.0–0.1)	0.86
		c by crown dieback class			
		Severe	0.755 (0.39)	7.1 (2.3–21.8)	
		Moderate	0.674 (0.33)	6.5 (2.5–17.2)	
		Slight	−0.229 (0.29)	2.6 (1.2– 6.0)	
		Healthy	0	Reference class	
Black oak	74/1083	*a*	6.563 (1.18)		
		b	−2.809 (0.40)	<0.1 (0.0–0.1)	0.61
		c by crown dieback class			
		Severe	1.901 (0.33)	29.7 (11.8–74.9)	
		Moderate	0.381 (0.26)	6.5 (3.2–13.3)	
		Slight	−0.792 (0.24)	2.0 (1.0–3.9)	
		Healthy	0	Reference class	
Scarlet oak	51/1134	*a*	6.058 (1.39)		
		b	−2.632 (0.45)	<0.1 (0.0–0.1)	0.35
		c by crown dieback class			
		Severe	1.110 (0.41)	8.4 (2.7–25.7)	
		Moderate	0.328 (0.33)	3.8 (1.6–9.3)	
		Slight	−0.421 (0.27)	1.8 (0.9–3.7)	
		Healthy	0	Reference class	
(B) Logistic mortality model: $p = \frac{1}{1+e^{-(a+b\log(\mathrm{dbh})+c\mathrm{CD})}}$, where p is the probability of mortality over 3 growing seasons, dbh is the diameter (cm), and CD is 1 for the selected crown dieback class with associated coefficient.					
White oaks	40/2455	*a*	1.872 (1.54)		
		b	−1.728 (0.54)	0.2 (0.06–0.51)	0.36
		c by crown dieback class			
		Severe	1.539 (0.33)	25.6 (9.8–66.9)	
		Moderate	0.692 (0.31)	11.0 (4.4–27.4)	
		Slight	−0.526 (0.28)	3.2 (1.4–7.3)	
		Healthy	0	Reference class	
Black oak	74/1083	*a*	2.865 (1.25)		
		b	−1.386 (0.37)	0.3 (0.1–0.5)	0.40
		c by crown dieback class			
		Severe	2.154 (0.31)	44.1 (18.7–104.3)	
		Moderate	0.439 (0.25)	7.9 (3.9–16.0)	
		Slight	−0.961 (0.23)	2.0 (1.0–3.7)	
		Healthy	0	Reference class	
Scarlet oak	51/1134	*a*	6.057 (1.39)		
		b	−2.632 (0.45)	0.1 (0.0–0.2)	0.46
		c by crown dieback class			
		Severe	1.590 (0.38)	20.2 (7.1–57.1)	
		Moderate	0.358 (0.31)	5.9 (2.5–13.9)	
		Slight	−0.535 (0.26)	2.4 (1.2–4.9)	
		Healthy	0	Reference class	

Crown dieback classes are healthy (<5% dieback), slight (5–33%), moderate (34–66%), and severe (>66%).

[a] Confidence interval computed using the Wald method.

[b] Small values indicate a lack of fit of the model.

B). The relationship was statistically significant ($p < 0.01$) for all three oak species. Adjusted by dbh, the odds ratios of tree mortality for slightly, moderately and severely declining trees versus healthy trees was, respectively, 2.0, 7.9 and 44.1 for black oak; 2.4, 5.9 and 20.2 for scarlet oak; and 3.2, 11.0 and 25.6 for white oaks (Table 2, part B).

Predicted mortality as a function of only tree crown width or only tree dbh was also statistically significant when estimated

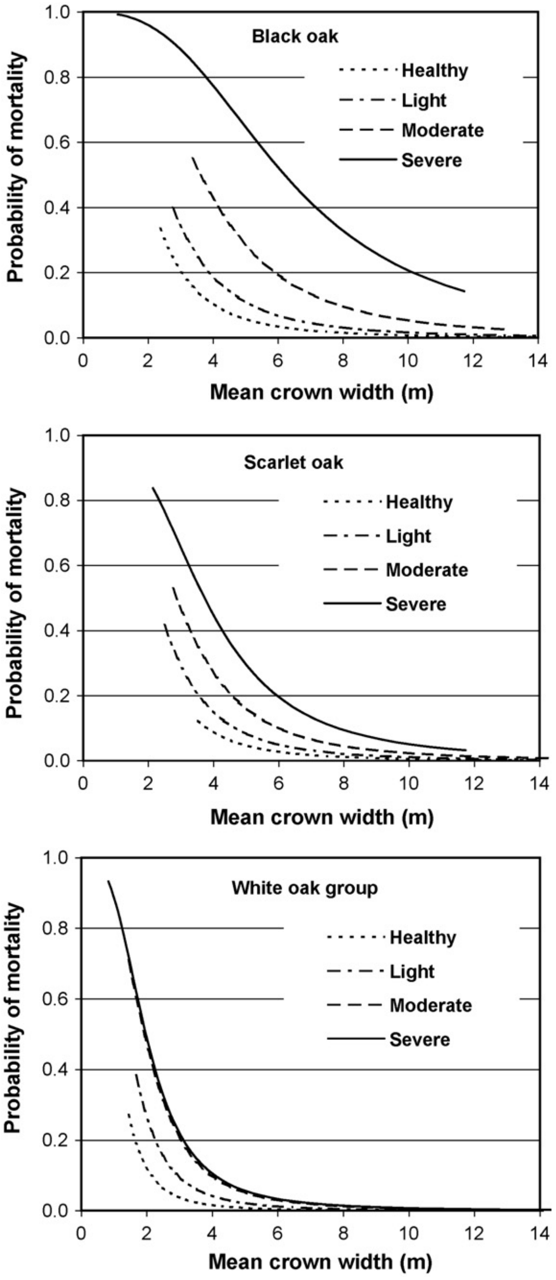

Fig. 4. Oak mortality probability over three growing seasons by species, crown width, and crown dieback class. Crown dieback classes are healthy (<5% dieback), slight (5–33%), moderate (34–66%), and severe (>66%).

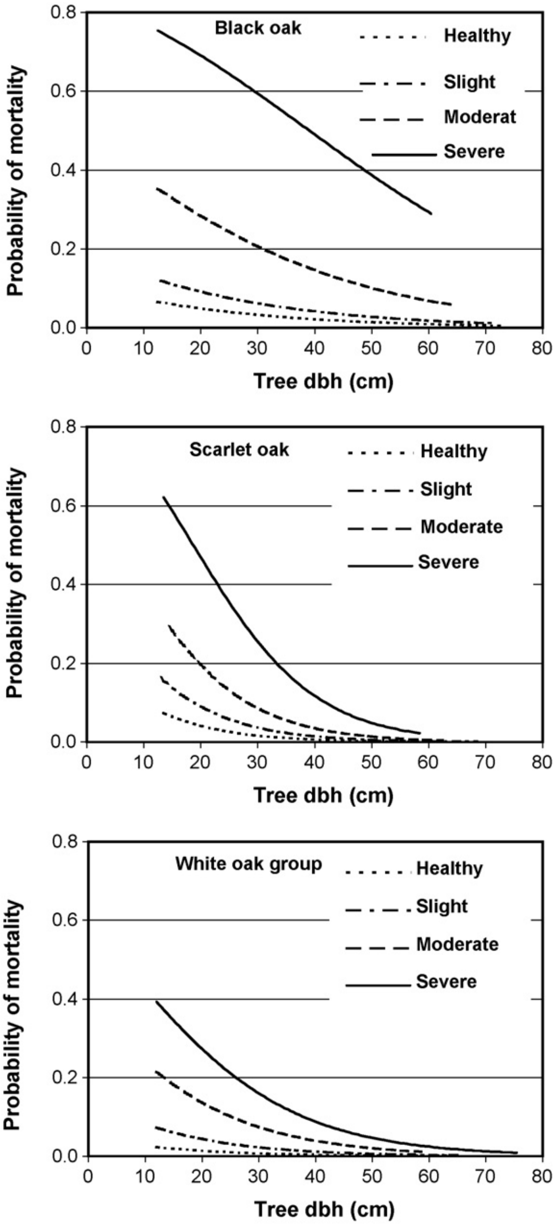

Fig. 5. Oak mortality probability over three growing seasons by species, dbh, and crown dieback class. Crown dieback classes are healthy (<5% dieback), slight (5–33%), moderate (34–66%), and severe (>66%).

with a logistic model (Table 4); mortality decreased with increasing tree crown width or dbh. However, the modeled relationship was significantly improved when crown dieback class was included in the logistic mortality model ($p < 0.01$).

4. Discussion

Although the period of observation from 2002 to 2006 was considered by local foresters to be a period of uncharacteristically high oak mortality related to oak decline, the majority of white oaks (76%) and of black and scarlet oaks (∼64%) were classified as having healthy crowns (Fig. 1A). The proportion of oak trees with moderate to severe crown dieback was small; about 10% for black and scarlet oaks and 6% for white oaks. Thus, damage to even a relatively small proportion of oak crowns stood out as uncharacteristically high crown damage. The acreage of declining oak trees with damaged crowns was substantially less than reported recently for areas of severe oak decline in northern Arkansas (Starkey et al., 2004).

The majority of sampled oak crowns had little or no dieback, but the majority of boles on sampled trees had evidence of oak borer activity (Figs. 1B and 2). For black and scarlet oak boles the majority of trees with healthy crowns showed some oak borer damage. White oaks were less affected, but 30% of white oaks with healthy crowns had some borer damage. Examined another way, trees having boles with evidence of more than 10

Table 3
Mortality probability by species, crown class, and crown dieback class over three growing seasons, 2002–2006

Crown class	Crown dieback class			
	Healthy	Slight	Moderate	Severe
White oak				
Dominant	0.0 (78)	20.4 (26)	–	–
Codominant	0.3 (658)	1.1 (189)	0.0 (28)	
Intermediate	0.7 (976)	2.7 (258)	6.6 (51)	15.4 (26)
Suppressed	3.3 (123)	2.8 (37)	33.3 (12)	23.1 (13)
Scarlet oak				
Dominant	0.0 (165)	1.3 (75)	5.3 (19)	–
Codominant	1.1 (453)	0.6 (180)	6.0 (50)	
Intermediate	9.7 (145)	20.7 (58)	31.2 (16)	66.7 (12)
Suppressed	–	–	–	0.7 (133)
Black oak				
Dominant	1.5 (67)	0.0 (17)	–	2.7 (498)
Codominant	6.0 (201)	20.6 (63)	57.9 (19)	8.3 (96)
Intermediate	5.9 (34)	20 (10)	–	–
Suppressed	–	–	–	–

Number of observations per cell are shown in parentheses; values are omitted for cells with fewer than 10 observations.

oak borer exit holes were not especially prone to moderate or severe crown dieback. Thus, evidence of oak borer damage was not particularly useful in discriminating healthy from declining trees and predicting tree mortality ($p = 0.58$).

Oak mortality in our study area was significantly related to crown dieback class and crown width, and the relationship could be explicitly modeled as a logistic function (Table 2, part A and Fig. 4). Mortality increased sharply for tree crowns less than 4 m in width. The majority of forest sampled in our study area was mature sawtimber; in those stands trees with crowns less than 4 m in width were often in the subcanopy. Even healthy oaks in the subcanopy are expected to experience relatively high competition-induced mortality. Thus, elevated rates of mortality were expected for trees with small crowns. Of greater significance is the strong relationship between observed mortality rates and crown dieback class (Fig. 4). Other factors being equal, mortality rates were highest for black oak, followed by scarlet oak. Mortality for white oak was significantly less. This is consistent with findings from other studies in the region. For example, in a 14-year study of the effects on thinning on oak decline Dwyer et al. (2007) also reported that white oaks exhibited fewer decline symptoms and lower mortality than black and scarlet oaks. However, the stand dynamics are somewhat more complicated. Dwyer et al. (2007) also found that white oaks experiencing moderate or severe crown dieback were unlikely to improve their condition over time. In contrast, black and scarlet oaks with declining crowns were variable in their response and about half the time showed improved crown health after 14 years.

Although crown width proved to be a significant indicator of tree mortality, it is difficult to measure and, thus, not well suited to field evaluation of a tree's prospects for survival. However, it has been previously documented that crown widths of healthy oaks in forested and in open environments can be expressed as a linear function of tree diameter (Gingrich, 1967; Minckler and Gingrich, 1970). Substituting diameter for crown width in the logistic regression of tree mortality slightly increases model error (Table 2), but it provides graphical (Fig. 5) or analytical (Table 2, part B) methods to estimate oak mortality when only species, dbh and crown dieback class are known. These variables are readily observable in the field when evaluating stand damage or while marking timber. Moreover, species, tree crown dieback, and tree diameter are recorded for trees measured in the systematic Forest Inventory and Analysis (FIA) forest inventory of the U.S. (USDA Forest Service, 2007). Thus, FIA plots in the study region can be coupled with the

Table 4
Estimated parameters for logistic regression of tree mortality over three growing seasons (2002–2006) as a function of species and tree diameter

Species (groups)	Number of dead/live trees	Model parameters	Estimated coefficients (S.E.)	Odds ratio and (95% CI)[a]	Hosmer–Lemeshow goodness-of-fit ($p >$ Chi-square)[b]
Logistic mortality model: $p = \frac{1}{1+e^{-[a+b\log(\mathrm{CW})]}}$, where p is the probability of mortality over 3 growing seasons and CW is the crown width (m)					
White oaks	40/2455	a	1.819 (0.71)		
		b	−3.759 (0.49)	<0.1 (0.0–0.1)	0.37
Black oak	74/1083	a	2.527 (0.61)		
		b	−2.859 (0.36)	<0.1 (0.0–0.1)	0.57
Scarlet oak	51/1134	a	2.907 (0.71)		
		b	−3.363 (0.44)	<0.1 (0.0–0.1)	0.01
Logistic mortality model: $p = \frac{1}{1+e^{-[a+b\log(\mathrm{dbh})]}}$, where p is the probability of mortality over 3 growing seasons and dbh is the diameter at breast height (cm)					
White oaks	40/2455	a	1.967 (1.63)		
		b	−2.068 (0.57)	<0.1 (0.0–0.4)	0.01
Black oak	74/1083	a	0.774 (1.10)		
		b	−1.021 (0.33)	0.4 (0.2–0.7)	0.81
Scarlet oak	51/1134	a	5.301 (1.32)		
		b	−2.635 (0.43)	<0.1 (0.0–0.2)	0.27

[a] Confidence interval computed using the Wald method.

[b] Small values indicate a lack of fit of the model.

regression model to estimate mortality risk across the Ozarks Highlands.

Although oak mortality can be modeled as a function of oak diameter alone or crown width alone (Table 4), inclusion of information about crown dieback class results in a model with significantly more explanatory power. Moreover, inclusion of crown dieback class explicitly links mortality estimation to the visible symptoms of oak decline.

5. Management implications

The above information can be used to guide management practices aimed at reducing volume or value losses to oak decline. Oak decline is typically found in stands that have reached sawtimber size (or the understory reinitiation stage of stand development). As demonstrated by Dwyer et al. (2007), harvesting declining sawtimber in stands experiencing oak decline most likely will not mitigate future decline, but it can capture volume from trees at high risk of mortality and increase the diameter and volume growth of the residual trees. A management approach for well-stocked stands experiencing oak decline would be to mark trees for removal, beginning with merchantable trees with the greatest probability of mortality. In most cases this will favor the removal of black and scarlet oaks showing symptoms of decline and retention of white oaks with little or no crown die back. For a given tree, if the probability of mortality over three growing seasons shown in Fig. 4 or Fig. 5 is greater than 12%, the odds are nearly even (50%) that the tree will not be alive at a re-entry of the stand 15–20 years later. This general approach is applicable to even-aged stands where improvement harvests or sanitation harvests (*sensu* Nyland, 1996) are prescribed or for selecting residual and reserve trees during regeneration harvests. It is also applicable to uneven-aged stands for selecting trees for removal during a typical re-entry for a 15- to 20-year cutting cycle.

The relationship of mortality to tree diameter (Fig. 5) indicates that larger trees are more likely to survive. However, for trees larger than about 40 cm dbh there is little differentiation in mortality rates due to tree diameter. A previous study of oak morality in healthy Ozark forests showed that dominant and codominant trees less than about 25 cm dbh had a lower rate of mortality than larger trees, other things being equal (Shifley et al., 2006). Thus, for trees within a given crown dieback class, tree diameter should not be a rigid criterion in selecting trees to remove or retain. Thrifty, vigorous oaks with healthy crowns and in dominant or codominant canopy positions are good choices for retention when thinning, even if there are trees with larger diameters. Healthy shortleaf pines in the overstory or mid canopy should generally be retained because they are usually better adapted to growth on sites that experience oak decline (Kabrick et al., 2008). In places where the stand presents numerous candidate trees for removal that have approximately equally probability of mortality, thinned trees should be selected to favor crop trees or to provide adequate growing space for residual stems. Regions with commercial markets for small diameter or low quality trees will provide more management alternatives for trees experiencing oak decline because of the potential for generating revenue when conducting sanitation operations.

In even-aged stands containing sawtimber and where thinning to remove trees at high risk of mortality will reduce stocking substantially below C-level on the Gingrich (1967) stocking guide, regeneration of the stand should be considered. Severely declining stands are often suited to regeneration using even-aged methods, but uneven-aged management with group selection is an alternative that can be considered in situations where thinning to remove clusters of declining trees will create a residual stand structure with numerous openings that are roughly two tree-heights in diameter or larger (e.g., Johnson et al., 2002).

When regenerating sites having extensive oak decline, managers should consider the option of converting the site to pine or a pine–oak mixture. In our study region, oak decline is often observed in mature stands where oak regeneration became dominant following harvest of stands that had been previously dominated by shortleaf pine (Kabrick et al., 2008). Black oak and scarlet oak can thrive on those pine-adapted sites for 40 or 50 years, but at greater ages pines are generally better able than these oak species to tolerate the periods of drought which inevitably occur. Alternatively, managers who choose to regenerate red oaks on sites that have experienced oak decline should be resolved to managing the future oak stands on shorter rotations and be ready to step in to mitigate future oak decline impacts as the stand matures.

6. Conclusions

Oaks as a major component of the upland oak–hickory forests represent 70% of stand basal area in the Ozark Highlands in southern Missouri. Episodic oak decline/crown dieback has been a chronic problem, and since in the late 1970s has resulted in high mortality, particularly for black and scarlet oaks. Most of the oaks that we examined had healthy crowns and only about 10% of the black and scarlet oaks and 6% of the white oaks exhibited moderate crown dieback (34–66%) or severe crown dieback (>66%). Other factors being equal, mortality rates were highest for black oak, followed by scarlet oak and least for white oak. Most of the oaks examined showed evidence of attack by oak borers, even those that had healthy crowns and otherwise appeared to be healthy. Analysis showed that oaks exhibiting borer exit wounds were not especially prone to moderate or severe crown dieback or accelerated mortality, suggesting that oak borer damage is not particularly useful for predicting tree mortality in the short term. However, oak mortality was predominately related to crown dieback class and to crown width or to dbh (i.e., a surrogate for crown width). Logistic regression models that were developed through our analyses can be used to estimate mortality from knowledge of species, dbh, and crown dieback class, information that is routinely collected during forest inventories. These models can be used to guide marking prescriptions during thinning and harvesting operations.

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