FACTORS ASSOCIATED WITH OAK MORTALITY IN MISSOURI OZARK FORESTS

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ABSTRACT.—Forest management to improve stand vigor and growth requires foresters to distinguish between trees that will respond favorably to treatment and trees that are likely to grow poorly or die. The Missouri Ozark Forest Ecosystem Project provided an opportunity to quantify factors associated with oak mortality in mature, fully-stocked, second-growth forests. We monitored more than 24,000 permanently-tagged oak trees from 1992 to 2002 and identified key factors associated with their survival or mortality. Factors considered included tree characteristics such as species, crown class, and diameter as well as site characteristics such as slope, slope position, aspect, and ecological land type. Classification and Regression Tree (CART) analyses showed that species and crown class were more important than site factors in identifying cohorts with high mortality. For a given diameter and species, tree mortality decreased with improved crown position, but mortality rates increased sharply with increasing diameter for dominant and codominant scarlet and black oaks. Mortality rates for dominant and codominant white and post oaks were stable or increased only slightly with increasing tree diameter. Mortality of black and scarlet oaks exceeded 20 percent per decade for dominant and codominant trees > 8 inches dbh. Managers can use these results to identify groups of trees with a high probability of mortality.

Forest management designed to improve stand vigor and growth requires distinguishing between trees that will respond favorably to treatment and trees that are likely to grow poorly or die. In doing so foresters must try to identify the tree and site characteristics that best indicate whether or not an individual tree will remain healthy or will die before the next treatment opportunity. Of course tree mortality is a normal part of forest dynamics. Most of the mortality in stands arises from competition for growing space and is largely the result of self thinning (Johnson and others, 2002). As trees get larger and require more growing space to survive, some trees are periodically crowded out and die. Events such as wildfire, drought, windstorms, and insect and disease epidemics also cause trees to die and often at rates exceeding those caused by competition alone (Johnson and others 2002).

Although mortality is fairly predictable at stand scales, it is more difficult to predict which individual trees are likely to die. However, this is precisely what foresters attempt to do when marking trees for harvest. While marking, they consciously (or perhaps subconsciously) evaluate the form and quality of each tree and look for characteristics that indicate whether or not an individual tree will survive and grow vigorously. They also consider many other factors such as stand density and site quality that influence tree growth and mortality. In Missouri, there is considerable concern about oak decline. Red oak group species (*Quercus spp L.*; subgenus *Erythrobalanus*) 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). Because of concern about oak decline, foresters in Missouri are more likely to remove red oak group species during stand improvement operations, especially those that are large (>18 inches DBH) or on poor sites even if the trees have no visible symptoms of decline (Kabrick and others 2002). However, these marking decisions are based upon the forester's intuition or experience rather than upon documented evidence.

Quantifying factors associated with the mortality of individual trees is challenging because it requires monitoring the survival of many individual trees for long periods. The Missouri Ozark Forest Ecosystem Project (MOFEP) afforded a rare opportunity to better quantify mortality rates of oaks. MOFEP is a long-term study to quantify the effects of forest management on upland oak systems. As such, a large number of

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individual trees were marked and are closely monitored. Here we report the results of our analysis of more than 24,000 oak trees monitored for ten years to determine if tree, stand, or site variables routinely collected during forest inventories could be used for predicting the survival of individual trees in second-growth oak forests.

Study Areas

The MOFEP study and experimental design is described elsewhere in detail (Brookshire and Shifley 1997, Shifley and Brookshire 2000, Shifley and Kabrick 2002). The study consists of nine sites ranging in size from 772 to 1,271 acres, primarily within the Current River Oak Forest Breaks and the Current River Oak-Pine Woodland Hills landtype associations of the Ozark Highlands. The Current River Oak Forest Breaks has narrow ridges and steep sideslopes with relief of 300-450 ft, which exposes the Roubidoux, Gasconade, and Eminence bedrock formations. The Current River Oak-Pine Hills has broad ridges with relief <300 feet and exposes only the Roubidoux and Gasconade bedrock formations. Upland soils of these landtype associations are primarily Ultisols and Alfisols formed in hillslope sediments or residuum; soils in upland waterways and bottomlands are primarily Ultisols and Alfisols formed in gravelly alluvium (Kabrick and others 2000, Meinert and others 1997).

Methods

Information about individual tree characteristics (e.g., species, crown class, diameter, diameter increment) were derived from 648 permanent vegetation plots distributed roughly equally among the nine MOFEP sites. Since the first inventory completed in 1992, these permanent plots have been re-inventoried approximately every three years to document the condition of woody vegetation. Characteristics recorded for each tree include species, DBH, or size class for trees < 1.5 inches DBH, and status (e.g., live, dead, den, cut, blow-down), and crown class (e.g., dominant, codominant, intermediate, suppressed) (Jensen 2000). Site characteristics (e.g., slope, land form, aspect, soil type, ecological land type, and land type association) for each plot were derived from a detailed landscape-scale soil mapping project conducted on MOFEP in 1994-1995 (Kabrick and others 2000, Meinert and others 1997).

Oaks are the dominant trees on the MOFEP sites and four oak species, white oak (*Quercus alba L.*), black oak (*Q. velutina Lam.*), scarlet oak (*Q. coccinea Muenchh.*), and post oak (*Q. stellata Wangenh.*) comprise 71 percent of the basal area (Kabrick and others, in press). Other oaks found at MOFEP include 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 comprise only 1 percent of the basal area. Shortleaf pine (*Pinus echinata Mill.*) (8 percent), pignut hickory [*Carya glabra (Mill.*) Sweet] (4 percent), black hickory (*C. texana Buckl.*) (4 percent), mockernut hickory (*C. tomentosa Poir. Nutt.*) (4 percent), flowering dogwood (*Cornus florida L.*) (3 percent), and blackgum (*Nyssa sylvatica Marsh.*) (2 percent) also are in the study area.

Data Analysis

We monitored 24,000 permanently-tagged oak trees from the initial inventory completed in 1992 to the inventory completed in 2002 and identified factors correlated to mortality. We limited our analysis to the four most abundant oaks (white oak, black oak, scarlet oak, and post oak) and trees that were ≥ 4.5 inches DBH during the initial inventory. We analyzed data from all nine MOFEP sites but only from stands that were not harvested during the past ten years. Data from plots were converted to an acre basis for analysis. We evaluated a suite of individual tree characteristics (tree DBH, species, crown class), stand condition characteristics (stand density and basal area), and site variables (aspect, slope, soil type, ecological land type, land form, land type association) for their ability to predict individual tree mortality.

Because there is a hierarchical structure and interdependence among certain variables, we used the nonparametric, hierarchical model— classification and regression tree (CART) — (Breiman and others 1984) to study the relationship of these variables to individual tree mortality. The binary response variable is whether a tree is dead (0) or is alive (1). We used CART to recursively partition 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 cutoff value of one of the explanatory variables. Therefore, the distribution patterns of dead trees in the data and factors (or factor interactions) and factor values associated with these patterns were revealed and explicitly represented by the regression "tree" or diagram showing the hierarchy among variables.

We used the 10-fold cross-validation to construct the best CART model which minimized the overall misclassification rates (Steinberg and Colla 2000). With the best CART model for each data set, we bootstrapped each node 1000 times and calculated the mean and 95 percent confidence interval (CI) of the probability of dead trees as a measure of mortality rate and variation within that node (risk group).

For cohorts identified by the CART model, we calculated the mean mortality per decade and ranked cohorts by mortality rate from highest to lowest. Once ranked, we calculated the cumulative mortality (i.e., the mortality rate for the remaining trees if all cohorts with a higher mortality rate are harvested) so that we could estimate the mortality rate for the residual stand. We also calculated the mortality change as the difference between successive cumulative mortality rates. Large differences in mortality change indicated where large reductions in mortality in the residual stand if the indicated cohort is removed. For simplification when summarizing results to provide guidance to managers, we selected a single threshold diameter (i.e., 12 inches DBH), the approximate midpoint between the 8-inch and 15-inch DBH thresholds identified by the CART model. By doing so, we were better able to use our findings to make practical recommendations to managers.

We also graphed mortality rates by species, crown class, and 2-inch dbh classes to illustrate trends and to compare results from the MOFEP site to those previously observed in Missouri (Shifley and Smith 1982).

Results

Of the 24,000 white oaks, post oaks, black oaks, and scarlet oaks that we monitored, more than 3,300 died during the 10-year sampling period for an overall mortality rate of 13.9 percent per decade (or 1.5 percent per year[1]). The variables most correlated to oak mortality, in order of importance, were: species, crown class, environmental variables (i.e., site location and ecological land type), and DBH (fig. 1; table 1). The order of importance varied slightly by species group.

Figure 1 also shows that approximately 21 percent of the red oak group species (scarlet oak and black oak) died and their mortality rate was four times greater than for white oak group (white oak and post oak) species. Red oak group species in the suppressed and intermediate crown classes had mortality rates 2.7 times greater than for those in the co-dominant or dominant classes and suppressed red oak group species had mortality rates that were 1.5 times greater than those in intermediate crown classes. Overall, mortality was greater for suppressed and intermediate red oaks located in sites within or near the Current River Oak-Pine Woodland Hills land type association. This particular land type association is dominated by droughty and nutrient-poor soils and is considered particularly susceptible to oak decline.

Within the white oak group, suppressed trees had mortality rates that were 3.4 times greater than for the other crown classes. Suppressed post oaks were twice as likely to die and intermediate post oaks were 3 times more likely to die as white oaks in these respective crown classes. Suppressed white oaks were more likely to die in ecological land types having higher site quality such as in bottomlands or on north-facing slopes.

For all species within each crown class, mortality increased with increasing diameter. Our analysis suggested that there were threshold diameters beyond which mortality increased significantly. These threshold diameters differed by species and site conditions (table 1). For example, mortality increased significantly for dominant and codominant white oak group species > 13 inches DBH regardless of environment. However, the threshold diameter for red oak group species was only 8 inches DBH for trees in sites within or adjacent to the Current River Oak-Pine Woodland Hills land type association, but was 15 inches DBH in the other sites.

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[1] In general the periodic mortality rate for a period of n years is equal to 1 minus the periodic survival rate. Annual survival rates are computed from periodic rates as one would compute compound interest: annual survival = (periodic survival)(1/n). Likewise periodic survival over n years = (annual survival)n. Similar conversions for mortality rates must be computed in terms of corresponding survival rates and then determined by subtraction.

Table 1. —Nodes for the CART partition of MOFEP mortality data (see fig. 1) with node population size, description of the partition threshold, and the 95 percent bootstrap confidence interval (CI) of the mortality rate (percent per decade) within each node. Terminal nodes are indicated by bold type.

Node#	Node size (%)	Description	95 Percent CI
1	24000(100)	All white, post, black and scarlet oak	13.5-14.4
2	13188 (55)	Black and scarlet oak	20.1-21.5
3	10812(45)	White and post oak	5.0-5.9
4	3608 (15)	Intermediate or suppressed black and scarlet oak	36.7-39.8
5	9580 (40)	Dominant or codominant black and scarlet oak	13.6-14.9
6	1961 (8)	Suppressed white and post oak	11.5-14.7
7	8851 (37)	Dominant, codominant and intermediate white and post oak	3.4-4.2
8	2016 (8)	Intermediate or suppressed black and scarlet oak on sites[1] 2-6, 9	29.1-33.1
9	1592 (7)	Intermediate or suppressed black and scarlet oak on sites[1] 1,7, 8	44.9-50.1
10	4658 (19)	Dominant or codominant black and scarlet oak on sites[1] 6-9	16.9-19.1
11	4922 (21)	Dominant or codominant black and scarlet oak on sites[1] 1-5	9.9-11.6
12	266 (1)	Suppressed post oak	20.3-31.2
13	1695 (7)	Suppressed white oak	9.7-12.6
14	4424 (18)	Intermediate white and post oak	4.6-6.0
15	4427 (18)	Dominant and codominant white and post oak	1.9-2.8
16	298 (1)	Suppressed black and scarlet oak on sites[1] 2-6,9	41.6-53.0
17	1718 (7)	Intermediate black and scarlet oak on sites[1] 2-6,9	26.3-30.2
18	249 (1)	Suppressed black and scarlet oak on sites[1] 1,7,8	60.2-71.9
19	1343 (6)	Intermediate black and scarlet oak on sites[1] 1,7,8	41.4-46.7
20	689 (3)	Dominant and codominant black and scarlet oak ≤ 8 inch DBH on sites[1] 6-9	7.0-11.1
21	3969 (15)	Dominant and codominant black and scarlet oak > 8 inch on sites[1] 6-9	18.4-20.7
22	4263 (18)	Dominant and codominant black and scarlet oak ≤ 15 inch DBH on sites[1] 1-5	8.2-10.1
23	659 (3)	Dominant and codominant black and scarlet oak > 15 inch DBH on sites[1] 1-5	17.5-23.7
24	877 (4)	Suppressed white oak on ELT[2] 11,17,19-23	5.6-9.1
25	818 (3)	Suppressed white oak on ELT[2] 5,6,7,15,18	12.8-17.7
26	780 (3)	Intermediate post oak	10.0-14.7
27	3644 (15)	Intermediate white oak	3.1-4.4
28	3096 (13)	Dominant and codominant white and post oak ≤ 13 inch DBH	0.9-1.8
29	1331 (6)	Dominant and codominant white and post oak > 13 inch DBH	3.5-5.7
30	2120 (9)	Intermediate white oak on ELT[2] 7,11,15,17,19-23	1.3-2.4
31	1524 (6)	Intermediate white oak on ELT[2] 5,6,18	5.3-7.7

[1] Site refers to Missouri Ozark Forest Ecosystem Project study sites 1-9.

[2] Ecological land types (Miller, 1981): Dry bottomlands (5); dry-mesic bottomlands (6); mesic toeslopes (7); dry, narrow ridges (11); dry, broad ridges (15); dry south slopes (17); dry-mesic north slopes (18); glade savanna (19); dry-mesic limestone forest (20); glade (21); xeric limestone forest (22); dry limestone forest (23).

Across all diameter and crown classes mortality rates per decade for white oak (5 percent) were < post oak (9 percent) < scarlet oak (19 percent) < black oak (22 percent). Mortality rates decreased with increasing crown class. Within a crown class mortality rates increased with increasing diameter; the increase was small for white and post oaks, but mortality rates for dominant and codominant scarlet and black oaks increased dramatically (to approximately 40 percent) with increasing tree diameter (fig. 2). Mortality rates for white and post oaks on the MOFEP sites were at or below historical rates for all Missouri; mortality rates for black and scarlet oaks exceed historical state-wide rates, most notably for large diameter trees (fig. 3).

The CART analysis provides direct guidance to forest managers. This is most easily seen when the terminal nodes in the CART Diagram (fig. 1, table 1) are rearranged in order of decreasing mortality probability (table 2). Table 2 clearly shows which subpopulations are most likely to die (e.g., suppressed black and

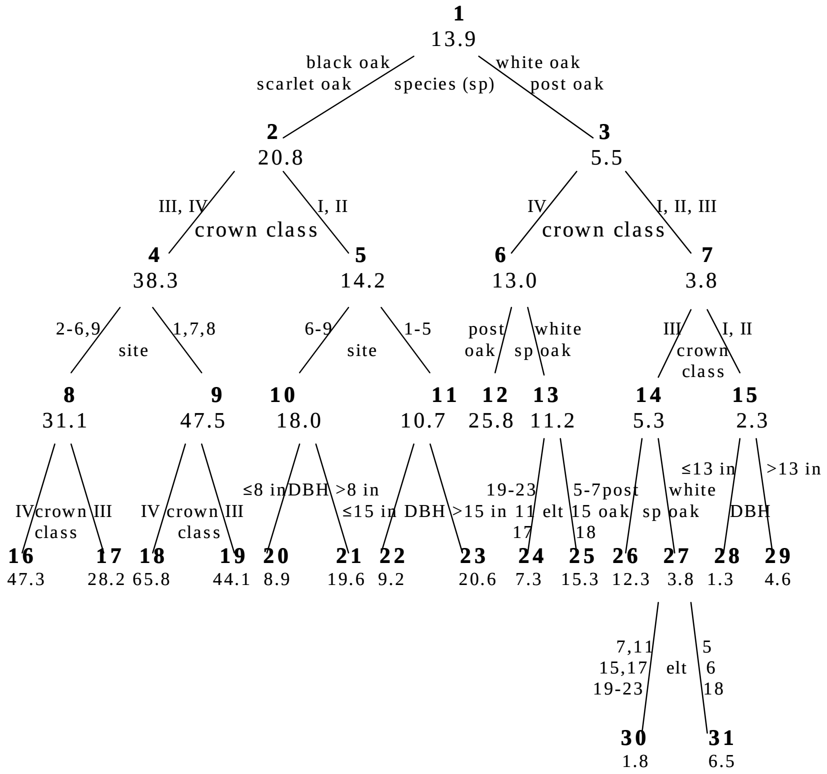

Figure 1.—CART partition of mortality for white, post, black and scarlet oaks in MOFEP plots, 1992 -2002. Nodes are numbered in bold type. Each node shows the mortality rate (percent) for the subpopulation. Variables that partition nodes are shown between node partitions. The threshold value for each variable is interpreted in Table 1.

scarlet oaks with mortality rates of 56 percent per decade) and which are most likely to survive another decade (e.g., dominant white and post oaks < 12 inches DBH with 1 percent mortality per decade).

Discussion

Tree species and crown class were the two most important predictors of tree mortality. Species in the red oak group had higher mortality rates than those in the white oak group as has been shown elsewhere in Missouri and the Central Hardwood Region (Shifley and Smith 1982, Smith and Shifley 1984). For a given diameter, trees in dominant or codominant canopy classes had substantially lower mortality rates than those in lower canopy classes: this was especially true for species that are shade intolerant such as scarlet oaks and post oaks (fig. 2). However, the population of trees larger than 12 inches DBH is comprised almost exclusively of dominant and codominant trees. The mortality rate of dominant and codominant black and scarlet oaks increased dramatically as tree diameter increased. A 20-inch dominant or codominant scarlet oak was no more likely to survive for 10 years than an intermediate scarlet oak in the 4- to 12-inch DBH range.

Environmental variables indicative of site quality played a secondary role and their effects differed by species. For example, on the more-productive ecological landtypes, there was higher mortality of intermediate canopy class white oaks. This suggests that on more productive ecological land types, competition-induced mortality occurred at higher rates than on less productive ecological land types. We anticipated greater oak mortality, particularly of red oak group species, in poorer, less-productive stands. As indicated by the CART regression tree (fig. 1, table 1) site location (in this case MOFEP experimental sites or compartments spanning about 900 acres each) did have a statistically significant relationship with mortality rates for black and scarlet oak (fig. 1 nodes 8,9,10,11). Thus, site location played a role in mortality rates for these species, and we know there are differences among sites in the types of soil that occur, topography, and the mix of ecological landtypes. However our attempts to further identify specific site characteristics by including variables such as slope, aspect, soil map unit, or ecological landtype provided little additional explanatory power to the analysis.

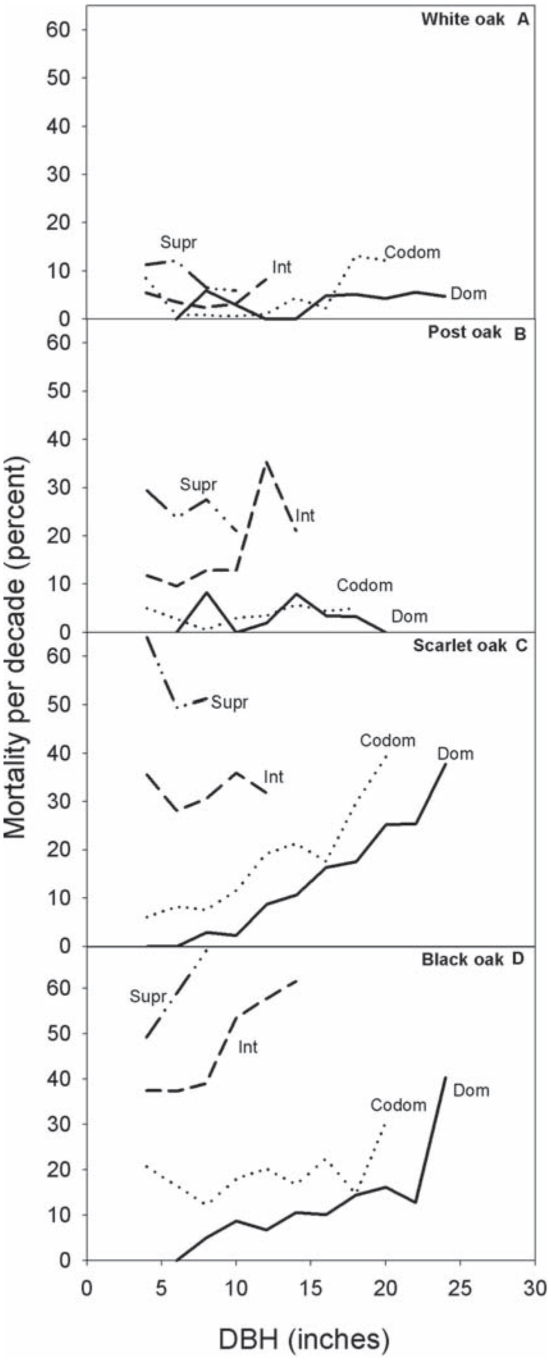

Figure 2.—Mortality rates per decade by species and crown class for MOFEP sites. As expected, mortality rates for a tree of given dbh increase markedly as canopy position decreases from dominant (Dom) to codominant (Codom), intermediate (Int), and suppressed (Supr) crown classes. Mortality rates for scarlet and black oaks increase with increasing diameter for dominant and codominant trees, a pattern that contrasts sharply with that for white and post oaks. Large black and scarlet oaks in the dominant and codominant canopy layers proved highly susceptible to mortality. As a rule of thumb, the bigger they are the sooner they fall.

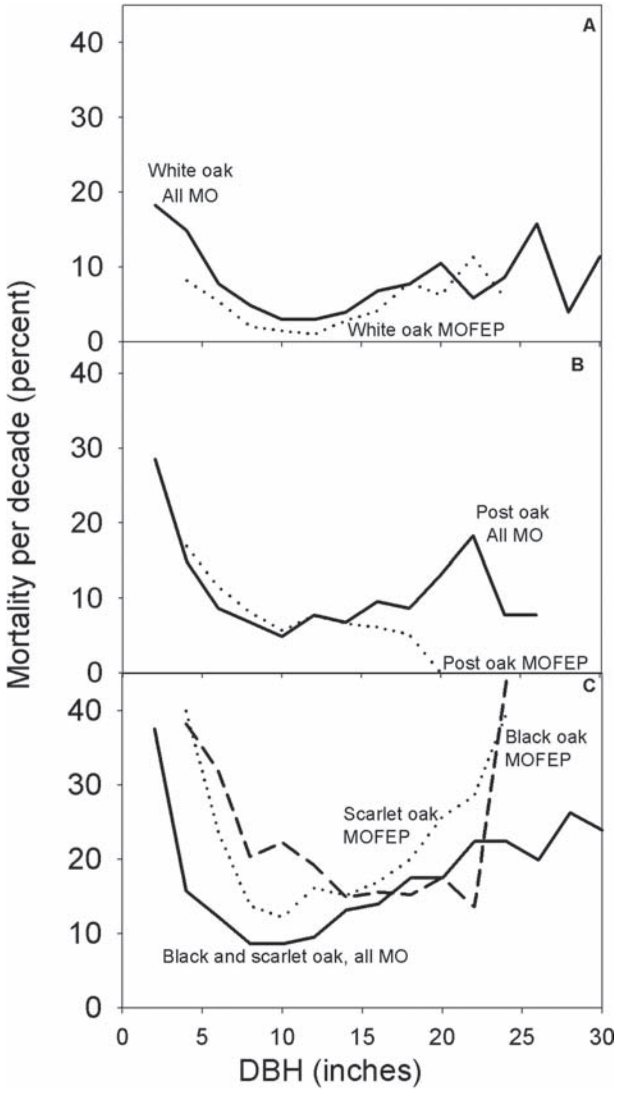

Figure 3.—Mortality rates per decade by species and dbh. Mortality rates for black and scarlet oak were roughly twice those of white and post oak. For white oak and post oak, mortality rates for MOFEP sites from 1992 to 2002 were generally less than reported for all Missouri from 1959-1972 as reported in Shifley and Smith (1982). However, mortality rates for black and scarlet oak on MOFEP sites were generally higher than the average for Missouri, 1959-1972.

Table 2.—Categories (subpopulations) of trees and related mortality rates in rank order from highest to lowest mortality probability. In general, removing cohorts in order starting at the top of the list will minimize the overall mortality rates for the remaining stand. However, cohorts such as suppressed trees are rarely cut and simply left to die through self-thinning. Mean mortality per decade indicates the mean mortality rate for that cohort. Cumulative mortality is the combined mortality rate for that cohort in combination with all those listed below it, and can be used to estimate the mortality rate for the residual stand. The column labeled mortality change is the difference between successive cumulative mortality rates; large values indicate the potential for large reductions in mortality in the residual stand if the indicated cohort is removed.

Categories	Mean mortality per decade (%)	Cumulative mortality (%)	Mortality change (%)
Suppressed black and scarlet oaks	56	14	1
Intermediate black and scarlet oaks	35	13	3
Suppressed post oaks	26	10	1
Dominant and codominant black and scarlet oaks > about 12 inches dbh	20	9	3
Intermediate post oaks and suppressed white oaks	9	6	1
Dominant and codominant black and scarlet oaks < about 12 inches dbh	9	5	2
Intermediate white oaks	4	3	1
Dominant and codominant white and post oaks > about 12 inches dbh	2 2	1	
Dominant and codominant white and post oaks < about 12 inches dbh	1	1	1

Our analysis suggested that variables representing stand density such as stems or basal area per acre were not correlated to increased mortality. Our findings are consistent with those of Starkey and Oak (1989) who also found no correlation between stand basal area and oak decline and oak mortality throughout the Central Hardwood Region. Although we cannot conclude whether reducing stand density will reduce oak mortality, we conclude that crown class alone is a better measure of an individual tree's ability to compete for light, water, and nutrients than are measures of stand density, thus explaining the high correlation between oak mortality and crown class in our analysis. Gottschalk and others (1998) found that crown vigor was a better predictor of oak mortality than crown class in stands that were defoliated by gypsy moth. However, crown vigor was not measured in our study so we were not able to evaluate its importance for predicting mortality in our stands that were not defoliated and where gypsy moth does not occur. We do note that Dwyer and others (1995) stressed the importance of crown vigor and measures of crown dieback for predicting oak mortality in the Missouri Ozarks. While measures of crown vigor undoubtedly are useful for predicting mortality of individual trees, foresters often conduct inventories during the dormant season and are unable to judge crown health or vigor. Our analysis identified the variables from a list of those routinely measured by foresters that are most useful for predicting mortality.

No attempt was made to determine the cause of death for the 3,300 trees that died. Such determinations are complex when multiple agents such as drought, competition, insects, and Armillaria root disease are involved. We can only speculate that the mortality that we observed was attributable to a combination of mortality induced by competition and mortality induced by other mechanisms including disease and oak decline. Trees in smaller diameter classes or lower crown classes most likely died from competition (self thinning of the stand) because they were shaded by dominant and codominants. This is particularly evident in the high mortality rates for intermediate and suppressed shade-intolerant species such as scarlet oaks, post oaks, and black oaks. However, we suspect that the disproportionately large number of scarlet oaks and black oaks in dominant or codominant crown classes that died most likely did so because of oak decline. This is evident for dominant and codominant black and scarlet oak on the MOFEP sites in the high mortality rates that increase with increasing tree DBH (fig. 2). Mortality rates for these two species are uncharacteristically high relative to rates for all Missouri from 1959 to 1972 (fig. 3).

For thinning and stand improvement operations table 2 provides a priority list for trees to remove. Operationally there is little reason to harvest suppressed (or in some cases even intermediate) trees. They will be eliminated naturally through competition and the associated mortality rates in table 2 simply indicate how many trees are likely to be gone at the end of the next decade. Table 2 clearly indicates the value in removing dominant and codominant black and scarlet oaks larger than 12 inches DBH. Those subpopulations of trees have mortality rates of about 20 percent per decade. Dominant black and scarlet oaks that are smaller in diameter have a 9 percent mortality rate. That is in contrast to dominant or codominant post oaks or white oaks that have mortality rates in the range of 1 to 2 percent per decade. The cumulative mortality column in table 2 indicates the expected mean mortality rate for that line and all groups listed below it (i.e. the rate of all classes above are harvested). The cumulative mortality values are based on averages for all trees and all sites. In application the species composition and tree size structure will vary among individual stands as will the associated mortality. The column of table 2 labeled mortality change is the difference in the cumulative mortality for successive entries. Large values indicate, based on the MOFEP data, which categories listed in the table have the greatest impact on the overall mortality rate.

Our findings substantiate the actions of many foresters in Missouri who have began the practice of marking for removal most sawlog-sized scarlet oaks and black oaks during stand improvement cuttings in even-aged stands or during selection harvesting in uneven-aged stands. Recent experience has taught them that large individuals of these species are not likely to survive until the next re-entry. This is a reasonable management strategy even if the individual tree is not showing dieback symptoms or other indications of decline because the onset of symptoms and mortality can occur rapidly and affect dominant and codominant scarlet and black oaks. Healthy white and post oaks with good crown structure and competitive position are good candidates for retention in a thinning or stand improvement operation.

Acknowledgements

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