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SURVIVAL ANALYSIS FOR A LARGE-SCALE FOREST HEALTH ISSUE: MISSOURI OAK DECLINE

C. W. WOODALL[1,*], P. L. GRAMBSCH[2], W. THOMAS[2] and W. K. MOSER[1]
[1]*USDA Forest Service, North Central Research Station, 1992 Folwell Avenue, St. Paul, Minnesota, U.S.A.;* [2]*Division of Biostatistics, School of Public Health, University of Minnesota, Minneapolis, Minnesota, U.S.A.*
*(*author for correspondence: e-mail: cwoodall@fs.fed.us)*

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Abstract. Survival analysis methodologies provide novel approaches for forest mortality analysis that may aid in detecting, monitoring, and mitigating of large-scale forest health issues. This study examined survivor analysis for evaluating a regional forest health issue – Missouri oak decline. With a statewide Missouri forest inventory, log-rank tests of the effects of covariates on the survivor function and equality of the survivor function among classes were conducted for selected oak species.

Additionally, hazard functions were determined for diameter classes for damaged and undamaged oaks. Results indicate that mortality appears to vary significantly among some inventory classes such as oak species, but not among other classes such as ownership class. Indicators of individual tree vigor (i.e., crown class and ratio) were more significant predictors of oak tree mortality than site/stand attributes (i.e., density and aspect). Finally, results indicate that even fast-growing oak trees are at high risk of mortality if damaged by disease. Survival analyses, such as those applied in this study, may enable testing of forest health hypotheses using large-scale inventories. In the context of Missouri's oak forest decline, study results suggest management efforts should focus on limiting the spread of disease damage, increasing the vigor of residual trees, and emphasizing small trees when developing stand prescriptions.

Keywords: hazard function, life-table, Missouri, oak decline, survival analysis

1. Introduction

1.1. Missouri's forests and oak decline

Approximately one-third of Missouri's land base is forested with oak-hickory forests occupying 10.7 million acres or 71% of Missouri's forestland area (Leatherberry and Treiman, 2002). Within the broader oak and hickory forest type, black and scarlet oaks comprise nearly 37% of Missouri's forestland area (Spencer *et al*., 1992) and 18% of the volume (Moser *et al*., 2004). In upland sites typical of the Missouri Ozarks, black and scarlet oaks each constitute 20% or more of the live basal area (Shifley *et al*., 2000). Missouri's oak forests of today are the result of past logging and land conversions that have severely affected their present-day health. In the late-1800s and early-1900s, Missouri's oak forests, containing mixtures of shortleaf pine and oaks, were logged extensively followed by subsistence farming and/or ranchers burning cut-over lands to encourage grass growth (Lawrence *et al.*, 2002). Subsequently, oak forests have sprouted in formerly pine-occupied areas (Lawrence *et al.*, 2002). Since Euro-American settlement, pine forests in Missouri have declined from approximately 4 million acres to current-day estimates of 541,000 acres (Moser *et al.*, 2004). Overall, Missouri's oak forests are currently dominated by inferior stump-sprouted progeny (Kessler, 1992) of advanced age (Spencer *et al.*, 1992) occupying relatively poor quality sites previously dominated by conifers (Lawrence *et al.*, 2002).

It has been proposed by Kessler (1992) that North America's oak forests may be entering an extended period of poor growth and susceptibility to invasive pests and droughts, a national forest health problem since 1960 (Thomas and Boza, 1984). The decline of oak forest health, evidenced by numerous symptoms and precipitated by various causal factors, is collectively termed "oak decline" (Thomas and Boza, 1984; Starkey and Oak, 1989; Lawrence *et al.*, 2002). Oak decline results from the interaction of predisposing stress factors (defoliating insects, drought, frost/ice damage, poor site quality, and advanced tree age) and secondary disease and insect pests (root fungi, canker fungi, and insect borers) (Starkey and Oak, 1989; Manion, 1991; Lawrence *et al.*, 2002). These stresses eventually weaken oak trees resulting in sparse foliage, thin crowns, crown dieback, reduced radial growth, and eventually death (Lawrence *et al.*, 2002). The large-scale decline and mortality of black and scarlet oaks in Missouri was first noted in the late 1970s (Dwyer *et al.*, 1995). Between 1971 and 1988, growing-stock mortality of Missouri's oak forests doubled (Spencer *et al.*, 1992). The volume growth of Missouri's oak forest types has been steadily decreasing with respect to other forest types in Missouri (Spencer *et al.*, 1992). With the effects of recent drought conditions and impending insect outbreaks (Lawrence *et al.*, 2002), the current decline and mortality of oaks in Missouri will continue to increase (FHM, 2002).

The management of oak decline has focused on identifying and mitigating the factors that cause it. Management principles proposed to improve the health of oak forests include maintaining tree species diversity, matching tree species to sites where they grow best, maintaining the overall health of forests through regular thinning, and avoiding excessive pruning or injury during logging (Lawrence *et al.*, 2002; Moser and Melick, 2002). Regional forest inventories, along with the Forest Inventory and Analysis program (FIA) of the USDA Forest Service, have been monitoring Missouri oak decline for several decades. FIA implemented a statewide annual inventory in 1999 building upon successive periodic inventories conducted in 1971 and 1989 (Leatherberry and Treiman, 2002). Both to augment practical oak forest management guidelines and better monitor the progress of oak decline in Missouri, the development of refined inventory mortality analysis techniques is critical. Past efforts to evaluate oak decline (Starkey *et al.*, 1989) lacked robust statistical procedures (Nebeker *et al.*, 1992). Because oak decline is a complex etiological combination of predisposing, inciting, and contributing factors (Manion, 1991; Oak *et al*., 1996), there is need for baseline data, long-term studies, and new analytical procedures (Kessler, 1989; Nebeker *et al*., 1992, Oak *et al*., 1996). As stated by Pedersen (1998), "if tree mortality is to be utilized as an indicator of forest ecosystem health . . . then an understanding of tree mortality is essential."

1.2. Survival analysis

Analytical methods developed by the medical sciences, collectively termed survival analysis, may provide the basis for development of new forest mortality analytical techniques. Survival analysis is most often defined as a class of statistical methods for studying the occurrence and timing of events – most often death (Allison, 1995). Survival analysis is unique in that it allows for censoring of observations and inclusion of time-dependent covariates, in addition to dealing with non-normal distributions (Collett, 1994; Allison, 1995). Waters (1969) first proposed using survival analysis to address forest mortality issues, but such applications have been restricted mainly to forest inventories in even-aged forest plantations (Morse and Kulman, 1984; Amateis *et al*., 1997; Volney, 1998; Wyckoff and Clark, 2000), intensive forest research plots (Reams *et al*., 1988; Burgman *et al*., 1994; Preisler and Slaughter, 1997), or stand table projections (Rose, 2002). Although there has been substantial work on the development of flexible estimation procedures for survival and hazard functions in forest research plots (Preisler and Slaughter, 1997; Volney, 1998), survival analysis techniques have not been widely applied to forest inventory analyses due to the inherent lack of detailed time and age information for large-scale inventories (Flewelling and Monserud, 2002). Given the current lack of forest inventory mortality analyses techniques (Manion and Griffin, 2001), a re-examination of the basics of survival analysis in the context of a large-scale forest inventory is warranted and may aid efforts to monitor and mitigate large-scale forest health issues such as the decline of Missouri's oak forests.

The goal of this study is to use survival analysis techniques to assess oak forest decline in Missouri. Specific objectives are:

(1) to conduct log-rank tests of equality of the oak survivor function between various classes (tree species, forest type, site index class, physiographic class, and ownership);
(2) to conduct log-rank tests for effects of various tree- and site-level covariates (county, aspect, slope position, slope, stand percent oak, stand basal area, crown ratio, crown class tree damage class, and stand site index) on oak mortality survivor functions;
(3) to compare/contrast hazard functions among three categories of inventory oak trees (all, undamaged, and disease-damaged);

TABLE I
Study dataset from the 1972 and 1989 FIA inventories of Missouri: Species, *n*, mean DBH, and DBH range

Species	n_1	n_2	Mean DBH (cm)	DBH range (cm)
Quercus alba	3653	227	29.6	13.0–62.7
Quercus coccinea	869	152	28.2	13.0–61.9
Quercus marylandica	522	241	25.5	13.0–55.9
Quercus prinoides	241	44	27.8	13.0–61.5
Quercus rubra	608	113	33.3	13.0–62.2
Quercus stellata	2379	269	27.5	13.0–62.7
Quercus velutina	3329	580	29.6	13.0–62.7

n_1 = sample *n* alive in 1972, n_2 = sample *n* dead in 1989.

(4) and to evaluate survival analysis techniques in the context of refining evaluation and mitigation of oak mortality in Missouri.

2. Methods

2.1. Data

Survival analyses were conducted using data from the 1972 and 1989 periodic FIA inventories for Missouri (Table I). Individual trees (observations) were included that met the following criteria: alive at time one (1972) and observed as either dead or alive at time two (1989), DBH $\geq$ 13.0 cm at time one (rounded up, minimum DBH for subplot trees as defined by FIA program), and no anthropogenic mortality (indicated by harvest activity). Additionally, in order to streamline the relative large datasets, only the most common oak species were selected for each state (Table I). For survival analyses, individual tree records were associated with numerous predictor variables: species class, forest type, site index, physiographic location class, ownership type, county, aspect, slope position, slope, stand percent oak, stand total basal area, crown ratio, crown class, and tree damage class (see Miles *et al*., 2001). The response variable for each individual tree record was tree status (dead or alive at time two) (see Miles *et al*., 2001).

2.2. Analysis

The survivor and hazard functions, central to survival analysis, are used to quantify the probability distribution of mortality in a population (Muenchow, 1986). The survivor function is defined as (Collett, 1994),

$$S(t) = P(T \geq t), \tag{1}$$

where *S*(*t*) is the probability that a death occurs at some time *T* at least as great as time *t*.

The hazard function is an instantaneous mortality rate and hence is a conditional probability defined as (Collett, 1994),

$$h(t) = \lim \_\Delta t \to 0 \frac{P(t \leq T \leq t + \Delta t | T \geq t)}{\Delta t}, \tag{2}$$

where *h*(*t*) is the probability that death occurs exactly at time *t*, given that it has not occurred before then.

The survival function may be estimated nonparametrically by using the life-table method given by (Allison, 1995),

$$\hat{S}(t\_i) = \prod \_j = 1^{i-1}(1 - h\_j), \tag{3}$$

where for interval *i*, t_i is the start of time and h_i is the conditional probability of death. For $i = 1$ and hence $t_i = 0$, the survival probability is set to 1.0.

The life-table nonparametric estimate of the hazard function at the midpoint of each time interval is given by (Allison, 1995),

$$h(t\_im) = \frac{d\_i}{b\_i \left(n\_i - \frac{w\_i}{2} - \frac{d\_i}{2}\right)}, \tag{4}$$

where for the *i*th interval, t_{im} is the midpoint, d_i is the number of deaths, b_i is the width of the interval, n_i is the number of individuals at the beginning of the interval, and w_i is the number of cases censored (exact time of death cannot be ascertained) within the interval. Note that the survival and hazard functions are mathematical functions of each other; given one, you can compute the other.

The null hypothesis, that the survivor functions are the same for two groups of individuals, may be tested by the non-parametric log-rank test statistic given by (Allison, 1995),

$$U = \sum \_j = 1^r(d\_1j - e\_1j), \tag{5}$$

where *U* is the summation over all unique event times (in both groups), and there are a total of *r* such times; d_{1j} is the number of deaths that occur in group 1 at time *j*; and e_{1j} is the expected number of events in group 1 at time *j*. The expected number of events is given by $n_{1j}d_j/n_j$, where n_j is the total number of cases that are at risk just prior to time *j*; n_{1j} is the number at risk just prior to time *j* in group 1, and d_j is the total number of deaths at time *j* in both groups. Squaring and dividing *U* by the estimated variance provides a chi-square statistic. Additionally, log-rank tests may be generalized to test whether quantitative covariates are associated with survival times.

As evidenced in survival analysis formulations, time to an event is the defining component of survival methods. Hence, the major obstacle to applying survival analysis to forest inventories is the lack of specific tree ages and the censoring of tree mortality (Flewelling and Monserud, 2002). However, age information is not necessary for implementing survival analyses (Allison, 1995). Any measurement unit that indicates changes in an individual's status between remeasurements may replace the traditional survival analysis variables of age and time. For forest inventories that remeasure trees at regular intervals, DBH and ΔDBH may assign individual trees within a population to classes defined by tree size and rate of growth (indicator of tree vigor). Whereas medical studies may determine survivor functions for demographic cohorts across calendar years, forest inventory survival functions may be determined for DBH classes across vigor classes.

In our study, the "clock" starts at the first forest inventory, when a subject begins to be "at risk" for the event or begins to be monitored for the event. Stating this in terms of DBH, the clock is ΔDBH (the increase in DBH from initial survey). Our survival function $S(\Delta DBH)$ gives the probability that a tree will continue to live until its diameter has increased by at least ΔDBH. For example, $S(8\ cm)$ estimates the proportion of the population of trees that will survive to increase their DBH by 8 cm or more. The "time interval" of our hazard function is diameter growth of 4 cm. This hazard function, where $k = \Delta DBH,$ can be interpreted as a ratio of the number of deaths per 4 cm growth in a large population of trees that are k cm larger in DBH than at the first measurement. Hence, for all previously stated formulations of the nonparametric survival and hazard function estimators and log-rank tests (Equations (3)–(5)), our study substituted ΔDBH for time. Although ΔDBH is typically a response variable in diameter growth models, in this study the hazard function does not predict diameter growth, rather it estimates risks of tree mortality by class of past tree diameter growth. Therefore, the survival and hazard functions employed in this study evaluate past mortality and growth trends among classes of individual trees instead of predicting future tree attributes.

Several software packages produce estimates of the survival and hazard functions. In this study, we used the PROC LIFETEST (SAS, 1999) and its life-table estimation method. Trees were grouped by initial DBH into 10-cm diameter classes and grouped by ΔDBH into 4-cm intervals. Log-rank tests were conducted to test for equality of the survivor function (Equation (5)) among the classes of species, forest type, site index, physiographic class, and ownership across DBH classes. Log-rank tests were conducted to determine the effects of covariates (Equation (5)) (county, aspect, slope position, slope, stand percent oak, stand basal area, crown ratio, crown class, tree decay class, and site index) for the survivor function across DBH classes. Finally, we examined the hazard function (Equation (4)) for three subsets of Missouri inventory oak trees: all inventory oak trees (inclusive of damaged trees), undamaged oak trees, and oak trees showing evidence of disease damage.

TABLE II

P-values* for log-rank test of equality of survivor function between various classes (species, forest types, site index, physiography, and ownership) by diameter class for selected oak species, Missouri, FIA inventory 1972–1989

	Classes				
Diameter class (cm)	Species	Forest type	Site index class	Physiographic class	Ownership class
13.0–22.9	0.0001	0.0375	0.0030	0.0461	0.1098
23.0–32.9	0.0001	0.0001	0.0779	0.0001	0.1798
33.0–42.9	0.0001	0.0021	0.3068	0.0604	0.0503
43.0–52.9	0.0001	0.3310	0.8648	0.0558	0.2032
53.0–62.9	0.0001	0.2685	0.6557	0.6790	0.0277

*significant differences among classes if p-value *le* 0.05.

3. Results

Log-rank tests indicate significant differences in the survivor function among defined DBH classes (Table II). For Missouri oaks, there is a significant difference in the survivor function between small oaks occurring in various forest types across Missouri (Table II). There was no significant difference among the survivor functions stratified by forest type for larger diameter trees (Table II). This result was more strongly evident with the apparent inequality among the survivor functions between individual species classes, regardless of tree size (Table II). For site index and physiographic classes, there were significant differences in the survivor function for only the smaller diameter trees (Table II). Among ownership classes, there were no significant differences in Missouri oak mortality (private, corporate, state, and federal) (Table II).

Log-rank test for effects of covariates on the survivor function among DBH classes indicate that crown ratio, crown class, and damage classes have a significant effect on the oak survivor function, while slope, aspect, and stand basal area have no significant effects regardless of DBH class (Table III). An exception to these trends was site index, which had a significant effect on oak survivorship for only the smallest diameter classes (Table III).

The hazard function across DBH classes by ΔDBH for all trees, undamaged trees, and disease-damaged trees indicated that undamaged trees had the lowest risk of mortality within the inventory cycle (13 years) of all the inventory trees (Figure 1). Disease-damaged trees had the highest risk of mortality across all DBH classes as compared to the hazard functions of the two other categories (Figure 1). When we consider the entire sample of oak trees, there is obvious separation in mortality risk among diameter classes, but only for the slowest growing trees (least vigor) (Figure 1a). Additionally, mortality risk was usually greatest for the largest and smallest trees, also ubiquitously known as the “bathtub curve” in the

TABLE III
P-values* for log-rank test for effects of various tree- and site-level covariates on survivor functions by diameter class for selected oak species, Missouri, FIA inventory 1972–1989

	Diameter classes (cm)				
Covariates	13.0–22.9	23.0–32.9	33.0–42.9	43.0–52.9	53.0–62.9
County	0.1905	0.0479	0.4956	0.8072	0.2533
Aspect	0.3952	0.7872	0.4683	0.4945	0.9350
Slope position	0.3418	0.8479	0.2888	0.6406	0.5947
Slope	0.1944	0.3803	0.3231	0.2183	0.9609
Stand percent oak	0.2221	0.9183	0.1826	0.8551	0.2261
Stand basal area	0.1765	0.4417	0.2488	0.3007	0.8234
Crown ratio	0.0001	0.0001	0.0001	0.0001	0.0001
Crown class	0.0001	0.0001	0.0004	0.0001	0.0001
Tree damage class	0.0001	0.0001	0.0001	0.0009	0.8722
Site index	0.0069	0.1702	0.5153	0.8948	0.6205

*significant effect of covariate if *p*-value *le* 0.05.

epidemiological sciences. For disease-damaged trees, trends in mortality risk are different (Figure 1c). Not only is there less separation among DBH classes and risk of mortality, there are higher risks of mortality carried through classes of diameter growth (individual tree vigor).

4. Discussion

Regional oak decline may be examined with log-rank tests of equality for survivor functions among user-defined classes. Because the dataset included white oaks, which appear to be less affected regionally by oak decline than other oaks, the species stratification indicated significant differences in mortality trends among oak species. Forest type classes did not show a clear trend in mortality differences. Only the mortality trends of smaller oak trees differed among forest types, suggesting that stress from overtopping competition and the resulting reduced tree growth could vary by species composition. However, for larger oak trees it appears as though mortality may occur regardless of forest type, suggesting less of a species composition effect on mortality and more of an individual tree age-induced vigor reduction effect. Because the survivor function was significantly different only for the smaller diameter classes among the classes of site quality (site index and physiographic classes), site quality appears to have a bearing only on oak mortality for small oak trees, again supporting the hypothesis that competitive stresses may be reducing the health of small oak trees. Research-plot studies by Starkey *et al.* (1989), Nebeker *et al.* (1992), and Oak *et al.* (1996) suggest a stronger influence of site quality on oak decline than found in this study. Undoubtedly, site quality

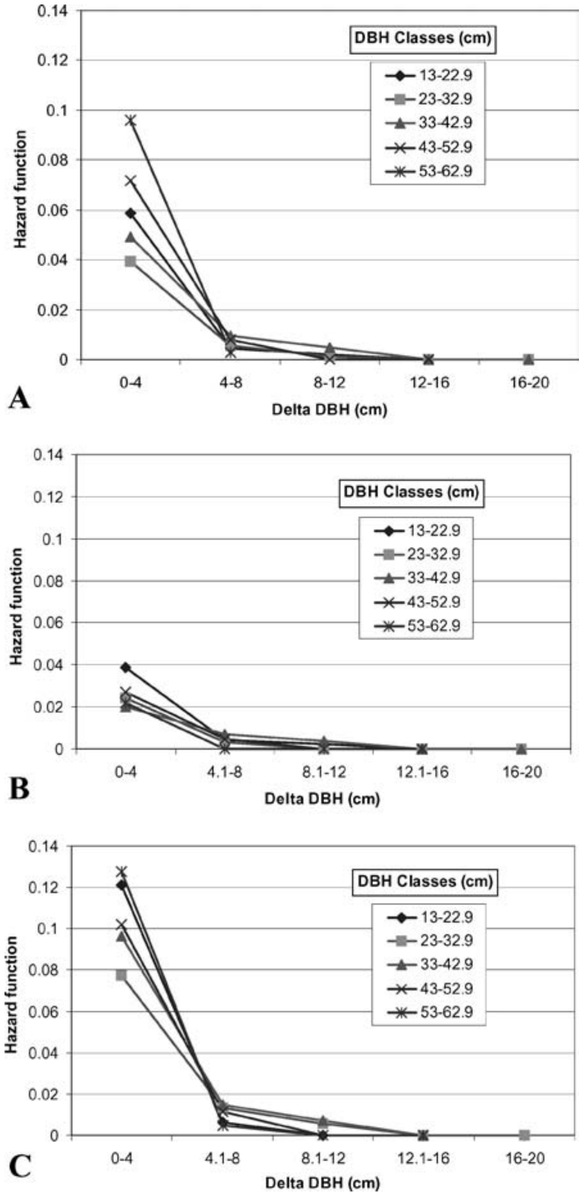

Figure 1. Hazard functions for inventory oak trees, Missouri, 1977–1990, USDA Forest Service FIA program (A: all oak trees, B: undamaged oak trees, C: disease-damaged oak trees).

affects numerous aspects of oak decline; however, our study suggests that a slow growing tree (low vigor) on a high-quality site may be at a higher risk for mortality than a tree experiencing rapid diameter growth (high vigor) on a low-quality site.

The equality of oak survivorship across diameter classes was further evaluated using log-rank test for effects of various tree and site/stand covariates. Once again, site/stand attributes may have less of an effect on oak mortality than tree attributes of crown ratio, crown class, and tree damage class. Although it is difficult to attribute differences in individual tree attributes (i.e., crown and damage characteristics) among site and oak decline effects, it is obvious that individual tree vigor may be the most significant indicator of oak survivorship, as opposed to an individual tree's location or stand-level attributes in Missouri. The apparent lack of influence of covariates such as slope, aspect, and stand basal area is affirmed by the results of a southwide study by Starkey and Oak (1989), yet are contradicted by some other observations in Missouri (Lawrence *et al.*, 2002). Direct comparisons between this and other studies are obscured by the fact that most past studies investigated only oak decline stands (Starkey *et al.*, 1989); therefore, no information on the mortality dynamics of healthy oak stands were integrated into their analyses. Using an inventory that sampled the full range of oak conditions, we found that the individual tree characteristics such as crown class, crown ratio, and tree damage are obvious indicators of tree vigor and may reflect an individual tree's resistance to regional declines in forest health such as found with oak decline. Finally, although possible differences in forest management activities among land ownerships may affect oak decline, log-rank tests indicate no significant differences in trends in oak mortality among land ownership categories. Although anecdotal evidence would suggest obvious differences in oak mortality among disparate land ownership categories, our study's large-scale inventory and broad ownership classes might obfuscate such fine-scale conclusions.

Graphing the hazard function for oak by diameter class enabled us to rapidly assess risks of tree mortality. Results indicated the smallest and largest oak trees were at most risk of mortality. Mortality may likely be competition-induced for smaller trees (Oliver and Larson, 1996) and stress/age-related for older/larger trees. The physiological manifestations of these individual tree stresses may be the same, but their origin may differ depending on age/size-classes. However, there can be significant risk of mortality in relatively fast-growing oak trees across all DBH classes, especially for disease-damaged trees. At a regional scale, examinations of trends in the hazard function may allow assessment of trends in mortality risk among classes of interest common in forest resource inventories (i.e., DBH, individual tree vigor, and damage categories).

The results of this study may be applied at various scales to benefit both large-scale forest health monitoring and stand-level management activities. The mortality analysis methods proposed in this study may be used both to test mortality hypotheses and assess mortality dynamics in large-scale forest resource inventories. There were numerous examples from this study of these types of practical outputs. First, oak mortality appears to vary among oak species regardless of tree size (DBH). Second, among classes of site quality and forest types, oak mortality appears to vary only for smaller DBH classes. Third, our study found no significant difference in mortality trends among classes of land ownership. Fourth, indicators of individual tree vigor (i.e., crown class and ratio) were more significant covariates of oak tree mortality than site/stand attributes (i.e., density and aspect), although there may be confounding risks of covariance among site and tree attributes. Fifth, there are apparent differences in risks of oak tree mortality among all inventory oak trees and disease-damaged trees whereby even vigorous, fast-growing oak trees are at high risk of mortality if damaged by disease. Although the results of such large-scale survival analyses must always be couched within the basis of locally available pathological and silvicultural information, the methodologies in this study offer forest managers another tool to monitor large-scale forest health issues such as Missouri oak decline.

Specifically addressing Missouri's oak forest decline, the results of this study indicate significant trends of mortality among classes of oak trees usually defined by individual tree attributes (i.e., crown ratio and DBH). More importantly, site quality and ownership variables appeared to have less of a significant effect on oak tree mortality suggesting that the decline of Missouri's oak forests is regional and less determined by smaller scale forest variables such as ownership or its aspect. Additionally, because the effect of mortality covariates decreases with increasing tree size, forest managers may have less ability to control the factors affecting the mortality of larger oak trees. Unfortunately, because study results indicate that disease-damaged trees are highly susceptible to mortality (even if vigorous and small), the extent of disease damage will limit the ability of foresters to control the outcome of silvicultural prescriptions meant to improve the health of Missouri's oak forests. Based on this study's results, Missouri's oak forest managers who wish to reduce the impact of oak decline should focus their efforts on limiting the spread of disease damage, increasing the health of residual trees, and emphasizing small trees in developing stand prescriptions.

5. Conclusions

Survival analyses, such as those applied in this study, may enable rapid analysis of forest health hypotheses using large-scale inventories. For oak decline in Missouri, it may allow allocation of limited forest management resources to address the most significant causes of oak decline. Although analyses such as these can never replace site intensive research of health issues, it may still provide strategic guidance for managing current and future forest health issues. Although a novel methodology for applying survival analysis in forest inventories, the methods of this study warrant future refinement and application to other forest health threats occurring at large scales.

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