D.B.H. and Survival Analysis: A New Methodology for Assessing Forest Inventory Mortality

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Abstract.—Tree mortality has typically been assessed in Forest Inventory and Analysis (FIA) studies through summaries of mortality by location, species, and causal agents. Although these methods have historically been used for most of FIA's tree mortality analyses, they are inadequate for robust assessment of mortality trends and dynamics. To offer a new method of analyzing tree mortality in forest inventories, we used survival analysis techniques to estimate survival and hazard functions for FIA periodic inventories in Minnesota. The study's method for applying survival analysis techniques to FIA inventories successfully estimates survivor and hazard models. Classifying trees into classes of d.b.h. and d.b.h. growth may facilitate applying of survival analysis techniques by providing a surrogate for tree ages and vigor. Applying survival analysis techniques to forest inventories allows FIA inventory analysts to test tree mortality hypotheses and summarize regional tree mortality trends, and affords a solid foundation for development of individual tree mortality models.

Tree mortality in forest inventories has traditionally been assessed using simple summary statistics. Mortality information in Forest Inventory and Analysis (FIA) State reports has typically included losses in timber volume due to mortality, summaries of mortality causal agents, locations of dead trees, and mortality trends by species (Leatherberry *et al.* 1995). More in-depth mortality analysis has been facilitated only through development of logistic regression models of individual tree mortality, a technique that is cumbersome and inadequate for large forest inventories (Eid and Tulius 2001). Current forest mortality analytical techniques lack methods for incorporating the time-dependent nature of tree mortality, testing hypotheses, censoring observations, and conducting tests for effects of covariates (i.e., stand basal area and crown ratio). Given the past diseases and epidemics that have greatly altered North American forest ecosystems (e.g., chestnut blight [*Cryphonectria parasitica*] and Dutch elm disease [*Ceratocystis ulmi*]) and the threats of future forest health hazards, novel and statistically robust techniques for assessing forest mortality would greatly benefit forest inventory analysts.

Analytical methods developed by the medical sciences, collectively termed survival analysis, may provide the basis for developing new forest mortality analytical techniques. Survival analysis is usually defined as a class of statistical methods for studying the occurrence and timing of events, such as death (Allison 1995, Collett 1994). Waters (1969) first proposed using survival analysis to address forest mortality, but such applications have been restricted to forest inventories in even-aged forest plantations (Morse and Kulman 1984, Wykoff and Clark 2000) due to the inherent lack of detailed time and age information for larger-scale inventories (Flewelling and Monserud 2002). Given the current dearth of forest inventory mortality analysis techniques, a re-examination of the basics of survival analysis in the context of the FIA inventories is warranted and may provide a novel mortality analysis methodology.

The primary goal of our study was to estimate and interpret the central functions of survival analysis (survivor and hazard functions) for an FIA inventory in the State of Minnesota. Specific objectives included:

1. To use d.b.h. and d.b.h. growth (Δd.b.h.) in applying survival analyses techniques to forest inventories.
2. To determine if survivor/hazard functions can represent actual mortality trends in a manner practical for ecological interpretation.

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Forest Survival Analysis Supposition

Time to an event is the defining component of survival methods. Hence, the major limitation often cited for the limited application of survival analysis to forest inventories is the lack of specific tree ages and the censoring of tree mortality (Flewelling and Monserud 2002). However, knowledge of age 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, d.b.h. and Δd.b.h. (time 2 d.b.h. - time 1 d.b.h.) may assign individual trees to cells within a matrix of tree size and vigor. Whereas medical studies may determine survivor functions for demographic cohorts across calendar years, forest inventory survival functions may be determined for d.b.h. classes across vigor classes. The survivor function *S(t)* is defined at a time *t* as the probability that the time to the event is greater than or equal to *t* (Collett 1994). In this 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 d.b.h., the clock is Δd.b.h. (the increase in d.b.h. from initial survey). Our survival function *S(Δd.b.h.)* gives the probability that a tree will die after it has grown by at least *Δd.b.h. = k cm*. For example, *S(4 cm)* estimates the proportion of the population of trees within the same d.b.h. class that will survive to increase their d.b.h. by 4 cm. Related to the survival function is the hazard function, *h(t)*. The hazard function gives the probability of an event occurring at time *t* given that the subject has survived up to *t*. In terms of d.b.h., *h(Δd.b.h.)* gives the probability that a tree that has survived and grown *k* cm will die at that size. Given the robust and established analyses of the survival modeling community, the individual tree variables of d.b.h. and Δd.b.h. may allow applying survival analysis to forest inventories, thereby providing a novel method of assessing forest mortality dynamics.

Methods

Survival analysis was conducted using data from the 1977 and 1990 periodic FIA inventories for the State of Minnesota (table 1). Individual trees (observations) were included that met the following criteria: alive at time 1 and observed as either dead or alive at time 2, d.b.h. ≥ 13.0 cm (rounded up, minimum d.b.h. for subplot trees as defined by FIA program), and no human-caused mortality. Additionally, to streamline the large data sets, only the most common species representing a wide range of growth habits and suffering from a variety of damage agents were selected for each State (table 1). Δd.b.h. was calculated as the difference in d.b.h. between time 1 and time 2. If a tree was dead at time 2, its d.b.h. was equal to the d.b.h. at time 2 or the d.b.h. at time 1, whichever was larger. Since a tree's d.b.h. may shrink following death, an estimate of the maximum d.b.h. the tree attained before death would better benefit survival analysis than an estimate of a decaying bole diameter.

All data set trees were grouped both by initial d.b.h. (10-cm d.b.h. classes) and Δd.b.h. (4-cm classes). PROC LIFETEST (SAS 1999) and its life-table estimation method were used to

Table 1.—*FIA inventory for the State of Minnesota used in survival analysis*

Species Group	Species	Number of trees
Red and jack pine	*Pinus banksiana, Pinus resinosa*	3,935
Black spruce and balsam fir	*Picea mariana, Abies balsamea*	14,972
Maples	*Acer saccharinum, Acer saccharum*	2,747
Balsam poplar	*Populus balsamifera*	4,448
Paper birch	*Betula papyrifera*	8,603
American elm	*Ulmus americana*	3,829
Aspen	*Populus tremuloides*	21,303
Red oak	*Quercus rubra*	2,962

estimate *S(Δd.b.h.)* and *h(Δd.b.h.)* by 10-cm d.b.h. classes for the entire data set. Additionally, *h(Δd.b.h.)* was estimated for the 23.0- to 32.9-cm d.b.h. class, stratified by species groups.

Results and Discussion

A survival function *S(Δd.b.h.)* was estimated for selected species in the 1977-1990 Minnesota inventories (fig. 1). The survival function was estimated separately for five initial d.b.h. classes. The survivor function displays the cumulative probability of trees surviving to the inventory remeasurement (time 2) across classes of Δd.b.h. For trees of a midsize diameter, there was approximately a 60-percent probability of mortality for trees growing less than 4 cm during the remeasurement interval. Using d.b.h. and Δd.b.h. for survival analysis application, the survivor function quantifies the stand dynamics that may cause tree mortality. The greatest tree mortality occurs in trees growing 4 cm or less during the inventory interval (13 years). The largest trees suffer greater mortality rates than smaller trees. In contrast to the survivor function, the hazard function expresses the rate of death at a specific interval midpoint (Δd.b.h. class), allowing mortality trends to be broadly assessed by d.b.h. and Δd.b.h. classes (fig. 2). Hazard functions varied both by initial d.b.h. classes and Δd.b.h. The largest trees with the smallest Δd.b.h. had the highest risk (hazard) of death, while smaller trees had lower hazards of death in the smaller classes of Δd.b.h. To examine *h(Δd.b.h.)* across species groups, the hazard functions for the 23.0- to 32.9-cm d.b.h. class, stratified by species group, were determined (fig. 3). Risk of mortality was distinctly different between all species groups across all classes of Δd.b.h. American elm had the greatest hazard function across all classes of Δd.b.h., while maples had the lowest hazard function.

The survivor and hazard functions may offer robust tools for analyzing forest mortality. The survivor function displays mortality cumulatively through the diameter distribution, while the hazard function may display specific d.b.h. midpoint mortality rates. As evident from the survivor and hazard function curves for Minnesota, d.b.h. classes with divergent or atypical mortality trends may be readily identified. For those that monitor forest health across regions of the United States, the analytical ability to identify and discern differences in mortality trends is crucial. We suggest that survivor curves for "typical" mortality may assume a characteristic survivor curve form. Divergences of survivor function curves from the "typical" curve bounds for specific tree populations may help identify problems in a rapid, statistically defensible manner. For large forest inventories, hazard functions may be able to attribute mortality to causal agents,

Figure 1.—*Survival functions for time one diameter classes by delta DBH (Time 2 DBH - Time 1 DBH).*

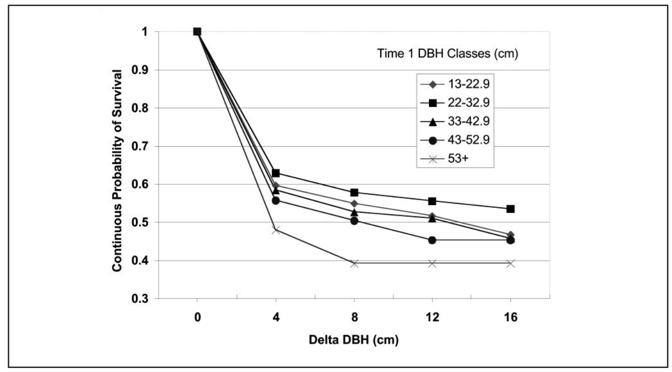


Figure 2.—*Hazard functions for time one diameter classes by delta DBH (Time 2 DBH - Time 1 DBH).*

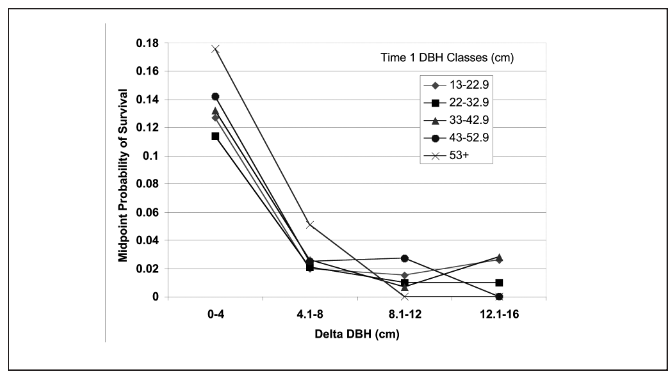
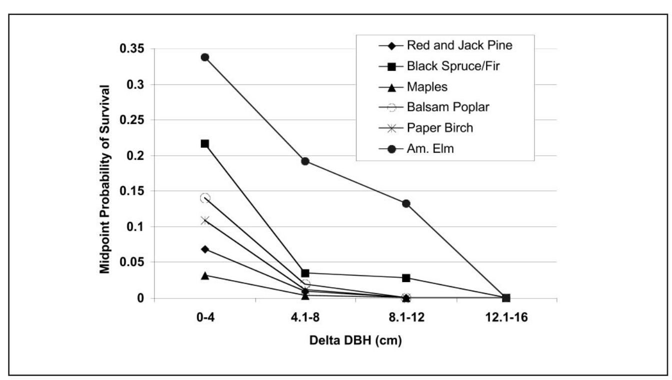


Figure 3.—*Hazard functions for time one DBH class 23-32.9 (cm) for various MN species.*



further refining forest health assessments. The hazard and survivor functions can together provide a rapid and comprehensive assessment of tree mortality for forest inventories as long as the survey interval time is approximately the same between remeasurements (FIA annual inventory remeasurement interval ≅ 5 years).

Interspecific tree mortality differences are critical to forest health assessments. Hazard functions, determined through this study's methodology, allow for comparing mortality risk rates among species and diameter classes. Although analysis using only one diameter class was presented from this study, there were obvious differences in hazard functions among species. This study's methodology may allow comparing hazard functions among species over successive inventory cycles. Detection monitoring of atypical mortality may be better facilitated through observing risks of mortality by species, d.b.h. class, and Δd.b.h. class (hazard functions).

A longitudinal unit can be any unit that measures a variable's transition from one state (i.e., class or condition) to another (Collett 1994). The greatest hurdle in applying survival analytical techniques to forest inventories is finding appropriate longitudinal units to quantify the transition of individual trees from alive to dead. If time or ages are used as longitudinal units in forest inventory analyses, a number of problems may be encountered. First, all observations are censored. The exact time of tree death is uncertain, with the inventory remeasurement date often serving as the longitudinal measure. Second, the survivor function curve is partially dependent on when and where the measurements were taken. For example, if the bulk of mortality is located in a certain area of the State that is inventoried at a discrete point in time, the resulting survival curve will be biased if time is used. Third, the age of a tree is difficult to estimate in large forest inventories. However, d.b.h. and Δd.b.h. are quantities that hypothetically increase until a tree dies. Thus, tree diameter may be used as a surrogate of age in survival analysis. Δd.b.h., although not a surrogate for time, may serve as a "stopwatch" for individual trees. At the start (time 1), the Δd.b.h. of all trees is 0. At the time of remeasurement (time 2) the "stopwatch" is stopped and trees are assigned to classes of Δd.b.h.. Time (years) may greatly relate to the survival of humans, while tree growth over intervals of time (i.e., annual diameter growth) may be a more meaningful measure in forest ecology. Using the variables of tree size and growth may allow survival analyses to be conducted on forest inventories and warrant future evaluation and possible application.

Conclusion

Forest inventory mortality analysis has predominantly been focused on logistic regression modeling at the individual tree-scale with scant data summarizations at the landscape scale. This apparent disparity in research efforts between forest ecosystem scales means few advances or technologies have been forwarded for robust analysis of forest mortality dynamics at the landscape scale. This study proposed a new approach to forest mortality assessment by combining established survival modeling techniques (survivor/hazard functions) with traditional measurements of forest stand attributes (d.b.h. distribution/diameter growth). This technique suggests a paradigm shift in forest mortality analyses and nonstandard application of survival analysis techniques. If this study's techniques withstand the test of time and peer review, a new forest mortality analysis approach may be gained that is more efficient and provides statistically defensible assessments of tree mortality for tree populations across different forest types, locations, and various damaging agents.

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