Incorporation of Precipitation Data Into FIA Analyses: A Case Study of Factors Influencing Susceptibility to Oak Decline in Southern Missouri, U.S.A.

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Abstract.—The Forest Inventory and Analysis program at the North Central Research Station focuses on understanding the forested ecosystems in the North Central and Northern Great Plains States through analyzing the results of annual inventories. The program also researches techniques for data collection and analysis. The FIA process measures the above-ground vegetation and the site (soils) factors, but not climatic data. This pilot study, centered around three inventory units in southern Missouri, assigned weather data obtained from the National Oceanic and Atmospheric Administration to particular forest inventory plots, based on nearest distance. We incorporated precipitation and maximum and minimum temperatures into a temporary database, then analyzed the growth and forest health data for the plots for any relationships among the climate data. We found an apparent relationship between precipitation and the hypothesized relationship between the variables believed to predispose the stand toward oak decline and mortality variables, particularly in larger, older trees. Adding precipitation as an independent variable helped increase the quality of the predictions of the mortality models in situations where we concentrate on size/age groups more prone to forest health problems. Finally, we found evidence of spatial patterns of precipitation across the Ozark Plateau in southern Missouri that appear to be correlated with landscape-level patterns of mortality. Management activities need to address the role of the predisposing variables in influencing susceptibility to oak decline. As the level of precipitation seems to exacerbate the predisposing variables' effects, historical patterns of rainfall and soil moisture retention need to be taken into account when regenerating and managing oak forests in the Missouri Ozarks.

The Central Hardwood forest ranges from eastern Oklahoma northeast to southern New England (Hicks 1998). Oak-hickory forests constitute the vast majority of acreage in the Eastern United States (Powell 1993) and in the Central Hardwood forest region. In the State of Missouri, oak-hickory forests constituted almost three-fourths of the total forest land area, and oaks made up 66 percent of all growing stock removals on timberland between 1999 and 2002 (Moser *et al.* 2004). Forest health problems affecting oak growth and survival could have a significant impact on Missouri's forest ecosystem and economy.

Oak decline is considered a "complex": a suite of pathogens and insects that together contribute to reduced growth, quality defects, and mortality (Manion 1981) for trees species in the red oak (*Erythrobalanus*) group, particularly black oak (*Quercus velutina* Lam.) and scarlet oak (*Quercus coccinea* Muenchh.). Consisting of the two-lined chestnut borer, the red oak borer, *Armillaria* fungus, and *Hypoxylon* canker (with additional impacts caused by four other insects [Wargo *et al.* 1983]), oak decline is native to the Central Hardwoods region and has long been endemic to oak forests (Starkey *et al.* 1989). Although evidence of oak decline has been observed in the Eastern United States since the 19th century (Millers *et al.* 1989), the complex has had an increasing impact on the forests of the Ozark Plateau of Missouri and Arkansas with evidence of crown dieback, growth reduction, and mortality in oak forests since the 1980s far exceeding historic levels. The severe drought of the late 1990s, combined with the advancing age of the Ozark forests,

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has intensified the spread and severity of the effects (Lawrence *et al.* 2002). Most red oaks in the Ozarks are at least 70 to 80 years old, and grow in rocky soil on broad ridges or south- and west-facing slopes. Typical oak decline symptoms include branch dieback from the tips, sparse foliage, and reduced growth. Mature red oaks with more than 30 percent dead limbs and branches are considered to have a high mortality rate.

This study on oak decline uses data from Forest Inventory and Analysis (FIA) plots, Forest Health Monitoring (FHM) plots, and other sources to describe the past, present, and future condition of oak forests on the Mark Twain National Forest (MTNF) and other forest land in southern Missouri.

Missouri Oaks: Many Potential Victims

Oak species dominate Missouri forests (Moser *et al.* 2004), particularly those in the Ozark region. Oak-hickory and oak-pine forests constitute 78 percent of the forest land of the State. Of the 16.3 billion cubic feet of volume of all live trees on forest land that are in hardwood species groups, 36.2 percent were in white oak species groups and 31.1 percent were in red oak species groups (Moser *et al.* 2004). Forest health problems have long been identified for Missouri oaks (Missouri Conservation Commission 1976). According to Kathy Kromroy of the North Central Research Station, the percentage of dead oaks is increasing, from 1.3 percent in 1972 to 9.6 percent in 1989). Mortality has reached epidemic proportions in Arkansas and Missouri (Lawrence *et al.* 2002) and has severely affected parts of the Mark Twain National Forest. While planning for the future, the MTNF asked the U.S. Department of Agriculture, Forest Service, North Central Research Station FIA, and Northeastern Area State and Private Forestry for data and trends based on the FIA data. In response, both units formed the Mark Twain Oak Decline (MTOD) collaborative study. The investigation sought to provide the answers the MTNF needed for their planning process, and to present the results of the research so that other interested groups may benefit from the effort.

In the process of putting together their forest plan, MTNF managers identified the following specific objectives for the study group:

- Determine if any changes occurred in growth and mortality between the inventories in 1989 and 1999–2002 attributable to oak decline.
- Determine the relevant indications of oak decline and which species, age class, crown closure, and/or crown position is most affected.
- Determine the distribution of these oak decline effects.

Five Factors Influencing Susceptibility to Oak Decline

Previous work developed interim management guidelines for forests susceptible to oak decline (Moser and Melick 2002). Underlying the recommendations were assumptions, based on personal observations and input from many field managers and other researchers, about the impact of five stand and site factors present in all susceptible forests (Millers *et al.* 1989, Moser and Melick 2002, Starkey *et al.* 1989, Nebeker *et al.* 1992). Moser and Melick postulated that the five site factors influenced the likelihood of attack by oak decline in the following ways:

1. **Site.** Ridgetops and south-west aspects frequently have poor nutrients and/or water availability.
2. **Age**. Stands more than 70 years old are susceptible.
3. **Species**. Scarlet and black oaks are the most prone to oak decline, particularly on poor sites.
4. **Density**. Trees in stands with higher densities are more stressed than those in lower density stands.
5. **Lack of diversity**. Stands with high proportions of susceptible oaks are more prone to oak decline.

Local climate, particularly precipitation, impacts productivity and stand dynamics, and unfavorable weather can exacerbate the effects of the five factors on already stressed trees. Many references describe the importance of climate to vegetation. Water is a source of oxygen used in photosynthesis (Nobel 1991). Zimmerman and Brown (1980, p. 162) state “the availability of water is the most singly important environmental factor limiting growth and distribution in trees.” After light, water is the most prominent limit to growth (Oliver and Larson 1995).

This paper attempts to determine the following:

- If weather, particularly precipitation, significantly influenced mortality.
- If adding precipitation as an independent variable increases the quality of predictions of mortality models.
- If spatial patterns of precipitation exist, and, if so, to determine if they show any relationship with landscape-level patterns of mortality.

Management Implications

Given the widespread nature of oak decline on the Ozark Plateau, not enough foresters, loggers, or markets are available to deal with all the areas potentially requiring management action. As an intermediate measure, Moser and Melick (2002) suggest some management guidelines focused on manipulating the five factors to avoid or reduce the opportunity for oak decline, or to at least mitigate its effects. The guidelines suggest increasing diversity, both in species and tree size (age), before oak decline is present. Species should be matched to the most appropriate sites: pines on south- and west-facing slopes and ridgetops, white oaks on midslopes, northeast slopes for northern red oaks, and dryer (north and east aspect) sites for scarlet and black oaks. Species that are especially susceptible, such as scarlet and black oaks, would be aggressively thinned to increase vigor and harvested by the time they reach 70 to 80 years of age.

Methodology

Incorporating Rainfall

We obtained daily precipitation records, generally dating back to 1948, for all National Weather Service weather stations in southern and central Missouri. We assigned a weather station to the nearest FIA inventory plot. The distance from plots to the nearest weather station varied from a few hundred yards to 17 miles. We then parsed and transferred these files into temporary tables in the North Central FIA database, with assignment values (such as State, county, plot) that we joined with standard plot data. In some cases, many plots were assigned to a particular weather station. Because oak decline events appear to be influenced by recent patterns of drought (Starkey *et al.* 1989), for the purposes of this study we limited our use of the climatic data to the average annual rainfall from 1990 to 1999.

Data Analysis

Table 1 lists the independent variables we examined and each corresponding factor. We used 1989 and 2002 data collected on FIA plots on the Mark Twain National Forest. In this case, the independent variables were 1989 FIA variables, except for the 1990–99 average annual rainfall; the dependent variables were the six mortality values for 2002, the remeasurement period. In addition to the basal areas of scarlet oak (species code 806) and black oak (species code 837), we also examined northern red oak (*Quercus rubra* L., species code 833) and white oak (*Q. alba* L., species code 802). We evaluated the correlations between the independent variables representing the five factors, average annual rainfall, and mortality and estimated the significance of adding precipitation to the model using equation 1.

Equation 1 is the formula for appraising the "value" of adding a variable to evaluate certain weather data as increasing model predictability. SS_1 = the sum of squares residual without the rainfall variable; SS_2 = the sum of squares residual with rainfall; p_1 = number of coefficients estimated without rainfall variable; p_2 = number of coefficients estimated with rainfall; n = total number of observations. We refer to this statistic as the "value" F-statistic, to distinguish it from the "model" F-statistic in Draper and Smith (1981).

$$F = \frac{(SS_1 - SS_2)/(p_2 - p_1)}{SS_2/(n - p_2)} \quad (1)$$

Table 1.—*Hypothetical factors and the Forest Inventory Analysis (FIA) dataset variables ("factor variables") examined in the overall oak decline study.*

Category	FIA dataset variable
Age	Stand age 1989
Density	Total BA 1989
	Oak BA 1989
Site	Site Condition 1989
	Aspect 1989
	Slope 1989
Species mix	BA 802 (white oak) 1989
and diversity	BA 806 (scarlet oak) 1989
	BA 833 (northern red oak) 1989
	BA 837 (black oak) 1989
Weather	Average Annual Rainfall 1990–99

Results

Correlations Between the Five Factors and Mortality

The hypothesis that the five factors and rainfall influence tree mortality, particularly that of oaks, is supported by the data in the correlation table (table 2). All mortality variables were negatively correlated with average annual rainfall. Most the variables representing the five factors (table 1) were positively correlated with the mortality variables, except for aspect. This last result probably is caused by the cardinal nature of aspect, with north and east (315° to 135°) sites, all other things being equal, being less susceptible to oak decline and the south and west aspects (135° to 315°) being more prone to oak decline. An ordinal or binary variable might have been a better choice for evaluation. Using equation 1, we calculated the F-statistic, examining the statistical significance of adding average annual precipitation from 1990–99 to the 10 site-specific variables.

We focused on mortality as evidence of forest decline. Several measures of per acre mortality reside in the FIA database, so we concentrated on measures of total biomass, numbers of trees, and growing stock volume. Total biomass mortality (expressed as dry weight) more closely mirrors the total site productivity. Mortality trees per acre represents the product of the number of trees found dead since the last inventory and the tree expansion factor. The minimum diameter of this category is 5 inches, probably representing middle-aged and older trees. Mortality trees per acre, combined with basal area, give some indication of density-dependent mortality. Finally, growing stock mortality focuses more on larger trees and separates those segments of the total tree population less likely to suffer from normal competitive pressures than trees 1 to 2 inches in diameter, for example. This last category would have to have a higher proportion of mortality resulting from oak decline than trees less than 5 inches in diameter.

Was Precipitation a Significant Addition to the Model? We calculated F = 4.215, greater than the 95-percent threshold value of 3.92 which was therefore statistically significant. Mortality trees per acre (oak species only) exhibit F = 5.880, again indicated that precipitation significantly improved the quality of fit of the model to the data.

Biomass mortality per acre for all species and for oak species alone was evaluated in the same manner. With F = 2.127 and F = 3.505, adding precipitation had no significant impact on estimating either mortality variable. Inserting precipitation into the model for growing stock mortality per acre for all species resulted in F = 4.460, indicating a significant addition. For growing stock mortality for oaks only, F = 3.307 suggested that the precipitation did not significantly improve the quality of fit of the model to the data.

How Much Did Including Precipitation Add to the Quality of Model Prediction? Table 3 also lists the model R^2 and F statistics with and without precipitation. For all six variables, R^2 decreased when precipitation was removed from the model. Mortality trees per acre for all species had $R^2 = 0.0678$ and $R^2 = 0.0579$ with and without average annual rainfall from 1990 to 1999. Mortality trees per acre, oak species only, had similar results, with $R^2 = 0.1113$ and $R^2 = 0.09813$ with and without rainfall. Dry biomass mortality per acre for all species had $R^2 =0.1745$ with and $R^2 = 0.1701$ without the precipitation variable. Dry biomass mortality per acre, oaks, had $R^2 = 0.2481$ with rainfall and $R^2 = 0.2443$ without. Rainfall was not a signif-

Table 2.—*Direction of correlation (sign) between the factor variables and rainfall vs. three mortality variables.*

Mortality variable 2002	Average rainfall 1990–99	Stand age 1989	Total BA 1989	Oak BA 1989	Site condition 1989	Aspect 1989	Slope 1989	BA 802 1989	BA 806 1989	BA 833 1989	BA 837 1989
Mortality trees per acre	-	-	+	+	+	-	+	+	-	+	-
Mortality trees per acre—oaks	-	-	+	+	-	+	-	-	-	-	+
Growing stock mortality per acre	-	+	+	+	+	-	+	+	+	+	+
Growing stock mortality per acre—oaks	-	+	+	+	+	-	+	+	+	+	+
Dry biomass mortality per acre	-	+	+	+	+	-	+	+	+	+	+
Dry biomass mortality per acre—oaks	-	+	+	+	+	+	+	+	+	+	+

icant addition to the variable mix for dry biomass for all species or oaks only. Dry biomass mortality per acre for all species and for oaks had R^2 of 0.1745 and 0.2481, respectively, with precipitation and 0.1701 and 0.2443 without precipitation. Finally, growing stock mortality per acre for all species had an $R^2 = 0.1503$ with and $R^2 = 0.1407$ without rainfall, whereas growing stock mortality per acre, oaks, had an $R^2 = 0.1697$ with and $R^2 = 0.1628$ without.

As a measure of the increase in quality of fit of the model to the data when including precipitation, the F-statistic was significant for mortality trees per acre and growing stock mortality per acre, but was not significant for dry biomass mortality per acre. Yet, dry biomass mortality exhibited the highest quality of model prediction. One conclusion might be that dry biomass more completely represents the accumulated total site productivity and is perhaps less sensitive to minor fluctuations in rainfall. The other two measures, mortality trees per acre and growing stock mortality per acre, focused on trees 5 inches in diameter and greater, and perhaps have higher percentages of trees in stressed situations and thus more sensitivity to fluctuations in precipitation. On the other hand, growing stock mortality does not include rough and rotten trees, so the demise of these supposedly healthy trees might be a more profound indicator of the effects of a lack of precipitation.

Why Is R^2 Not Approaching 100 Percent? Statistical models of biological systems rarely achieve perfection in their predictive ability. The more complex the system, the more opportunity for influence by unforeseen or nonsystematic variables such as individual land owner management, site-specific edaphic and microclimatic influence, or a host of potential interactions among trees and other biota or among the trees themselves. Has oak decline really kicked in? Much evidence exists of oak decline, such as growth reduction, crown dieback, evidence of pathogens and insects, but, unlike in earlier periods, mortality has not yet responded. Finally, while our weather data is more precise than regional assessments, the relatively few number of stations vis-à-vis our plots still leaves us with some landscape-level generalizations.

"Optimal" Number of Variables

As a further test of the value of rainfall in understanding mortality data on FIA plots, we constructed an algorithm to evaluate all combinations of independent variables with mortality trees per acre in 2002 as the dependent variable. The results of this run (Ron McRoberts, North Central Research Station, pers. comm.) show that the fewest number of variables that were still statistically significant as predictors of mortality trees per acre ($F > 3.92$, $n = 408$) were the following:

- Total basal area 1989.
- Basal area of scarlet oak 1989.
- Basal area of black oak 1989.
- Site condition 1989.
- Annual rainfall 1990–99.

Spatial Arrangement of Rainfall and Mortality Across the Landscape

Finally, we examined the spatial arrangement of rainfall and mortality across the landscape. Although the study is ongoing, early indications suggest some interesting patterns. Figure 1 shows a bubble plot of average annual rainfall across all plots

Table 3.—*Analysis of mortality measurements as a function of independent factor variables.*

Mortality Measure	R^2 (all variables)	Model F-statistic (all variables)	R^2 (no precipitation)	Model (no precipitation)	Value F-statistic for annual precipitation variable	Significant at 95 percent?
Mortality trees per acre	.0678	2.625	.0579	2.446	4.215	Yes
Mortality trees per acre—oaks	.1113	4.520	.09813	4.330	5.880	Yes
Dry biomass mortality per acre	.1745	7.630	.1701	8.158	2.127	No
Dry biomass mortality per acre—oaks	.2481	11.91	.2443	12.86	3.505	No
Growing stock mortality per acre	.1503	6.382	.1407	6.516	4.460	Yes
Growing stock mortality per acre—oaks	.1697	7.375	.1628	8.305	3.307	No

in the three Ozark units. Larger circles represent higher levels of precipitation. Note the band of low-rainfall plots across the center of the map. This figure should be compared to figure 2, where we graphed mortality over roughly the same area, illustrating mortality with shading (light for high mortality and dark for low mortality). Note that many of the areas of high mortality in figure 2 occur in the same locations as areas of low rainfall in figure 1, suggesting that the areas of high mortality might be influenced by the relative lack of rain. Of course, other factors such as site and age demand investigation, but these early results are promising.

Conclusions

The first question addressed in this study was whether precipitation significantly improved the estimated relationship between the five factors variables and the mortality variables. The answer appears to be yes, particularly in situations where the trees were potentially stressed to begin with, such as larger, older trees.

We also sought to discover if, by adding precipitation as an independent variable, we increased our understanding and the quality of the predictions of the mortality models. Here again, the answer is yes, in situations where we are able to concentrate on size/age groups prone to forest health problems, as opposed to smaller/younger trees where normal competition-induced mortality played a role.

Finally, we were curious whether spatial patterns of precipitation existed across the Ozark Plateau in southern Missouri and if they might show any relationship with landscape-level patterns of mortality? The answer is yes, but we need more detailed further investigations to confirm it.

Management activities need to take into account the role of the five factors in influencing susceptibility to oak decline. As low levels of precipitation seems to exacerbate the five factor's effects, historical patterns of rainfall and soil moisture retention need to be taken into account when regenerating and managing oak forests in the Missouri Ozarks.

Figure 1.—*Bubble plot of average annual rainfall, in inches, attributed to each FIA plot; larger circles represent higher levels of precipitation. Inset shows location of study area in southern Missouri, U.S.A.*

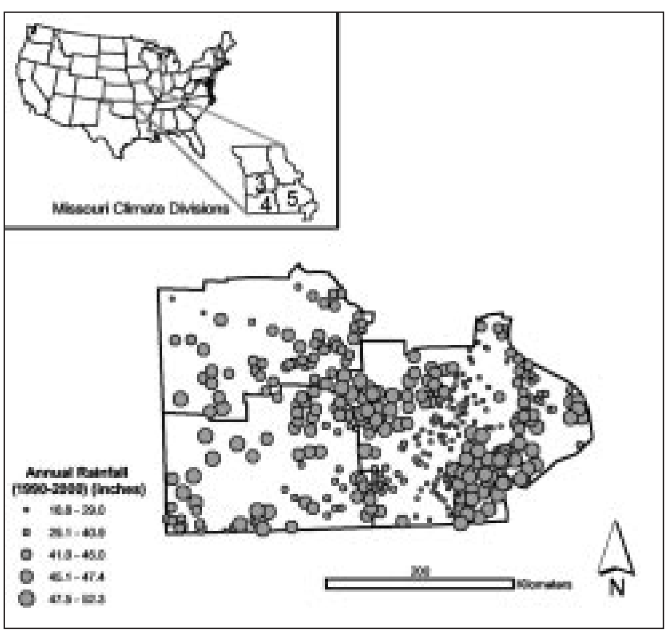
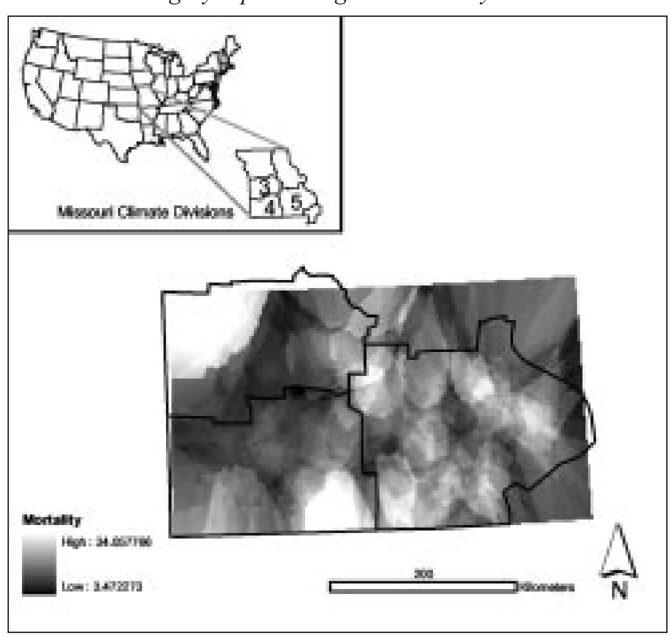


Figure 2.—*Two-dimensional interpolation of tree mortality, where the x-y axes denote location and the shading represents annual mortality, with white or light gray being higher mortality and the darker gray representing less mortality.*



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