RED OAK DECLINE AND MORTALITY BY ECOLOGICAL LAND TYPE IN THE MISSOURI OZARKS

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Abstract—Oak decline, the precipitous mortality of mature oak trees, has been a chronic problem in xeric oak ecosystems and is reaching unprecedented levels in red oak group (*Quercus* section *Lobatae*) species in the Ozark Highlands. The high rates of mortality are leading to rapid changes in species composition, forest structure, and related changes in fire risk, insect populations, and colonization patterns of root diseases such as Armillaria. Based on intensive analysis of more than 455 half-acre plots of the Missouri Ozark Forest Ecosystem Project (MOFEP), we compared red oak mortality change by ecological land types (ELT) using a multiple comparison test. There were significant differences in red oak mortality between certain ELTs. Using ANCOVA, we found that the abundance of red oak species was a major contributor; stand structure and tree attributes played a marginal role. The result is helpful for interpreting the landscape-scale change of red oak decline and mortality.

Keywords: Ecological land type, mortality, oak decline.

INTRODUCTION

For more than a century, episodes of oak decline periodically have occurred wherever oaks are prominent throughout North America and Europe (Kessler 1989, Starkey and others 1989). Since the 1970's, oak decline has been a common and chronic problem throughout the oak-dominated forests of the Missouri Ozarks (Law and Gott 1987). By 1999, oak decline had become widespread and locally severe on more than 400,000 acres of forests throughout the Interior Highlands of Missouri, Arkansas, and Oklahoma (Heitzman and Guldin 2004, Heitzman and others 2004).

In the Missouri Ozarks, widespread episodes of decline generally have followed periods of drought (Law and Gott 1987, Lawrence and others 2002). Red oak group species (*Quercus* section *Lobatae*) have been particularly susceptible, especially those that are physiologically mature and growing on drought-prone, nutrient-deficient sites such as on ridges or south-facing slopes and on soils that are shallow or rocky (Law and Gott 1987). High mortality of red oak group species in Missouri Ozark forests has been associated with Armillaria root disease (Bruhn and others 2000) and infestation by oak borers and other insect pests (Lawrence and others 2002, Starkey and others 2004).

The high mortality rates associated with oak decline are leading to rapid changes in species composition and forest structure. Where large numbers of red oak group species are declining and dying, they are being replaced by white oak group species (*Quercus* section *Quercus*) and other hardwoods (Kabrick and others 2004). Rapid onset of mortality temporarily increases the density of snags and the volume of coarse woody debris, changing wildfire risk and the behavior of prescribed fire. In some locations, unprecedented numbers of oak borers have infested the dead and dying red oaks (Lawrence and others 2002). In addition to the ecological ramifications, these large outbreaks of wood-boring insects have severely reduced the merchantability of red oak sawtimber.

Because of the significance of oak decline to forest management, we wanted to know whether an ecological classification system was useful for identifying places where the incidence of oak decline and mortality would be greater or have more impact. Ecological classification schemes are used to hierarchically classify forest systems at multiple scales (Bailey 1996). At the finest levels, ecological land

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types (ELTs) are mapped approximately at stand scales, each comprising distinctly different vegetation communities and environmental conditions. In theory, different ELTs can be used to identify where red oak group species are likely to be abundant and where site conditions are likely to hasten the onset of oak decline. We examined the differences in the distribution and the decadal mortality rates of red oak group species to determine how they differ among ecological land types in Missouri Ozark forests.

METHODS

We used data from The Missouri Ozark Forest Ecosystem Project (MOFEP), a long-term study examining the effects of forest management practices on upland forest flora and fauna in oak-dominated forests. MOFEP comprises nine study sites ranging from 312 to 515 ha. Study sites are located within the Current River Oak Forest Breaks or the Current River Oak-Pine Woodland Hills land type association (LTA) in the Ozark Highlands (Kabrick and others 2000, Nigh and Schroeder 2002). The Current River Oak Forest Breaks LTA has narrow ridges and steep side slopes with relief of 90-137 m which exposes the Roubidoux, Gasconade, and Eminence bedrock formations. The Current River Oak-Pine Woodland Hills LTA has broad ridges with relief < 95 m and exposes only the Roubidoux and Gasconade bedrock formations. Within these LTA's at the study area, ten ecological land types have been identified (fig. 1).

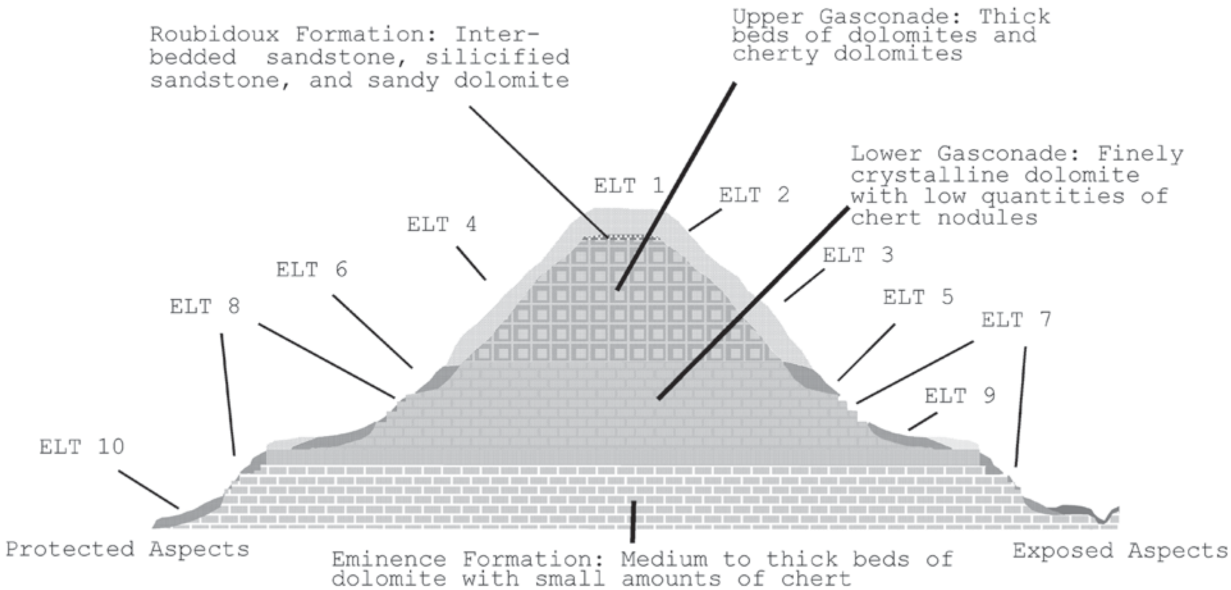
Since the first inventory on MOFEP was initiated in 1990, the 648 0.2-ha permanent plots have been inventoried approximately every three years (completed in 1995, 1998, and 2002) to document the condition of the woody vegetation. Information recorded included: species, size class or dbh for trees > 4 cm dbh, status (e.g., live, dead, den, cut, blow-down), and crown class (Jensen 2000). From this dataset, we examined the fate of all black oaks (*Quercus velutina* Lam.) and scarlet oaks (*Q. coccinea* Muenchh.) > 11 cm dbh that were alive during the initial inventory. We examined the fate of black oaks and scarlet oaks because these two species are most susceptible to oak decline (Law and Gott 1987) and together comprise 98 percent of the red oak group basal area in the Missouri Ozarks (Kabrick and others 2004). We also restricted our analysis to a subset of 455 of the 648 vegetation plots that were not harvested as part of MOFEP treatments. We monitored the total basal area (BA), the number of trees per ha (TPH), and quadratic mean diameter (QMD) of 13,176 live black and scarlet oaks through 2002 for each ELT on the nine MOFEP sites. We used Duncan's multiple-range test (SAS® Institute Inc. 2000) to compare mean BA, TPH and QMD among ten ELTs. We incorporated the initial condition (BA, TPH, and QMD of live black and scarlet oaks in year 1990) as covariates, respectively, in analysis of covariance (ANCOVA) to determine whether the detected differences among ELTs resulted from original abundance or were associated with other characteristics.

RESULTS AND DISCUSSION

The cumulative mortality of black oaks and scarlet oaks (BA or TPH) differed significantly ($p < 0.01$) among ELTs (table 1). Two prominent groups of ELTs were identified. The first group (ELTs 1 through 6 and 9) had greater mortality than the second group (ELTs 7, 8, and 10). No significant difference was further identified within groups.

Greater cumulative mortality occurred on ELTs that are droughty and nutrient deficient (fig. 1). For example, ELTs 1 through 3 are located on convex summit and shoulder slope positions and ELT 9 occurs at the convex-shaped ends of structural benches where soil water readily drains to lower slope positions. The soils of these ELTs, as well as those of ELT 5 and 6, contain 35 to > 60 percent cherty gravel or cobbles, diminishing their ability to hold and supply water. Moreover, the soils have low cation exchange capacity and low base saturation, limiting their ability to hold and provide nutrients. Of this group of ELTs, the water and nutrient supply capacities increase gradually from ELT 1 (having lower capacity) to ELT 6 and 9 (having greater capacity). Similarly, there appears to be a corresponding gradient in cumulative basal area of black oaks and scarlet oaks that died (table 1).

In contrast, the second group of ELTs (7, 8, 10), where cumulative mortality was lower, generally have greater water supply capacity, nutrient supply capacity, or both (fig. 1). ELT 10 occurs on silty footslopes



Ecological Land Types	Description
1. Roubidoux/Upper Gasconade Summits	Slopes: < 8 percent; soils: moderately-deep to deep, gravelly or cobbly with low base saturation; overstory: black oak, white oak, scarlet oak, shortleaf pine; ground flora: *Vaccinium* spp.
2. Roubidoux/Upper Gasconade Shoulders	Slopes: 8 - 20 percent; soils: moderately-deep to deep, gravelly or cobbly with low base saturation; overstory: black oak, scarlet oak, shortleaf pine; ground flora: *Vaccinium* spp.
3. Exposed Roubidoux/ Upper Gascondade Backslopes	Slopes: > 20 percent; aspect: 135 - 315 degrees; soils: deep, gravelly or cobbly with low base saturation; overstory: black oak, scarlet oak, white oak, shortleaf pine; ground flora: *Vaccinium* spp., *Desmodium* spp.
4. Protected Roubidoux/ Upper Gascondade Backslopes	Same as ELT 3 except aspect: 315 - 135 degrees; overstory: white oak, black oak, scarlet oak; ground flora: *Vaccinium* spp., *Desmodium* spp., *Smilacena* spp.
5. Exposed Lower Gascondade/Eminence Backslopes	Slopes: > 20 percent; aspect: 135 - 315 degrees; soils: deep, gravelly or cobbly becoming clayey with depth and having moderate base saturation; overstory: white oak, black oak; ground flora: *Vaccinium* spp., *Desmodium* spp.
6. Protected Lower Gascondade/Eminence Backslopes	Same as ELT 5 except aspect: 315 - 135 degrees; soils: deep, gravelly or cobbly with moderate base saturation; overstory: white oak dominates; ground flora: *Cimicifuga* spp., *Desmodium* spp.
7. Exposed Variable-Depth-to Dolomite or Dolomite Glades	Slopes: variable; Aspect: 135 - 315 degrees; soils: depth is variable and outcrops are common or extensive, gravelly or cobbly becoming clayey with depth and having high base saturation; overstory: chinkapin oak, white ash; ground flora: *Smilax* spp., *Tephrosia* spp., *Silphium* spp.
8. Protected Variable-Depth-to Dolomite	Same as ELT 7 except aspect 315 - 135 degrees; soils: clayey with high base saturation, outcrops occur but are not extensive; overstory: sugar maple, white ash, black walnut, chinkapin oak, ground flora: *Cimicifuga* spp. *Lindera* spp., *Smilax* spp.
9. Lower Gasconade/ Eminence Benches and Shoulders	Slopes: < 20 percent; soils: deep, gravelly or cobbly with low base saturation; overstory: black oak, scarlet oak, white oak, shortleaf pine; ground flora: *Vaccinium* spp., *Desmodium* spp.
10. Footslopes	Slopes: 8 - 20 percent; soils: deep, silty with moderate base saturation; overstory: white oak, hickories; ground flora: *Desmodium* spp., *Smilacena* spp.

Figure 1—Upland ecological land types (ELT) of the study area. ELT names include slope aspect (for slopes > 20 percent), bedrock formation, and slope position. Landscape profile identifies the composition of the bedrock formation and illustrates the approximate landscape location for each ELT. Overstory or ground-flora species are either dominant or diagnostic and are listed in order of importance. Detailed descriptions of the ELTs are provided by Nigh and others (2000).

Table 1—Black oak (*Quercus velutina* Lam.) and scarlet oak (*Q. coccinea* Muenchh.) initial abundance and cumulative mortality, determined as basal area, trees per hectare, and quadratic mean diameter for ecological land types on the nine MOFEP sites[a]

ELT	Live black oaks and scarlet oaks at year 1992			Cumulative mortality of black oaks and scarlet oaks during 1992 – 2002		
	BA	TPH	QMD	BA	TPH	QMD
	m^2/ha		*cm*	*m^2/ha*		*cm*
1	10.7 a	144 abc	31.2 a	2.36 a	34 a	27.8 ab
2	10.6 a	157 abc	30.2 a	1.97 a	36 a	28.0 ab
3	10.1 a	185 a	27.6 ab	1.99 a	33 a	29.1 a
4	10.7 a	146 abc	31.7 a	1.97 a	27 ab	32.7 a
5	9.4 a	171 ab	27.9 ab	1.63 a	31 a	26.3 ab
6	9.0 a	121 cd	31.4 a	1.90 a	31 a	26.9 ab
7	2.4 b	58 e	22.4 c	0.33 b	6 d	25.6 ab
8	3.9 b	82 de	25.7 bc	0.62 b	12 cd	20.7 b
9	9.5 a	135 bc	29.1 ab	1.58 a	23 abc	27.5 ab
10	4.0 b	61 e	30.3 a	0.67 b	15 bcd	26.3 ab
Pr > F	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.16

[a] Abundance and diameter differences among ecological land types were identified with Duncan's multiple-range test. Within columns, values followed by a different letter indicate significant differences ($\alpha = 0.05$).
MOFEP = Missouri Ozark Forest Ecosystem Project; ELT = ecological land type; BA = basal area; TPH = trees per hectare; QMD = quadratic mean diameter.

where water and nutrient supply are relatively high. ELT 8 occurs on lower, north-facing slopes where the underlying dolomite is sufficiently near the soil surface to provide large quantities of the base cations Ca and Mg; however, the bedrock is not too near the surface to restrict root development. The anomaly was ELT 7 because the underlying and outcropping dolomite of this ELT restricts growing space for trees. We also found that the abundance of black oaks and scarlet oaks was considerably lower on this ELT than on the others. This led us to question whether the cumulative oak mortality was related to the abundance or diameter (i.e., a surrogate for tree age) of black oaks and scarlet oaks at the initiation of the study.

We found few differences among ELTs in the QMD of live or dead oaks. When the study was initiated the black and scarlet oaks on ELT 7 were slightly smaller than elsewhere, but the QMD of the black oaks and scarlet oaks that died during the study period was the same as for the other ELTs. This suggests that greater cumulative mortality of some ELTs was not due to the presence of larger (and presumably older) black oaks and scarlet oaks.

However, we found higher cumulative mortality of black oak and scarlet oak was strongly correlated to a greater abundance of these species at the initiation of the study (table 1). ANCOVA indicated that this association was highly significant ($p < 0.01$). After accounting for this abundance effect, we found the cumulative mortality was no longer significantly different among ELTs (BA: $p = 0.86$; TPH: $p = 0.10$) at the 95 percent confidence level (table 2). This suggested that the mortality rate of black oaks and scarlet oaks did not differ proportionally among ELTs.

In combination, these findings provide a new perspective on the oak decline problem. Much like studies reported elsewhere, our findings confirm that there is greater cumulative mortality of black oaks and scarlet oak on sites that are drought prone and nutrient deficient (Heitzman and others 2004, Law and Gott 1987, Lawrence and others 2002). Moreover, they demonstrate that ELTs can be used to identify across the landscape where the cumulative mortality of these species is likely to be greater. However, they also

Table 2—Least square means and standard errors of dead basal area, trees per hectare and quadratic mean diameter of black oaks (*Quercus velutina* Lam.) and scarlet oaks (*Q. coccinea* Muenchh.) at year 2002 for each ecological land type adjusted by initial condition at year 1992 in the analysis of covariance

ELT	BA	TPH	QMD
	m^2/ha		*cm*
1	1.8 ± 0.3	30 ± 3.8	25.7 ± 2.3
2	1.4 ± 0.2	29 ± 3.6	26.9 ± 2.1
3	1.6 ± 0.2	20 ± 3.5	30.6 ± 1.8
4	1.4 ± 0.2	22 ± 3.2	30.1 ± 1.9
5	1.3 ± 0.2	20 ± 3.7	27.5 ± 2.1
6	1.7 ± 0.2	32 ± 3.5	24.6 ± 2.1
7	1.5 ± 0.3	22 ± 3.8	30.3 ± 2.4
8	1.5 ± 0.3	22 ± 4.0	24.5 ± 2.6
9	1.3 ± 0.2	21 ± 3.5	27.5 ± 2.1
10	1.5 ± 0.2	30 ± 3.6	25.2 ± 1.9
Pr > F	0.86	0.10	0.24

ELT = ecological land type; BA = basal area; TPH = trees per hectare; QMD = quadratic mean diameter.

suggest an alternative pathway leading to accelerated mortality of black oaks and scarlet oaks. Rather than accelerating mortality, the drought-prone and nutrient-deficient site conditions of some of the ELTs may have favored the colonization of black oaks and scarlet oaks following the extensive logging and farming practices during the early 1900s. When young, these species are adapted to poor site conditions (Johnson and others 2002). Consequently, black oaks and scarlet oaks must have been more competitive for growing space, displacing other oaks and other tree species and eventually becoming the dominant species. Because black and scarlet oaks become highly susceptible to oak decline as they mature, the cumulative mortality of these species is higher anywhere that physiologically-mature black oaks and scarlet oaks are more abundant.

Our findings do not discount the role of environmental stress in triggering the onset of oak decline. Episodes closely follow periods of drought (Law and Gott 1987, Lawrence and others 2002, Stringer and others 1989). However, it appears that the water supply differences among ELTs have little impact on the mortality rate of individual black oaks or scarlet oaks. The total number or basal area of dead black and scarlet oaks is higher on ELTs that have more of those species, but the proportion of those trees that die is comparable across all ELTs we examined. Stringer and others (1989) also noted that site moisture regime did not appear to play a role in oak decline in eastern Kentucky. There may be a physiological explanation for why site moisture regime does not appear to be important. Jenkins and Pallardy (1995) suggested that in the Missouri Ozarks, oaks on poorer sites allocate more photosynthate to their roots than oaks on nearby higher quality sites. This mechanism enables oaks on the poorer sites to withstand the deleterious effects of extreme drought as well or better than those on higher quality sites. This may partially explain why the mortality rate of black oaks and scarlet oaks is about the same regardless of ELT.

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