Do Improvement Harvests Mitigate Oak Decline in Missouri Ozark Forests?

John P. Dwyer, John M. Kabrick, and James Wetteroff

ABSTRACT

Since the 1970s, oak decline has been a chronic problem throughout the oak-dominated forests of the Missouri Ozarks. Prior research indicates that environmental stress, particularly drought, leads to the onset of oak decline. Consequently, some scientists and managers have advocated thinning and intermediate harvesting to maintain or improve tree vigor and growth, thereby leaving stands less susceptible to pathogens and pests that are frequently the ultimate cause of mortality of declining trees. However, few studies have experimentally evaluated the effectiveness of cutting treatments for mitigating oak decline, and some scientists have cautioned that cutting in declining stands exacerbates the problem. We conducted a replicated, 14-year study in southeastern Missouri to determine if improvement harvests would reduce the severity of oak decline symptoms and increase forest growth compared with untreated stands. Although we found that improvement harvests did not mitigate oak decline, they did not make decline worse and had the benefits of increasing the diameter growth of trees in the residual stand. Even in the absence of the improvement harvests, more than 70% of red oaks that initially exhibited little or no crown dieback remained in the same crown dieback classes during the 14-year study period. We also observed that more than 50% of the red oaks that initially exhibited moderate to severe decline symptoms appeared to improve during the study, regardless of harvest treatment. In contrast, fewer than 18% of declining white oaks improved during the study period.

Keywords: oak decline, improvement harvest, Missouri Ozark forests

Oak decline is one of the most widespread health issues plaguing oaks (Starkey and Oak 1989, Starkey et al. 1989). For more than 100 years, it has occurred periodically throughout North America and Europe wherever oaks are prominent (Kessler 1989, Starkey et al. 1989). Since the 1970s, 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 ac of forests throughout the Interior Highlands of Missouri, Arkansas, and Oklahoma (Lawrence et al. 2002, Heitzman and Guldin 2004, Heitzman et al. 2004).

Oak decline develops when oaks are under physiological stress and are subsequently attacked by root pathogens or insects (Kessler 1989, Starkey et al. 1989, Jung et al. 2000). In Missouri, widespread episodes of decline generally have followed periods of drought (Law and Gott 1987). Red oak group species (*Quercus* section *Lobatae*) have been particularly susceptible, especially those that are physiologically mature and growing on droughty sites such as on ridges or south-facing slopes (Law and Gott 1987). A high mortality of red oak group species in the Missouri Ozark forests also has been associated with Armillaria root disease (Bruhn et al. 2000). Since 1999, populations of red oak borers (*Enaphalodes rufulus* Haldeman), two-lined chestnut borers (*Agrilus bilineatus* Weber), and other insects also have increased in association with declining oak forests (Lawrence et al. 2002, Starkey et al. 2004).

Because much of the research on oak decline indicates that environmental stress, particularly drought, leads to the onset of oak decline, forest scientists and managers have advocated silvicultural practices for reducing the vulnerability to decline (Stringer et al. 1989, Kessler 1992, Dwyer and Kurtz 1994). Recommended practices include thinning and intermediate harvesting for removing vulnerable tree species and reducing stand density thereby improving the vigor and growth of residual trees and leaving the stand less susceptible to pathogens and pests associated with oak decline.

One of the recommended silvicultural alternatives proposed in Missouri is to conduct improvement harvests in declining stands. Improvement harvests generally remove diseased, defective, and poor-quality trees to increase overall stand quality (Nyland 1996). In stands where oak decline is prevalent, declining trees can be harvested to increase light, water, and nutrients available to the remaining healthy trees. However, few studies have experimentally evaluated the effectiveness of improvement harvests for mitigating oak decline. Moreover, some scientists caution that harvesting in declining stands will make the problem worse for a number of reasons including increasing the incidence of Armillaria root disease in the residual stand. Root disease can increase after harvesting because the food base for pathogenic *Armillaria* spp. is increased by the damage to residual trees during felling and skidding and to the stumps left by harvesting (Starkey et al. 1989, Kessler 1992, Burrill et al. 1999). Because there is so little experimental information

Received May 23, 2005; accepted January 11, 2006.

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Table 1. Preharvest composition and harvest removals at the two study areas.

Treatment designation	Species group	Preharvest: Trees per acre (no.)	Preharvest: Mean diameter (in.)	Preharvest: Basal area (ft^2/ac)	Harvest removals: Trees per acre (no.)	Harvest removals: Mean diameter (in.)	Harvest removals: Basal area (ft^2/ac)
Control	White oaks[a]	47	9.3	27			
	Red oaks[b]	49	12.6	44			
	Hickories[c]	6	7.2	3			
	Elm[c]	1	6.4	<1			
	Blackgum[c]	<1	8.8	<1			
	Maple[c]	—	—	—			
	Overall	103	10.7	75			
Improvement harvest	White oaks[a]	43	9.0	22	3	13.8	3
	Red oaks[b]	52	12.9	49	22	14.5	26
	Hickories[c]	5	8.9	3	1	13.5	<1
	Elm[c]	1	5.5	<1	—	—	—
	Blackgum[c]	—	—	—	—	—	—
	Maple[c]	<1	6.2	<1	—	—	—
	Overall	102	10.9	74	26	14.4	30

Values are the means of the 12 plots allocated to each treatment (control versus improvement harvest) and include only live trees ≥5-in. dbh.
[a] White oaks included white oak (*Q. alba* L.) and post oak (*Q. stellata* Wangenh.).
[b] Red oaks included black oak (*Q. velutina* Lam.), scarlet oak (*Q. coccinea* Muenchh.), and southern red oak (*Q. falcata* Michx.).
[c] Hickories (*Carya* spp. Nutt.), elm (*Ulmus* spp. L.), blackgum (*N. sylvatica* Marsh.), and maple (*Acer* spp. L.).

about the effectiveness of methods for mitigating oak decline, we conducted this study to determine if improvement harvests would reduce the severity of oak decline symptoms and improve the growth of the residual trees.

Methods

We initiated this study in 1990 at University Forest Conservation Area in Butler County, Missouri. University Forest Conservation Area is located in the Black River Ozark Border ecological subsection (Nigh and Schroeder 2002) and contains about 7,100 ac of oak-hickory forest managed by the Missouri Department of Conservation. Oaks are the dominant tree species with scarlet oak (*Quercus coccinea* Muenchh.), black oak (*Quercus velutina* Lam.), white oak (*Quercus alba* L.), post oak (*Quercus stellata* Wangenh.), and southern red oak (*Quercus falcata* Michx.) comprising most of the stocking (Wetteroff 1993). Other abundant species include hickories (*Carya* spp.), elm (*Ulmus* spp.), maples (*Acer* spp.), and blackgum (*Nyssa sylvatica* Marsh.).

We studied two sites with different soils and topography (Graves 1983). The first location (36°53′56″ N lat. 90°21′47″ W long.) was established on soils mapped as Captina silt loam (5 to 9% slopes) and Clarksville very gravelly silt loam (14–35% slopes). Soils of the Captina series (fine-silty, siliceous, active, mesic, and Typic Fragiudults) formed in a thin mantle of silty material overlying hillslope sediments and residuum weathered from limestone and dolomite. They have a fragipan at depths ranging from 16 to 38 in. and are moderately well drained. Soils of the Clarksville series (loamy-skeletal, siliceous, semiactive, mesic, and Typic Paleudults) are formed in gravelly hillslope sediments overlying residuum weathered from limestone and dolomite. However, these soils do not have a fragipan and are excessively well drained. The soils at the second location (36°55′5″ N lat., 90°23′48″ W long.) were mapped as Loring silt loam (5–9% slopes). Soils of the Loring series (fine-silty, mixed, active, and thermic Oxyaquic Fragiudults) formed entirely in loess. These soils have a fragipan at depths from 14 to 35 in. and are moderately well drained.

We established 12 0.5-ac square plots at each site during May and June 1990. On each plot, we numbered and inventoried all trees 5-in. dbh or more. Data collected included tree number, species, dbh (nearest 0.1 in.), crown class, crown dieback, and status (live or dead). Crown classes were dominant, codominant, intermediate, and suppressed (Smith 1986). When the study was initiated, canopy dominants and codominants were 65–80 years old (Wetteroff 1993). Crown dieback classes were healthy (less than 5% crown dieback), slight (5–33% crown dieback), moderate (34–66% crown dieback), and severe (more than 66% crown dieback). For dead trees, we recorded the probable or suspected cause (e.g., fire, windthrow, insect infestation, disease, competition, drought, lightning, or unknown).

At both locations, oak decline has been a chronic problem since the early 1970s (Law and Gott 1987). Our initial inventory showed that 22% of the basal area of the red oak group species exhibited moderate or severe decline and nearly 15% of the basal area was dead. Of the red oak group species, southern red oak generally exhibited very little crown dieback and appeared to be healthier than scarlet oak and black oak. Overall, white oak group species were substantially healthier than red oak group species; only about 4% of the white oak basal area exhibited moderate or severe decline and 7% was dead.

Six of the 12 0.5-ac plots at each site were randomly selected to receive improvement harvests and the remaining plots were used as controls. Our definition of improvement harvest follows Nyland (1996). Our intention was to conduct commercial harvests to (1) remove oaks that appeared to be declining and at high risk of dying before the stand was to be regenerated and (2) reduce stand density approximately to or slightly below B level (Gingrich 1967) to maximize growth of the residual trees while maintaining full or nearly full stocking. However, marking only those oaks that appeared to be at high risk would leave some areas fully or overstocked and other areas understocked or include areas having low commercial value. To balance our residual stocking goals and to ensure a commercially viable harvest, we had to leave some declining oaks and remove some healthy ones. Pretreatment data and improvement harvest removals are shown in Table 1. Most of the oak basal area harvested was in the slight or moderate crown dieback classes (Table 2). To ensure that our improvement harvests would simulate those conducted operationally on private or public land, all timber marking and sale administration was done by professional foresters from the Missouri

Table 2. Pretreatment distribution and harvest removals of trees ≥5-in. dbh by crown dieback classes in plots designated for improvement harvests.

	Crown dieback class					
	None (<5% dieback)	Slight (5–33% dieback)	Moderate (34–66% dieback)	Severe (>66% dieback)	Dead	Total
	Basal area (ft^2/ac)					
White oaks						
Pretreatment	14.5	6.7	0.6	0.3	2.1	24.3
Removals	1.0	2.3	0.1	0.0	0.0	3.3
Red oaks						
Pretreatment	7.6	30.6	10.1	0.9	6.6	55.8
Removals	3.6	15.2	6.2	0.7	0.6	26.3

The category "dead" included all standing dead trees within plots.

Table 3. Proportion of basal area by crown dieback classes in control and harvested stands at the two study areas.

		Crown dieback class				
Species group	Treatment designation	None (<5% dieback)	Slight (5–33% dieback)	Moderate (34–66% dieback)	Severe (>66% dieback)	Dead
		Percent of basal area				
Pretreatment						
White oaks	Control	58	29	3	1	9
	Treated	60	28	3	1	9
Red oaks	Control	5	53	23	1	18
	Treated	14	55	18	2	12
14-yr Posttreatment						
White oaks	Control	37	53	1	1	8
	Treated	38	54	<1	1	7
Red oaks	Control	9	55	7	3	26
	Treated	12	57	8	<1	23

Trees included were ≥5-in. dbh.

Department of Conservation. Application of the cutting treatments was completed by fall and early winter of 1990.

Fourteen years later during the summer of 2004, we reinventoried each plot using the same procedures as when the study was initiated. Of the 1,426 trees that we originally inventoried, we were unable to find 54 that presumably had died, fallen, and decayed beyond recognition. These trees were labeled as "missing" and were excluded from subsequent analyses. We also found 440 ingrowth trees that we numbered, inventoried, and included in our analyses.

We used analysis of variance (ANOVA) to determine whether (1) the plot-level proportion of trees in each of the crown dieback classes and (2) tree diameter growth differed between treated plots and control plots. Harvest treatment effect was considered fixed but the study locations were considered random. Therefore, we used the treatment by location interaction as the error term for analyzing the treatment effect. For all analyses, we examined red oak and white oak species groups separately. For analyzing the change in proportion of trees in each of the crown dieback classes, we grouped data into two crown dieback classes; the first group included trees with 33% or less crown dieback and the second group included trees with more than 33% crown dieback (declining trees). We also examined residuals and determined that transformations were not necessary to normalize the data. For analyzing diameter growth, we included the initial diameter as a covariate and the initial crown dieback class as a factor to account for their potential influence on tree growth. We considered effects to be significant if $P < 0.05$. For all analyses, we found no significant treatment by site interactions indicating that the trees responded in the same manner at both locations.

Results

Before conducting the improvement harvests, the plots had an average basal area of 75 ft^2/ac for live trees 5-in. dbh or more. During the improvement harvests, 30 ft^2/ac was removed, of which 10% was in the white oak group and 87% was in the red oak group (Tables 1 and 2). Most of the red oaks in the severe crown dieback class were harvested, but in terms of total basal area, most of the removals had slight or moderate crown dieback. During the 14 years after harvests, the basal area of live trees 5-in. dbh or more in control plots increased from 75 to 80 ft^2/ac. This increase was small but not unexpected for fully stocked mature stands. In the harvested plots, the basal area increased from 44 ft^2/ac immediately after harvesting to 61 ft^2/ac 14 years later, an increase of 1.2 ft^2/ac per year. This is a reasonable growth rate for the region considering the stand composition and advanced age (Johnson et al. 2002)

The improvement harvest had very little effect on the health of the residual trees during the study period. The proportions of trees in each crown dieback class before and 14 years after treatment were not significantly different between harvested and control plots (Table 3). For trees exhibiting little or no crown dieback when the study was initiated, the proportions of stems that remained the same, suffered increased dieback, or died during the 14-year monitoring period were nearly identical ($P > 0.09$) in treated plots and controls (Figure 1). For declining trees, the impact of the improvement harvest was not as clear. For example, improvement harvests significantly ($P = 0.03$) increased the proportion of declining red oaks that remained in the same crown dieback classes and nominally ($P =$

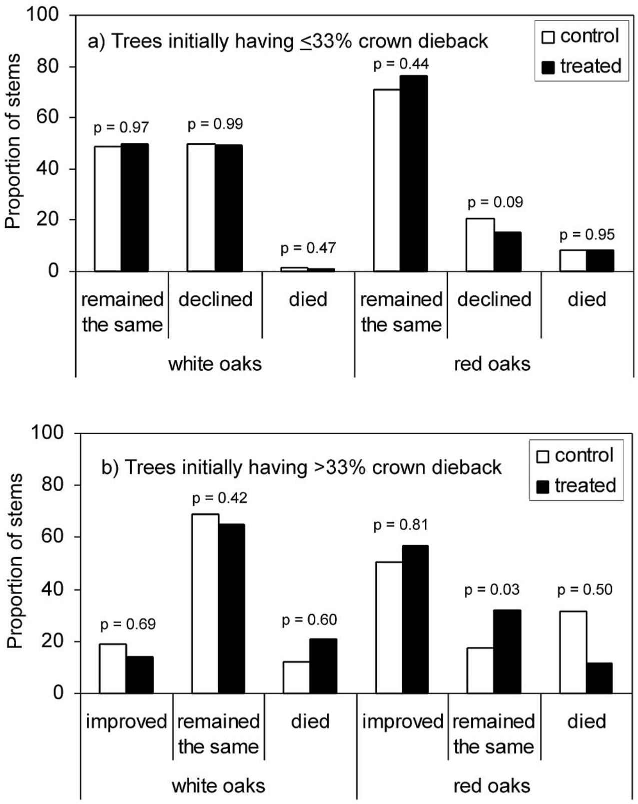

Figure 1. Change in the proportion of white oak and red oak group trees exhibiting crown dieback during the 14-year study period by treatment; (a) trees initially healthy or with slight decline (33% or less crown dieback) and (b) trees initially exhibiting moderate to severe decline (more than 33% crown dieback).

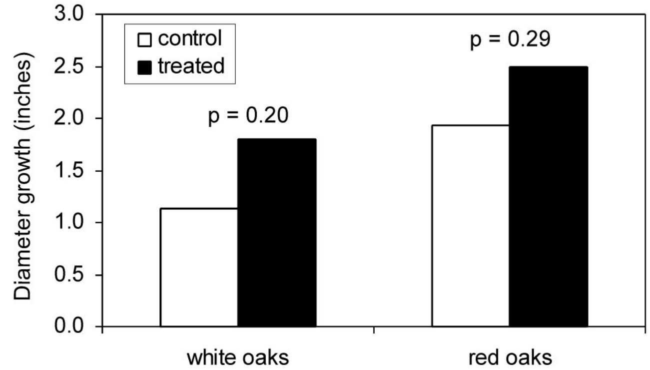

Figure 2. Fourteen-year diameter growth of white oak and red oak group trees by treatment in the study area. Data included only those trees that were alive throughout the experiment.

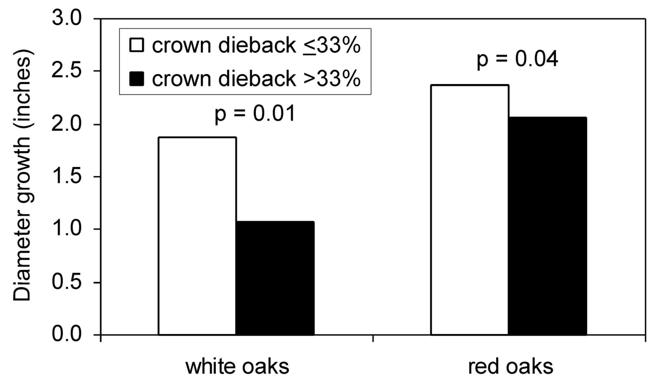

Figure 3. Fourteen-year diameter growth of white oak and red oak group trees initially having 33% or less crown dieback and those initially having more than 33% crown dieback. Data included only those trees that were alive throughout the experiment regardless of treatment.

0.50) decreased the proportion that died compared with unharvested controls. For declining white oaks, there were no significant differences ($P > 0.42$) between harvested and control plots.

The red oak and white oak species groups differed ($P < 0.01$) in their responses to harvest treatments (Figure 1). More than 70% of red oaks that initially exhibited little or no crown dieback remained in the same crown dieback classes during the study period compared with only 50% for white oaks. However, healthy red oaks had a slightly greater mortality rate during the study period than did healthy white oaks. We also observed that more than 50% of the red oaks that initially exhibited moderate to severe decline symptoms appeared to improve during the study, regardless of harvest treatment. In contrast, fewer than 18% of declining white oaks improved during the study period.

The improvement harvest nominally increased the diameter growth of the residual trees (Figure 2). Although not statistically significant, red oak diameter growth increased 29% and white oak diameter growth increased 58%. We also found that the initial crown dieback class was a significant factor ($P < 0.04$) in our analysis of diameter growth (Figure 3). During the study period, white oaks initially having 33% or less crown dieback had a diameter growth rate that was 1.7 times greater than white oaks initially exhibiting more dieback. For red oaks, the diameter growth rate of trees that initially exhibited 33% or less crown dieback was 1.1 times greater than for those initially exhibiting more severe crown dieback (Figure 3).

Discussion

Our study showed that improvement harvests did not mitigate many of the symptoms of oak decline. The distributions of trees by crown dieback classes in harvested and control plots were nearly identical to each other before treatment and 14 years after treatment. During the 14-year monitoring period of our study we found that a substantial number of oaks continued to decline or die regardless of treatment. There was some evidence that the improvement harvests caused more of the declining red oaks to remain alive and be retained compared with the controls. However, there was no evidence that the improvement harvests actually caused declining red oaks to regain foliage or recover from decline. In fact, the mortality rates that we observed are similar to those of managed and unmanaged stands elsewhere in the Missouri Ozarks (Kabrick et al. 2004).

We were surprised by the large proportion of red oaks initially exhibiting moderate to severe crown dieback that appeared to improve (nearly 50%), regardless of treatment. This suggests that some red oaks have the ability to recover foliage even if crown dieback is moderate to severe. Few others have documented the recovery of individual oaks from decline although Kessler (1992) noted that oak-hickory forests of eastern North America have recovered from declines after stress agents were alleviated. Much of the decline observed in our research sites and elsewhere in the region was thought to be triggered by periods of drought during the 1980s, (Law and Gott 1987, Jenkins and Pallardy 1995). Weather data collected within 6 mi of the research sites and compiled by the High Plains

Regional Climate Center showed that annual rainfall during most of the 14-year study period had increased to levels at or above the 50-year average. The exception was during 1999–2001, when drought triggered another episode of decline throughout the Ozark Highlands (Lawrence et al. 2002, Heitzman et al. 2004). Although our data do not allow us to link conclusively the onset or recovery from oak decline to climatic conditions, our findings suggest that the recovery of declining oaks was unrelated to the improvement harvests that we conducted. Otherwise, the harvested plots would have responded differently than the unharvested controls.

Our findings have important implications for forest managers because they show how crown condition can be used to forecast the future health or mortality of individual red oaks and white oaks. Our data showed that most (about 70%) red oaks having relatively healthy crowns (crown dieback that is 33% or less) are likely to remain healthy for at least 14 years, a duration approximately corresponding to a typical forest entry period. Elsewhere in the Missouri Ozarks, Johnson and Law (1989) came to a similar conclusion but for a 5-year time period after an oak decline event. However, the fate of a declining red oak is less predictable. Red oaks exhibiting moderate or severe crown dieback are as likely to remain in poor health or die as they are to recover. If a forester is considering whether to harvest the tree because it appears to be at risk, then other criteria must be considered such as its present value for timber or wildlife or whether it must remain in the stand to satisfy stocking goals.

The relationship between crown dieback and future health for white oaks appears to be quite different from red oaks. White oaks with little or no crown dieback appear to be at very low risk of dying even though they are as likely to decline as they are to remain healthy. White oaks exhibiting moderate or severe crown dieback are unlikely to show any improvement during the next 14 years and are most likely to grow slowly and continue to decline or die.

Although our findings cast some doubt about whether forest management practices can mitigate oak decline in affected stands, they show that improvement harvests did not accelerate decline relative to unharvested stands. Other authors have expressed concern that the stumps left by partial cutting or residual trees damaged by felling and skidding operations provide substrate for *Armillaria* spp., thereby potentially spreading root rot fungi to otherwise healthy trees (Starkey et al. 1989, Kessler 1992). However, we found that the proportion of trees exhibiting decline symptoms and the mortality rates in our controls were about the same as in treated plots. Our results suggest that harvesting declining trees is not likely to inadvertently harm residual trees. Rather, the improvement harvests appeared to have a positive impact by increasing the diameter growth of the residual trees and increasing the overall basal area growth. This is an important finding considering the amount of decline in and the advanced age of these stands when treatments were implemented. This positive growth response of mature trees was consistent with the findings of others examining growth responses of mature trees after crop tree releases in stands not suffering from oak decline (Graney 1998, Smith and Miller 1991, Ward 2002) and after areawide thinning (Johnson et al. 2002).

Our findings apply to mature and largely unmanaged oak stands where oak decline is already prevalent. This does not diminish the usefulness of our findings because most of the forests in the Ozark Highlands are of similar age and composition, have had similar stand histories, and suffer from oak decline. Recent estimates indicated that more than 100,000 ac in Missouri (Lawrence et al. 2002) and more than 300,000 ac in Arkansas (Heitzman and Guldin 2004, Heitzman et al. 2004) were dominated by mature oaks and exhibited moderate to severe oak decline symptoms attributed to widespread drought during the late 1990s and early 2000s. Law et al. (2004) anticipate recurring episodes of oak decline because of the abundance of mature red oaks throughout the Missouri Ozarks. What remains to be examined is whether oak decline can be prevented in oak-dominated stands that have been managed from a young age with silvicultural treatments including conducting timely thinnings and other stand improvement methods to reduce competition-induced stress and enhance the vigor and growth of the residual stand.

Conclusion

Overall, improvement harvests in declining oak stands do not appear to mitigate or accelerate oak decline. They have the added benefits of increasing the diameter growth of the residual trees and increasing the basal area growth of the residual stand. The amount and severity of crown dieback offers some indication of the future health of both red oaks and white oaks, even in the absence of the improvement harvests. Individual red oaks having healthy crowns were likely to remain healthy for at least 14 years and those exhibiting moderate or severe crown dieback often were able to partially restore lost foliage. Individual white oaks having healthy crowns appear to be at very low risk of dying, even though they are as likely to decline as to remain healthy. Unlike red oaks, white oaks exhibiting moderate to severe crown dieback are unlikely to recover lost foliage.

Literature Cited

Bruhn, J.N., J.J. Wetteroff Jr., J.D. Mihail, J.M. Kabrick, and J.B. Pickens. 2000. Distribution patterns of *Armillaria* species in upland Ozark Mountain forests with respect to site, overstory species composition, and oak decline. *Eur. J. For. Pathol.* 30:43–60.

Burrill, E.A., J.J. Worrall, P.M. Wargo, and S.V. Stehman. 1999. Effects of defoliation and cutting in eastern oak forests on *Armillaria* spp. and a competitor, *Megacollybia platyphylla. Can. J. For. Res.* 29:347–355.

Dwyer, J.P., and W.B. Kurtz. 1994. Pre-outbreak management recommendation for 60-year-old declining oak stands in the Ozarks. *North. J. Appl. For.* 11:98–101.

Gingrich, S.F. 1967. Measuring and evaluating stocking and stand density in upland hardwood forests in the Central States. *For. Sci.* 13:38–53.

Graney, D.L. 1998. Ten-year growth response of red and white oak crop trees to intensity of crown release. P. 163–168 in *Proc. of 9th Biennial southern silvicultural research conf.*, Waldrop, T.A. (ed.). USDA For. Serv. Gen. Tech. Rep. SRS-20. Asheville, NC. 628 p.

Graves, L.H. Jr. 1983. *Soil survey of Butler County and part of Ripley County, Missouri*. USDA Soil Conservation Serv., Washington, DC. 141 p.

Heitzman, E., and J.M. Guldin. 2004. Impacts of oak decline on forest structure in Arkansas and Oklahoma: Preliminary results. P. 142–146 in *Proc. of 12th Biennial southern silvicultural research conf.*, Connor, K.F. (ed.). USDA For. Serv. Gen. Tech. Rep. SRS-71. Asheville, NC. 600 p.

Heitzman, E., R.M. Muzika, J. Kabrick, and J. Guldin. 2004. Assessment of oak decline in Missouri, Arkansas, and Oklahoma. P. 510 in *Proc. of 14th Central hardwood forest conf.*, Yaussy, D.A., D.M. Mix, P.C. Goebel, and R.P. Long (eds.). USDA For. Serv. Gen. Tech. Rep. NE-316. Newtown Square, PA. 539 p.

Jenkens, M.A. and S.G. Pallardy. 1995. The influence of drought on red oak group species growth and mortality in the Missouri Ozarks. *Can. J. For. Res.* 25:1119–1127.

Johnson, L.J., and J.R. Law. 1989. A five year record of change for a declining scarlet oak stand in the Missouri Ozarks. P. 103–107 in *Proc. 7th Central hardwood forest conf.*, Rink, G., and C.A. Budelsky (eds.). USDA For. Serv. Gen. Tech. Rep. NC-132. St. Paul, MN. 313 p.

Johnson, P.S., S.R. Shifley, and R. Rogers. 2002. *The ecology and silviculture of oaks*. CABI International, New York. 503 p.

Jung, T., H. Blaschke, and W. Obwald. 2000. Involvement of soilborne *Phytophthora* species in Central European oak decline and the effect of site factors on the disease. *Plant Pathol.* 49:706–718.

KABRICK, J.M., S.R. SHIFLEY, R.G. JENSEN, Z. FAN, AND D.R. LARSEN. 2004. Factors associated with oak mortality in Missouri Ozark Forests. P. 27–35 in *Proc. 14th Central hardwood forest conf.*, Yaussy, D.A., D.M. Mix, P.C. Goebel, and R.P. Long (eds.). USDA For. Serv. Gen. Tech. Rep. NE-316. Newtown Square, PA. 539 p.

KESSLER, K.J. JR. 1989. Some perspectives on oak decline in the 80's. P. 25–29 in *Proc. 7th Central hardwood conf.*, Rink, G., and C.A. Budelsky (eds.). USDA For. Serv. Gen. Tech. Rep. NC-132. St. Paul, MN. 313 p.

KESSLER, K.J. JR. 1992. *Oak decline on public lands in the central forest region*. USDA For. Serv. Res. Note NC-362. 4 p.

LAW, J.R., AND J.D. GOTT. 1987. Oak mortality in the Missouri Ozarks. P. 427–436 in *Proc. 6th Central hardwood forest conf.*, Hay, R.L., F.W. Woods, and H. DeSelm (eds.). The Univ. of Tennessee, Knoxville. 526 p.

LAW, J.R., R. MELICH, C. STUDYVIN, AND J.R. STEINMAN. 2004. Oak decline in Missouri: History revisited. P. 257–258 in *Proc. on Upland oak ecology symp. History, current conditions, and sustainability*. USDA For. Serv. Gen Tech. Rep. SRS-73. Asheville, NC. 311 p.

LAWRENCE, R., B. MOLTZAN, AND K. MOSER. 2002. Oak decline and the future of Missouri's forests. *Missouri Conserv*. 63:11–18.

NIGH, T.A., AND W.A. SCHROEDER. 2002. *Atlas of Missouri ecoregions.* Missouri Department of Conservation, Jefferson City, MO. 212 p.

NYLAND, R.D. 1996. *Silviculture: Concepts and applications.* McGraw-Hill, Boston. 633 p.

SMITH, D.M. 1986. *The practice of silviculture*, 8th Ed. John Wiley and Sons, New York. 527 p.

SMITH, H.C., AND G.W. MILLER. 1991. Releasing 75- to 80-year-old Appalachian hardwood sawtimber trees: 5-year d.b.h. response. P. 402–413 in *Proc. of 8th Central hardwood forest conf.*, McCormick, L.H., and K.W. Gottschalk (eds.). USDA For. Serv. Gen. Tech. Rep. NE-148. Radnor, PA. 605 p.

STARKEY, D.A., AND S.W. OAK. 1989. Silvicultural implications of factors associated with oak decline in southern upland hardwoods. P. 579–586 in *Proc. of 5th Biennial southern silvicultural research conf.*, Miller, J.H. (comp.). USDA For. Serv. Gen. Tech. Rep. SO-74. New Orleans, LA. 618 p.

STARKEY, D.A., S.W. OAK, G.W. RYAN, F.H. TAINTER, C. REDMOND, AND H.D. BROWN. 1989. *Evaluation of oak decline areas in the South.* USDA For. Serv. Prot. Rep. R8-PR 17. 31 p.

STARKEY, D.A., F. OLIVERIA, A. MANGINI, AND M. MIELKE. 2004. Oak decline and red oak borer in the Interior Highlands of Arkansas and Missouri: Natural phenomena, severe occurrences. P. 217–222 in *Proc. on Upland oak ecology symposium: History, current conditions, and sustainability.* USDA For. Serv. Gen Tech. Rep. SRS-73. Asheville, NC. 311 p.

STRINGER, J.W., T.W. KIMMERER, J.C. OVERSTREET, AND J.P. DUNN. 1989. Oak mortality in Eastern Kentucky. *South. J. Appl. For.* 13:86–91.

WARD, J.S. 2002. Crop tree release increases growth of mature red oak sawtimber. *North. J. Appl. For*. 19:149–154.

WETTEROFF, J.J. 1993. *Management and prediction of red oak decline in the Missouri Ozarks.* MSc thesis, Univ. of Missouri–Columbia, Columbia, MO. 220 p.