Individual and Stand-Level Components of Oak Decline

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Introduction

The pre-settlement forest canopy structure of the Ozarks was commonly open, particularly where frequent and intentional burning by Native Americans maintained fire mediated communities such as oak-pine forests and savannas (Batek et al. 1999; Guyette et al. 2002). The upland oaks (*Quercus* sp.) of the Ozarks and shortleaf pine (*Pinus echinata* Mill.) are adapted to disturbance, including fire, as characterized by their ability to resprout following topkill (Burns and Honkala 1990). The forest composition has changed drastically in Missouri since the presettlement period (Batek et al. 1999; Cunningham & Hauser 1989; Fletcher and McDermott 1957). Currently, pine-forests occur on less than twenty percent of the land area it did 150 years ago (Fletcher & McDermott 1957; Cunningham & Hauser 1989).

The red oak group, primarily black (*Q. velutina* Munch.) and scarlet (*Q. coccinea* Lam.) replaced the original shortleaf pine forest sites in the Ozark Highlands. Fire frequency in the Missouri Ozarks was positively related with the abundance of shortleaf pine and negatively with the abundance of black oak from data compiled from land survey records (ca. 1830) (Batek et al. 1999).
Oak decline was first recorded in the 1970's (Law and Gott 1987) and attributed to climatic stresses. A larger epidemic of red oak mortality has been apparent of late (Starkey et al. 2003). Conclusive evidence of the relative importance of contributing factors, spatial and temporal is still lacking, although Jenkins and Pallardy (1995) emphasized the importance of severe drought in red oak mortality. Certain soils and topographic positions (flat, high ridges) in which shortleaf pine and post oak once dominated tend to be more xeric or contain a fragic layer which can impede root growth and water uptake during sever water stress.

The process of oak decline within an individual has largely been characterized (Houston 1992), also see figure 13. Stand-level decline has been hypothesized (Mueller-Dombois 1992, Smith and Long 2001) but no empirical data has determined this to be a real phenomenon or just the aggregation of individual responses.

Study Area

Two sets of plots were used in this study. The first set was randomly selected from UTM Coordinates within the Current River Sub-section. This sub-section is the most dissected and densely forested landscape in Missouri. A second selection of plots were measured on the Missouri Ozark Forest Ecosystem Project located in the center of the sub-section. Figure I indicates the major forest types of the area and the ellipse encompasses the general area of the study. Figure 2 is a projection of landcover in Missouri, the densely forested Current River sub-section is evident.

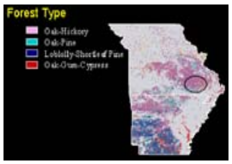


Figure 1. Forest Types of the Ozarks

Figure 2. Landcover and sub-sections of Missouri

Methods

Data was taken in 2002-2003; Dbh was measured on all species; height, crown conditions and increment cores were taken for up to10 overstory pines and red oaks on 84, 0.5 acre MOFEP plots; additionally, all red oaks and pines were measured on 76, 0.2 acre plots across SE Missouri. In total, over 1500 oak and pine trees were cored, measured and aged (Figure 3). All datable rings (over 100,000) were counted, measured and initially cross-dated by using signature years. Cross-dating was checked by COFECHA (Holmes 1986). Ring series were converted into annual basal area increment (BAI), which more closely related to total tree growth over time than ring width (LeBlanc 1996). Individual trees were assigned a vigor classes after testing patterns of growth (BAI) and comparing them with tree vigor (crown conditions).

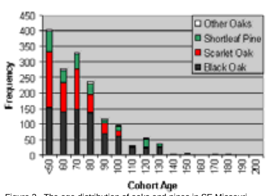


Figure 3. The age distribution of oaks and pines in SE Missouri

Assistant Jessie B. coring a shortleaf pine on a 100°+ July day.

Measuring Tree Vigor

Direct measures of crowns, when adjusted by exclusive crown area (Webster and Lorimer 2003) or a variant thereof suffer from the exponential increases in "efficiency" in trees which have a large live crown ratio but are relatively narrow. Such is often the case in oaks which have suffered dieback and re-grown the majority of their leaf area on epicormic sprouts directly off the bole of the tree. This growth pattern is efficient, by reducing the number of nodes and path length (Rust and Roloff 2002). However, this is a "last-ditch" effort at survival; it is not necessarily vigorous or a successful pattern of crown architecture in a competitive environment. An index of crown vigor was formulated to discount this bias for the assessment of oak decline.

The index of tree vigor (TVI) is, at its most basic, a ratio of the estimated leaf area to the estimated stem surface area of the tree. It was measured by taking direct measurements of the crown, and adjusting them by density, a measure of the amount of foliage within the available crown space, (resulting in an estimate of crown surface area, CS) and the relative position of the crown (CSI). This metric was then adjusted for the total size of the tree using a species-specific equation that uses the height and dbh to predict stem surface area (SS) (Whittaker and Woodwell1967).
An example of the approximation of crown surface area (CS) and TVI is as follows:

$$CS = [(Pi \times Cr^2) + ((2 \times Cr \times Pi) \times (H \times CR)) \times D]$$

Example (Fig. 4): $CS = [(Pi \times 5^2) + ((2 \times 5 \times Pi) \times (25 \times .45)) \times .75] = 90.9\ m^2$

Tree Vigor Index (TVI) = CSI / SS
Crown Surface Index = CS × (1- CR),
Stem Surface = Pi × DBH × H / 2 × C,

Example (Fig. 4): $TVI = [(90.9m^2 \times .55) / (.5m\ (25m / 2) \times 1.268) = 6.31$

Where;
Pi = 3.14159,Cr = crown radius, H = height, CR = crown ratio, D = density,
C is a constant =1.268 and DBH= diameter at breast height, H= total tree height.

Example of Vigor Class Determination

These two increment cores and resultant BAI series came form the same plot. 18505 (upper increment core) was classified by TVI (=7.34) and BAI tests as "healthy". 18304 (lower increment core) was classified by TVI (=1.578) as declining. The period of differentiation of these two trees (which are relatively old) came during the major drought of (1952-1954). Note that 18304, the tree now declining, grew faster as a juvenile and was affected more seriously by the drought though it likely had a superior competitive position (dbh in 1952 was approximately 10.5cm, versus 8cm for tree 18505). Though data are not shown, high early growth rates were followed by a dramatic shock due to drought; in each case tested, for trees greater than 60 years old, the mean annual BAI of the first half of the decline-tree chronologies was significantly higher (p<.01) than their currently vigorous counterparts.

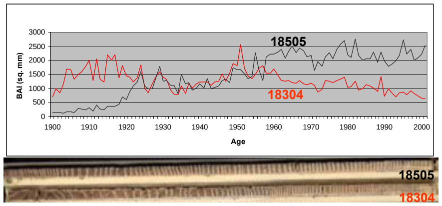


Figure 6. Example of Healthy and Declining Tree Cores and Associated Basal Area Increment Pattern

Long Term Growth of Declining and Healthy Trees

BAI growth for declining (n=175) and healthy (n=587) trees were differenced by a red oak tree-ring chronology constructed to maximize climate signal. The result is a 'standardized' pattern of BAI accrual in the diverging populations.

It is risky to assess the mean chronology of growth patterns as they may not represent true patterns within individuals or unknown sub-populations. Although there should be a continuous response for the time since an inciting event that a declining tree dies, inciting events, by definition, are singular and do not occur on a continuous scale. For instance, in figure 7, the average chronology shows a smooth temporal pattern of decline with associated shocks following droughts of 1971-72 and 1980. However, tree 18304 (figure 6) started declining soon after the 1950's drought and shows little response to later droughts. Though there are problems inherent, It is instructive to put growth and decline in a larger temporal context, as the patterns are obviously divergent in figures 7 and 8.

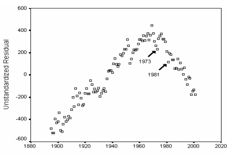


Figure 7. Long-term growth pattern for declining trees.

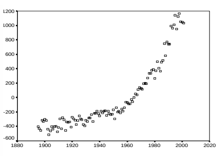


Figure 8. Long-term growth pattern for healthy trees.

Tree Vigor and Estimates of Growth

Four methods of assessing forest decline were hypothesized. These included quartiles of the distribution of CSI, an estimate of crown surface area; a vigor class decision module provided by statistical testing (Leblanc 1996); quartiles of a distribution of leaf area change estimated by linear regression of BAI data (Rogers 1983); and quartiles of TVI, described earlier. A cross-validation process using n-1 vigor classifications was summed to find the most consistent method. Results indicated that TVI had the most intersections with the other three methods, minimizing type 1 error. TVI also most closely resembled a normal distribution but was slightly skewed (i.e. its composite nature and adjustment for tree surface area did not entirely counter the positively skewed distribution of tree size and age of the sample).

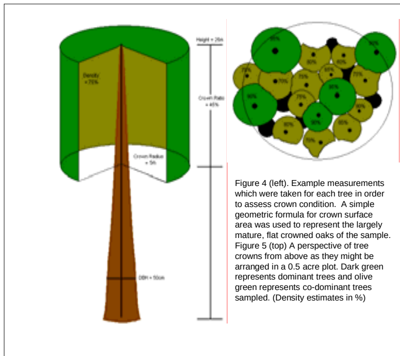


Figure 4 (left). Example measurements which were taken for each tree in order to assess crown condition. A simple geometric formula for crown surface area was used to represent the largely mature, flat crowned oaks of the sample. Figure 5 (top) A perspective of tree crowns from above as they might be arranged in a 0.5 acre plot. Dark green represents dominant trees and olive green represents co-dominant trees sampled. (Density estimates in %)

Black Oak versus Scarlet Oak by Vigor Classes

Figures 9 and 10 are an epidemiological approach to summarize the relative health of black oak and scarlet oak in different age classes. Age class labels approximate mean and median ages for the groups. The results indicate that black oak is more likely to be in decline. However, this is due in part to its longevity and ability to persist under decline conditions for a long time after onset; max. age for black oak approaches 225 years whereas the max age for scarlet oak is 150 years.

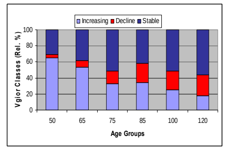


Figure 9. Black oak vigor classes by age group.

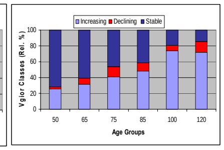


Figure 10. Scarlet oak vigor classes by age group

Testing of Predisposing Factors

Two-way ANOVAs of tree age versus tree species and other *a priori* stand-level classifications were performed on all red oak trees (1358); with TVI as an independent variable. TVI within age groups, as presented here, or blocked by plot, conforms to the assumptions for ANOVA. The classifications tested (Table 1) are as follows: Vigor status, mean TVI among three vigor classes; Species, mean TVI among black and scarlet oaks; Landform, mean TVI among four landform classes: Parent Material, the effect of three dominant geologies on TVI, Stocking, the effect of current stocking levels on TVI, Stocking Difference, level of TVI as classified by recent mortality; Site Index, the effect of four site index classes on TVI.
Mean TVI is shown among site index and stocking difference classes in figures 11 and 12.
Stocking difference was calculated as the difference between current stocking and stocking with trees recently dead (mean age of 3.2 years since death, data not shown), this was used as a classification variable among trees, to test for stand-level effects on individuals.

Independent Variable Class	Overall p-value / Type III F-Value	Interaction p-value / Interaction F-Value	Age Group 50	Age Group 65	Age Group 75	Age Group 85	Age Group 100	Age Group 120
Vigor Status (N=1358)	< .0001 / 130.43	0.0381 / 1.93	ab ac† bc†	ab† ac bc†	ab† ac† bc†	ab† bc†	ab† bc†	ab† bc†
Species (N=1358)	< .0001 / 15.38	0.0167 / 2.18	ab†	ab†	ab†	ab†	ab†	
Landform (N=1358)	0.1836 / 1.62	0.2551 / 1.21	ac	bc	ac†			
Parent Material (N=1358)	0.0128 / 4.37	< .0001 / 6.27		ac	ab† ac† bc†		ab	ac bc
Stocking (N=1358)	0.3161 / 1.18	0.0001 / 2.46	bf cd† ce† cf†	ab ac† ad† ae†	ad† af† bd de† df			bc
Stocking Difference (N=1358)	< .0001 / 4.45	< .0001 / 2.7	bc† bd† be† bf†	bc† cd ce	bd† bf† bg† cd† cf† cg de† ef† eg	ae bc† bd† be†	bc† bd be bf† bg† cg† dg† eg† fg†	
Site Index (N=1358)	0.0014 / 5.2	< .0001 / 3.32	bd cd†	bd† cd	bc† bd† bc† bd†		ad† bc† bd† cd	ab ac

All letter combinations imply a significant difference in TVI between independent variables as classified below of at least p=.05, † is significant at p=.01
Vigor Status: a=Stable, b=Decline, c=Increasing; Species: a=scarlet oak, b=black oak
Landform: a=exposed, b=protected, c=variable, d=flat/ridge; Parent Mat.: a=Roubidoux, b=U. Gasconade, c=L. Gasconade
Stock Diff.: a= 10, b=20, c=30, d=40, e=50; Site Index: a= (<61), b=(61-70), c=(71-80), d= (>81)
Stocking: a= (<86), b=(86-95), c=(96-105), d=(106-115), e=(116-125), f= (>125)

Table 1. Results from two way ANOVA testing predisposing factors

Figure 11. Mean tree vigor by site index class.

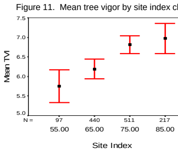
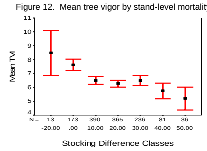


Figure 12. Mean tree vigor by stand-level mortality.



Discussion of Predisposing Factors

Overall
Vigor status, species, parent material, stocking difference and site index proved significant.

Species
Means indicated that black oak has significantly poorer crown conditions within age groups. Scarlet oak dies at an earlier age when afflicted by decline whereas black oak can persist for many years before death. Figures 9 and 10 indicate the significantly larger portion of black oaks in decline. Scarlet oaks show symptoms of decline but die so quickly that they are under-represented here, in comparison to relative percent of basal area mortality.

Landform
The amount of variability within landform classes was too high to prove significant. It is obvious on the ground that mortality is primarily on ridges and upper slopes. However after discussion and observation it appears that only ridges and xeric shoulders which include a fragipan or extremely rocky soil are prone to decline and red oak mortality.

Parent Material
The prevalence of decline on soils derived from Roubidoux sandstone is quite evident. Roubidoux is associated with soil high on the landscape where historic fire frequency was greatest (Guyette et al. 2002) and where *Armillaria* is most prevalent (Bruhn et al. 2000). These soils are the "highest and driest" landscapes and are more prone to form fragipans and subsequently are affected more seriously by drought. It is most likely that parent material does not predispose oaks to decline but is an indicator of oak decline potential due to its covariance with a number of other variables that affect tree vigor.

Stocking
This stand-level factor was not significant overall, however, this is due to the lack of differences in older age groups. The majority of mortality occurs between stand ages 60-80, resulting in a stand made up of surviving, larger individuals with low competition for resources (Clark 1990) and variable stocking levels. The interaction between age and stocking was significant. Our data suggest that stands with higher densities are predisposed to mortality due to drought and decline between ages 60-80 when inter-tree competition is highest. After stand structure and stocking changes from mortality (i.e. after stand age 80-90), it no longer is a predisposing factor.

Stocking Difference
Means of TVI suggest that surviving red oaks on sites suffering the highest recent mortality rate have significantly poorer crown conditions than low-mortality sites (Figure 12).

Site Index
Sites with poor to average potential productivity have greater mortality and significantly worse crown conditions (Figure 11) than do better sites. Although, on the most xeric, poor sites, it has been observed that few red oaks survive to be adults so symptoms of decline and overstory mortality rates are actually lower.

Figure 13.
76 year old scarlet oak in decline.

Declining oaks dieback first in the small diameter branches of the outer crown progressively to include primary branches as seen in this picture. Though this tree has been growing in a large canopy gap (subsequent to death of other declining oaks), with abundant resources, it has not responded with increased vigor. Crown conditions of conifers in Europe have been shown to be temporally variable with some trees recovering (Schweingruber 1996) The process of shoot dieback and decline in oaks is for the most-part an irreversible process eventually leading to death.

Relative Importance of Predisposing Factors

Although a number of factors were found to significantly affect tree vigor, the ANOVA does not indicate causality or the relative importance of each factor. Results from backward selection linear models (BSLR) were used to rank the factors thought to predispose red oaks to decline. BSLR was was run on the random selection of individual tree data as well as means at the plot level. A conservative p-value to enter the model was set at .01 and variables were removed if p > .05.

BSLR, at the individual and the plot level, both included four variables and showed that age described the most variance in TVI. The plot level data included stocking difference, geology and SI, respectively as the variables describing the most variance. Individual tree data suggested that after age, parent material, stocking difference, and SI, respectively were most important.

This data suggests as previously thought, that age is by far the most important single variable. Within age, parent material is the most important predisposing factor. Roubidoux sandstone are the most xeric landscapes and form fragipans, the combination of which are likely the secondary mechanisms of decline. Site index was also found to be a significant predisposing factor. This in our opinion is due to the large difference in average tree vigor on the best sites as compared to the average to poor sites in which decline occurs.

Conclusions

Cohort senescence (Mueller-Dombois 1992) is only possible if a large portion of the composition is dominated by even-aged, susceptible species, which is often the case in the upland Ozark forests. Evidence suggests that pre-mortality stocking does influence tree vigor significantly and that there is an age threshold for red oak decline around 60 to 65 years. As such, cohort senescence is a viable predisposing factor. However, the mechanism responsible for synchronized mortality is a series of droughts combined with a virulent and pathogen *Armillaria* root disease (over 90% of recently dead trees inspected suffered Armillaria colonization. Recent mortality appears to have abated with more adequate rainfall (data not shown) though drought conditions would certainly change this pattern.

Pockets of major mortality were predisposed by site factors such as parent material and site index , which relates to the presence of fragipans or extremely rocky soil on xeric ridges. The scarlet and black oaks on these sites were often stressed severely by the droughts of 1952-54, 1971-72 and 1980. The additional stress of the recent set of milder droughts from 1998-2001 has been the final factor synchronizing mortality within previously declining red oaks across the Ozarks.

Tree increment cores judge growth and vigor of trees with more precision if decline conditions are in question, such as in sugar maple (*Acer saccharum* Marsh.)(Duchesne et al 2003). However, in cases in which oak decline is readily apparent, crown conditions can be used effectively to judge individual tree vigor and tree growth and vigor. Those whom use or analyze data from FIA and FHM inventories might well improve their assessment of decline and forest health by refining their scale to go within the plot-level. Plot data needs to be used to characterize stand dynamics (Hyink and Zedaker 1987) but should include crown conditions grouped within crown class and species rather than standardizing conditions across species.

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